

Southern California Earthquake Center

Annual Report for 2010

NSF Cooperative Agreement 0529922

I. Introduction

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

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

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

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

- I. Introduction
- II. Planning, Organization, and Management of the Center
- III. Research Accomplishments
- IV. Communication, Education, and Outreach Activities
- V. Director's Management Report
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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 and >45 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

Table II.1. SCEC Board of Directors

Institutional and At-Large Representatives

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

Ex-Officio Members

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

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 Associate Director for Information Technology, Phil Maechling.

B. External Advisory Council

SCEC's Advisory Council (AC) is an external group charged with developing an overview of SCEC operations and giving advice to the Director and the Board. Mary Lou Zoback (of RMS Associates) completed her three year term as chair of the AC in 2010. Jeff Freymueller (University of Alaska) will be the new chair for a three year term beginning in 2011. The Advisory Council's 2010 report is reproduced in Section VI. In addition to Zoback, retiring AC

member in 2010 are Lloyd Cluff, Patti Guatteri, Kate Miller, and John Rudnicki. New AC members include Roger Bilham, Donna Eberhart-Phillips, Meghan Miller, Farzad Naiem, John Vidale, and Andrew Whittaker.

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

Table II.2. Leadership of the SCEC Working Groups

Disciplinary Committees

Seismology:	Egill Hauksson (chair)* Elizabeth Cochran (co-chair)
Tectonic Geodesy:	Jessica Murray (chair)* Rowena Lohman (co-chair)
Earthquake Geology:	Mike Oskin (chair)* James Dolan (co-chair)

Focus Groups

Unified Structural Representation:	John Shaw (leader)* Kim Olsen (co-leader)
Fault and Rupture Mechanics:	Judi Chester (leader)* Ruth Harris (co-leader)
Crustal Deformation Modeling:	Liz Hearn (leader)* Kaj Johnson (co-leader)
Lithospheric Architecture and Dynamics:	Paul Davis (leader)* Thorsten Becker (co-leader)
Earthquake Forecasting and Predictability:	Terry Tullis (leader)* Jeanne Hardebeck (co-leader)
Ground Motion Prediction:	Brad Aagaard (leader)* Steve Day (co-leader)
Seismic Hazard and Risk Analysis:	Paul Somerville (leader)* Nico Luco (co-leader)

Special Project Groups

Southern San Andreas Fault Evaluation:	Tom Rockwell (chair)* Kate Scharer (co-chair)
Working Group on California Earthquake Probabilities:	Ned Field (chair)*
Collaboratory for the Study of Earthquake Predictability:	Tom Jordan (chair)* Danijel Schorlemmer (co-chair)
Extreme Ground Motion:	Tom Hanks (chair)*
Petascale Cyberfacility for Physics-Based Seismic Hazard Analysis:	Phil Maechling (chair)*

SCEC's mission. 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 2010 began with the working-group discussions at the annual meeting in September, 2009. An collaboration plan was issued in October, 2009, and 173 proposals (including collaborations) requesting a total of \$5.3M were submitted in November, 2009.

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 13-14, 2010, 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 1-2, 2010. 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 coordinates 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 funds from special projects, such as ShakeOut, the Earthquake Country Alliance, and business outreach. 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 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 CEO activities is given in Section IV.

III. Research Accomplishments

This section summarizes the main research accomplishments and research-related activities during 2009-10 as of the time of this report. The research reported here was funded by SCEC with 2010 research funds. While the presentation is organized sequentially by disciplinary committees, focus groups, and special project working groups, it is important to note that most SCEC activities are crosscutting and could be presented under multiple focus groups.

Disciplinary Activities

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

Seismology

Four projects were funded in the Seismology Infrastructure focus group in 2009-10. These were the Southern California Earthquake Data Center, the Borehole Seismometer Network, the Portable Broadband Instrument Center, and a Caltech/UCSD collaboration assembling earthquake catalogs and measuring earthquake properties and structure. In addition, several innovative projects were funded as part of the seismology research effort.

Southern California Earthquake Data Center (SCEDC)

Major 2009 Accomplishments

1. 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 1,229,564 days of continuous data for 387 stations and parametric and waveform data for 16,004 local events and 446 teleseismic earthquakes.
2. The SCEDC purchased 64 2xTB disks to more than double the storage capacity of the waveform archive.
3. In response to user recommendations at the SCEDC town-hall meeting, the SCEDC began continuous archiving of all HN borehole channels as of Oct 1, 2009.
4. The SCEDC continues to make improvements Station Information System (SIS) with the Southern California Seismic Network (SCSN). The SCEDC replaced its single SIS with two Dell Power Edge R610 web servers. The user interface has been improved so that users can store non-response information such as telemetry equipment and layout.
5. The SCEDC hosted a mirror site to the SCEC Earthquake Response Content Management System (ERCMS) for the November 2009 ShakeOut. The SCEDC will continue to host this mirror site for SCEC.
6. The SCEDC has added QuakeML as a catalog search format. Web services for QuakeML format are also now available. Development of these services will serve as a foundation for greater capabilities for users to access data.
7. The SCEDC will continue to serve out fault data to the SCEC WGCEP group. The SCEDC is working with SCEC intern Michael Ihrig to produce a Google Map version of the Clickable Faults Map.

8. SCEDC has released a new version of the STP client that can access both the SCEDC archives in Pasadena, and the NCEDC archives at UC Berkeley, giving SCEC researchers access to continuous waveforms throughout California.
9. As part of a NASA/AIST project in collaboration with JPL and SIO, the SCEDC will receive real time 1 sps streams of GPS displacement solutions from the California Real Time Network (<http://sopac.ucsd.edu/projects/realtime>; Genrich and Bock, 2006, J. Geophys. Res.). These channels will be archived at the SCEDC as miniSEED waveforms, which then can be distributed to the user community via applications such as STP. This will allow seismologists access to real time GPS displacements in the same manner they access traditional seismic data.
10. The SCEDC is now distributing a subset of seismograms (20 km and 40 km spacing) and GPS data computed for the 2008 ShakeOut scenario. The seismic data are velocity waveforms at 40 sps in SAC format. The GPS waveforms are 1 sps displacements in SAC format. Seismic waveforms for GPS station locations are also available.
11. The SCEDC has made an interactive site to view the vertical and horizontal cross sections of the latest tomographic model of Southern California. Users can view vertical cross sections perpendicular to major faults or in north-south, east-west grid. Users can also view horizontal cross sections by different depth intervals as well as play a slideshow of cross sections.

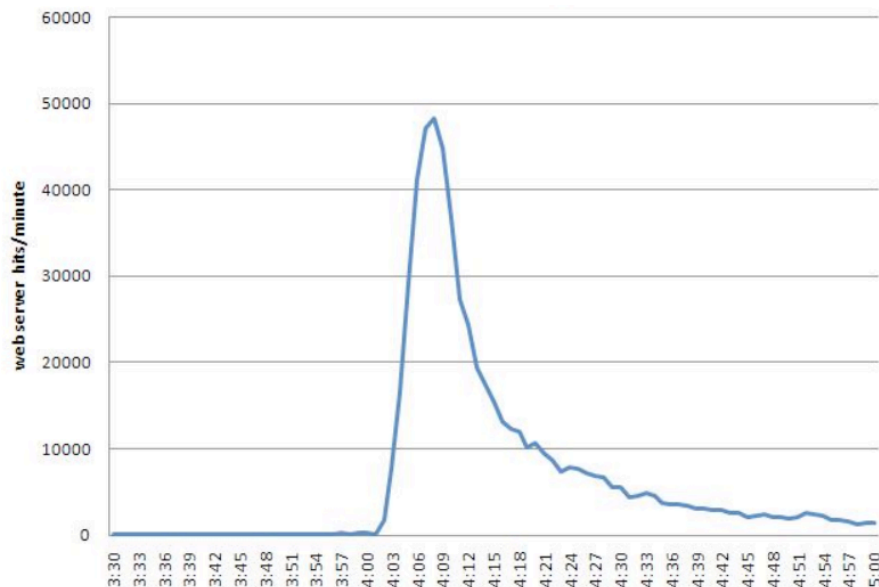


Figure 1. Web hits on SCEDC server showing a large increase in traffic seconds after the M4.4 earthquake in Pico Rivera on March 16, 2010.

The Data Center is a central resource of SCEC and continues to be an integral part of the Center. In 2009, the SCEDC continued to provide online access to a stable and permanent archive of seismic waveforms and earthquake parametric data. The seismological data archive held at the SCEDC has contributed significantly to the publication of many scientific papers pertinent to the region, most of which have SCEC publication numbers. The Caltech/USGS

catalog archived by the SCEDC is the most complete archive of seismic data for any region in the United States.

The SCEDC has allowed the data to be distributed to a much broader community of scientists, engineers, technologists, and educators than was previously feasible (Figure 1). The electronic distribution of data allows researchers in the world-wide scientific community to analyze the seismic data collected and archived in southern California and contribute their results to the SCEC community.

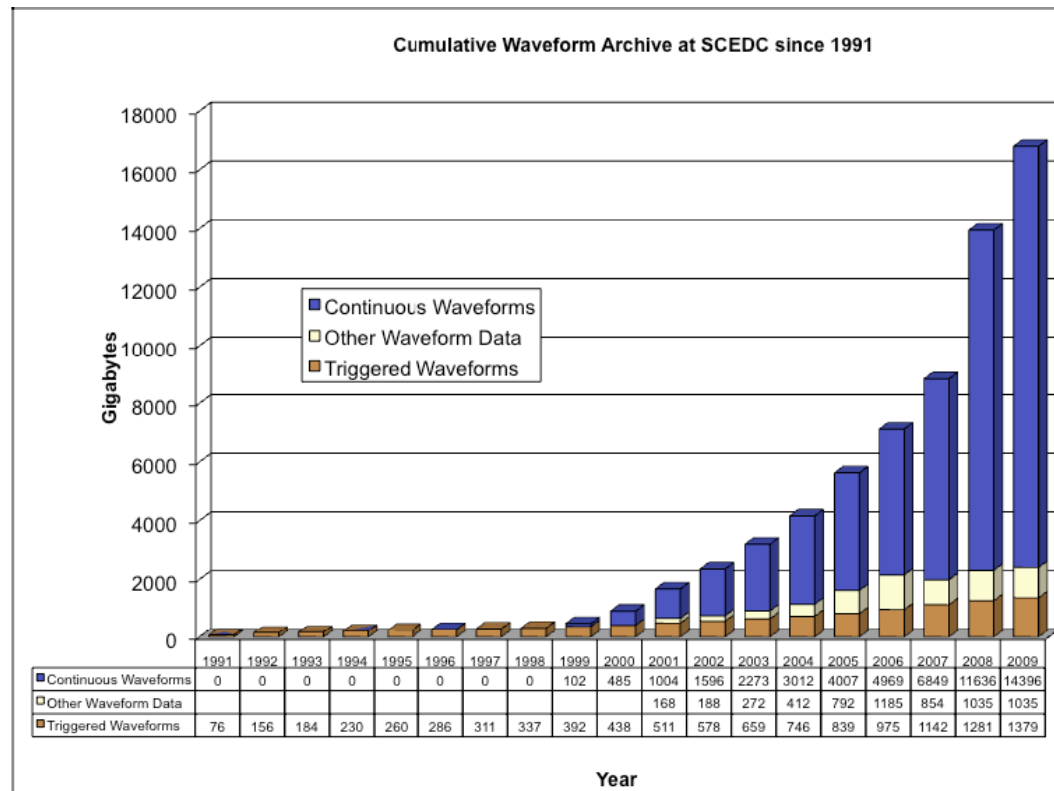


Figure 2. Cumulative waveform archive at SCEDC since 1991.

The archive at the SCEDC currently has the following holdings:

The Caltech/USGS catalog of over 627,838 earthquakes spanning 1932-present.

- 16.81 terabytes of continuous and triggered waveforms (Figure 2).
- millions of phase picks.
- 83.4 million triggered waveform segments.
- Nearly 10 years of continuous broadband and high sample short period waveform recording of representing more than 8,745,239 days of continuous waveforms.
- 20.3 million amplitudes available for electronic distribution.
- Triggered data for more than 9,789 significant teleseismic events.

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

The ever-expanding waveform archive of over 400,000 local earthquake records provides an invaluable resource for seismology research that has only begun to be exploited; however, efficiently mining these data requires the development of new analysis methods, an effort that goes beyond the limited resources of individual scientists. Through coordinated efforts common tools and data products have been developed that can be used by researchers to accomplish many SCEC goals.

The HASH algorithm (Hardebeck and Shearer, 2002 and 2003) was applied to determine focal mechanisms from the SCSN data set of first motion polarities. Removing azimuth, take-off angle, and distance filters maximized the number of mechanisms. The method developed by Shearer and Hauksson only requires more than 8 first motions for each mechanism and an azimuth gap of less than 180° . This results in 137,000 mechanisms. The algorithm provides the strike, dip, and rake for one of the two planes of each mechanism, as well as error estimates. Error estimates are analyzed to look for obvious trends that would make it possible to determine filtering values to optimize the selection of reliable mechanisms.

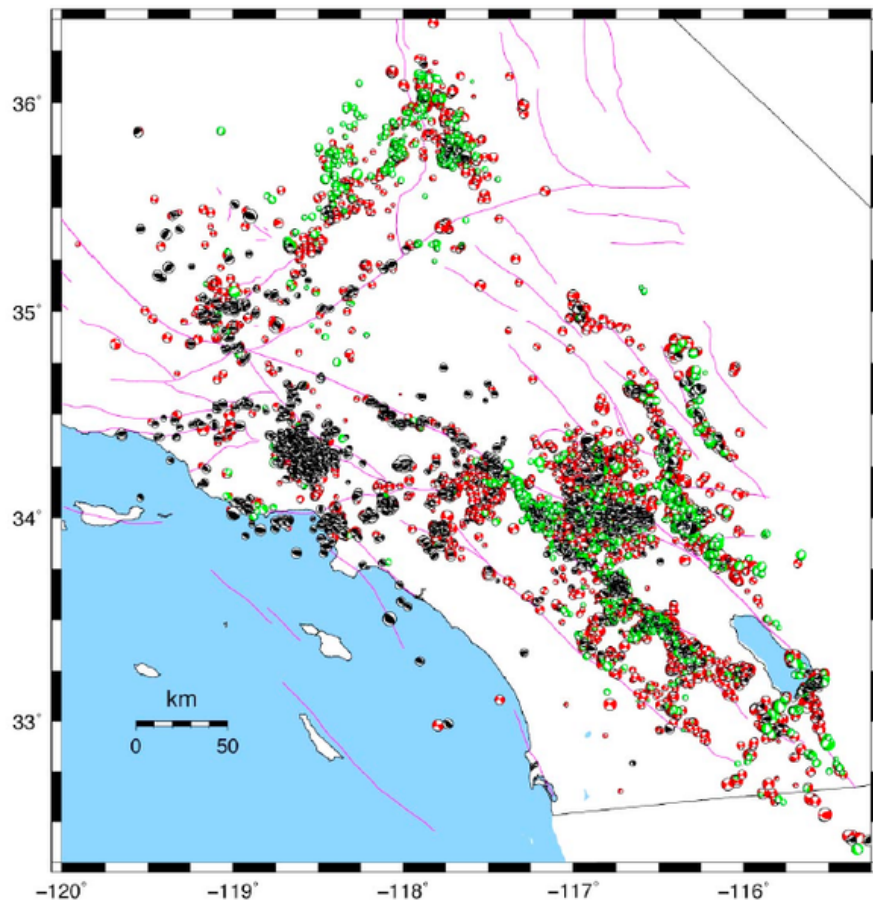


Figure 3. The ~15,000 focal mechanisms (1981 – 2009) (A, B, and C quality) selected using similar criteria as J. Hardebeck used for the previous catalog. First, the strike-slip (red) is plotted. Second, the normal (green), and thrust mechanisms (black) are plotted on top – reducing somewhat the prominence of the strike-slip events.

The average quality of the focal mechanisms and style of faulting has remained similar from 1981 to 2009. The results show that strike-slip faulting mechanisms occur across southern California and are most common along the major late Quaternary faults (Figure 3). Normal faulting mechanisms are dominant along the Salton Trough, and the northern end of the San Jacinto fault, and also occur in the southern Sierra Nevada and Coso regions. Thrust faulting mechanisms occur within the Transverse Ranges, and beneath Banning Pass extending to the west across the Los Angeles and Ventura basins.

Overall, Shearer and Hauksson found the plate boundary is characterized by strike-slip faulting with small regions of compression and extension, which results in spatial overlaps of different types of focal mechanisms. In addition, it was found that normal faulting is more common at depths between 3 and 10 km while thrust faulting is more common 3 to 5 km deeper. The temporal behavior of all the focal mechanism parameters and their errors are very similar from 1981 to 2009. Thus the tectonics of southern California as expressed by ongoing seismicity has remained similar, and the predominant style of faulting changed only during major earthquake sequences.

Analysis of Southern California Seismicity Using Improved Locations and Stress Drops

Using recent dramatic improvements in earthquake locations, focal mechanisms and stress drop estimates, a variety of issues can be addressed, including whether space/time clustering of seismicity obeys ETAS-like triggering relationships, whether precursory seismicity varies as a function of event size, and what are the space-time details of small earthquake stress drops. Preliminary analysis of stress drops reveals no obvious relationship between stress drops and the location of faults and tectonic features. It is not yet understood what may be controlling the large observed variations in stress drop and this will be a focus of future work.

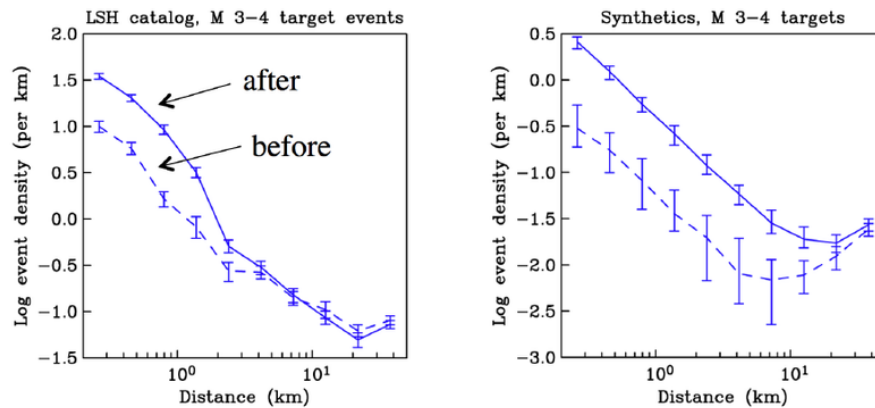


Figure 4. Event density as a function of distance in one-hour windows before and after M 3–4 target earthquakes, comparing the LSH catalog of southern California seismicity (left) with predictions of an ETAS-like triggering model (right). One-standard error bars are computed using a bootstrap resampling method.

Results suggest that there are at least some physical differences in the state existing before larger earthquakes compared to smaller earthquakes. Shearer is building on these results to study the more general problem of determining which features of the space/time clustering observed in seismicity catalogs are well-explained by ETAS-like models and which features more likely

reflect underlying physical processes. The results suggest that triggering is only resolvable to distances of about 3 km for M2-4 mainshocks, far less than the distances suggested by Felzer and Brodsky (2006) (Figure 4).

Refining and Synthesis of 3D Crustal Models and Seismicity Catalogs for Southern California

Hauksson et al. analyzed relocated background seismicity (1981-2005), and several geophysical crustal properties to improve our understanding of the brittle part of the crust in southern California, often referred to as the seismogenic zone. Crustal deformation in southern California is dominated by right-lateral shear stress caused by relative motion of the Pacific and North America plates. The major late Quaternary faults are the zones of weakness that accommodate plate boundary deformation. They also control the spatial distribution of seismicity. The dilatational crustal deformation field that causes crustal thinning or thickening is superimposed on the shear deformation but does not seem to have a significant effect on the distribution of earthquakes.

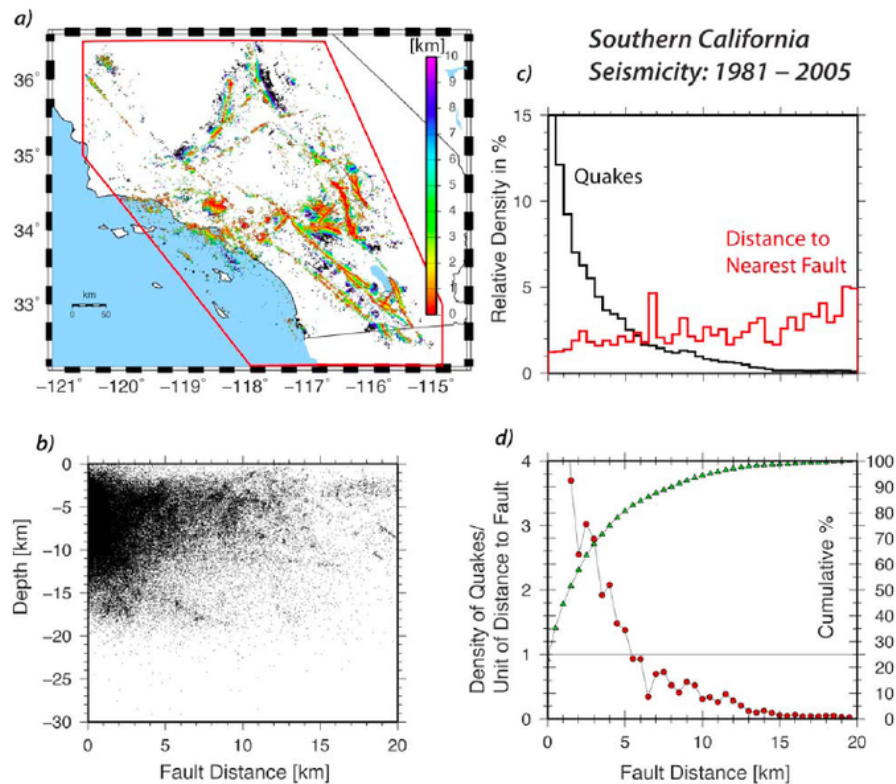


Figure 5. Fault-distance and seismicity. (a) Fault-distances for earthquakes of $M \geq 1.8$ are plotted in color. The fault traces are not included. (b) Each hypocenter is plotted at the respective distance from the nearest principal slip-surface of a late Quaternary fault. (c) Relative density of quakes and ‘fault-distance’ values for each 1 km of distance, and relative density of distances measured from a regular grid across southern California. (d) Normalized density of quakes per 1 km step in fault-distance, and cumulative number of quakes.

Seismicity preferentially occurs near the late Quaternary faults, in crust with average geophysical properties (Figure 5). Density, isostatic gravity, Vp/Vs variations, and volumetric strains affect the locations of seismicity less than proximity of late Quaternary faults. About 90% of the earthquakes occur within the available range of each of the modeled geophysical variables. As an example, the heat flow of 50 to 100 mWm², isostatic gravity of -50 to 0 mGals and GPS dilatation of -60 to 40 nanostrains/yr. Similarly, they occur at elevations less than 1600 m, depth to Moho, and average crustal Vp/Vs of 1.73 to 1.81. Relatively few earthquakes are present if the crust is too thin or too thick or the elevation is too high. Similarly, if the crust is too thin, the heat flow is very high and the deformation is spread among several faults covering a wider region. If the crust is too dense or there is minimal Quartz content, earthquakes are unlikely. Similarly, if the Vp/Vs, and density are low, and the elevation is high, the crust is too thick to accommodate through going faulting. The dynamic volumetric strains as well as modeling favor earthquakes in extensional regimes, with some earthquakes occurring in compressional regimes provided the strain rate is high enough.

Correlation between seismic clustering properties and regional physical conditions

Enescu et al. (2009) investigate the relations between properties of seismicity patterns in Southern California and the surface heat flow using a relocated earthquake catalog. They first search for earthquake sequences that are well separated in time and space from other seismicity and then determine the Epidemic Type Aftershock Sequence (ETAS) model parameters for the sequences with a sufficient number of events. The productivity parameter α of the ETAS model quantifies the relative productivity of an earthquake with magnitude M to produce aftershocks. By stacking sequences with relatively small and relatively large α values separately, they observed clear differences between the two groups. Sequences with smaller α have a relatively large number of foreshocks and relatively small number of aftershocks. In contrast, more typical sequences with larger α have relatively few foreshocks and larger number of aftershocks. The stacked pre-mainshock activity for the more typical latter sequences has a clear increase in the day before the occurrence of the main event. The spatial distribution of the α values correlates well with surface heat flow: areas of high heat flow are characterized by relatively small α , indicating that in such regions the swarm-type earthquake activity is more common. Our results are compatible with a damage rheology model that predicts swarm type seismic activity in areas with relatively high heat flow and more typical foreshock-mainshock-aftershock sequences in regions with normal or low surface heat flow. The high variability of α in regions with either high or low heat flow values indicates that at local scales additional factors (e.g., fluid content and rock type) may influence the seismicity generation process.

Zaliapin and Ben-Zion (2010) also examine the relationship between spatial symmetry properties of earthquake patterns along faults in California (CA) and local velocity structure images to test the hypothesis that ruptures on bimaterial faults have statistically preferred propagation directions. The analysis employs seismic catalogs for twenty five fault zones in CA. They distinguish between clustered and homogeneous parts of each catalog using a recently introduced earthquake cluster analysis and calculate an asymmetry index for the clustered portion of each examined catalog. The results indicate strong asymmetric patterns in early-time spatially-close aftershocks along large faults with prominent bi-material interfaces (e.g., sections of the San Andreas fault), with enhanced activity in the directions predicted for the local velocity contrasts, and absence of significant asymmetry along most other faults. Assuming the observed asymmetric properties of seismicity reflect asymmetric properties of earthquake ruptures, the

discussed methodology and results can be used to develop refined estimates of seismic shaking hazard associated with individual fault zones.

Quantifying Heterogeneity of Active Fault Zones using Fault Trace and Earthquake Focal Mechanism Data

Wechsler et al. (2010) perform a systematic comparative analysis of geometrical fault zone heterogeneities using derived measures from digitized fault maps that are not very sensitive to mapping resolution. They employ the digital GIS map of California faults (version 2.0) and analyze the surface traces of active strike-slip fault zones with evidence of Quaternary and historic movements. Each fault zone is broken into segments that are defined as a continuous length of fault bounded by changes of angle larger than 1° . Measurements of the orientations and lengths of fault zone segments are used to calculate the mean direction and misalignment of each fault zone from the local plate motion direction, and to define several quantities that represent the fault zone disorder. These include circular standard deviation and circular standard error of segments, orientation of long and short segments with respect to the mean direction, and normal separation distances of fault segments. They also examined the correlations between various calculated parameters of fault zone disorder and the following three potential controlling variables: cumulative slip, slip rate, and fault zone misalignment from the plate motion direction. The analysis indicates that the circular standard deviation and circular standard error of segments decrease overall with increasing cumulative slip and increasing slip rate of the fault zones. In other words, the range or dispersion in the data, which provide measures of the fault zone disorder, vary with cumulative slip and slip rate (or more generally slip rate normalized by healing rate), which is attributable to the fault zone maturity. The fault zone misalignment from plate motion direction does not seem to play a major role in controlling fault trace heterogeneities. The frequency-size statistics of fault segment lengths can be fit well by an exponential function over the entire range of observations.

Bailey et al (2010) present a statistical analysis of focal mechanism orientations for nine California fault zones with the goal of quantifying variations of fault zone heterogeneity at seismogenic depths. The focal mechanism data are generated from first motion polarities for earthquakes in the time period 1983–2004, magnitude range 0–5, and depth range 0–15 km. Only mechanisms with good quality solutions are used. They define fault zones using 20 km wide rectangles and use summations of normalized potency tensors to describe the distribution of double-couple orientations for each fault zone. Focal mechanism heterogeneity is quantified using two measures computed from the tensors that relate to the scatter in orientations and rotational asymmetry or skewness of the distribution. The relative differences in the focal mechanism heterogeneity characteristics are shown to relate to properties of the fault zone surface traces such that increased scatter correlates with fault trace complexity and rotational asymmetry correlates with the dominant fault trace azimuth. These correlations indicate a link between the long term evolution of a fault zone over many earthquake cycles and its seismic behavior over a 20 year time period. Analysis of the partitioning of San Jacinto fault zone focal mechanisms into different faulting styles further indicates that heterogeneity is dominantly controlled by structural properties of the fault zone, rather than time or magnitude related properties of the seismicity.

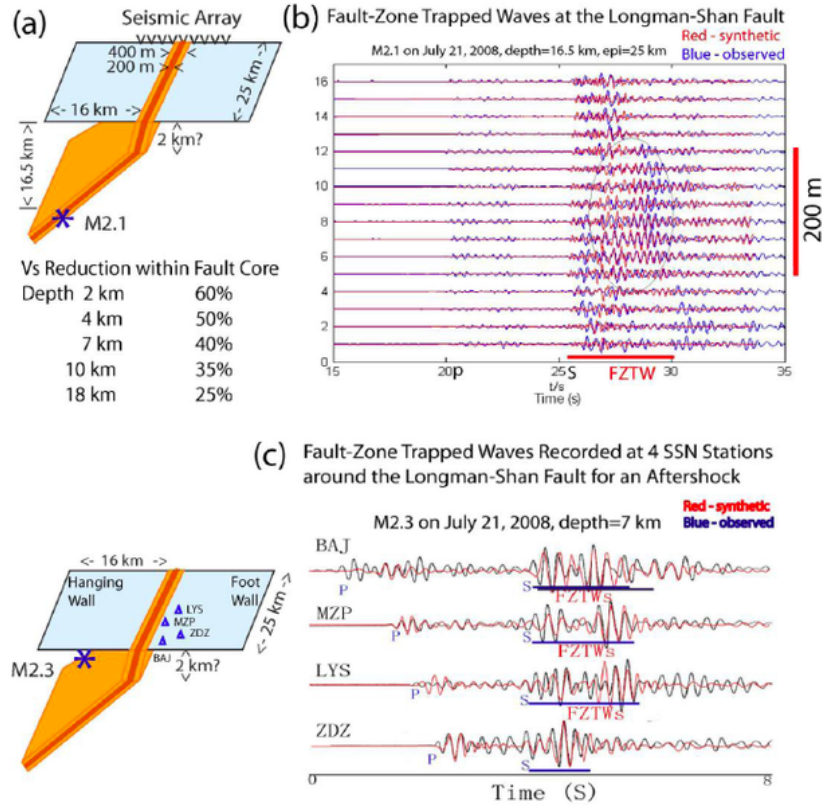


Figure 6. (a) Depth-dependent fault-zone model used to simulate FZTWs recorded at the Longman-Shan fault. The fault dips at 75 degrees above 2 km and then dips at 45 degrees at greater depths. Velocities within the 200-m-wide fault core are reduced by 25-60% from wall-rock velocities, with the maximum reduction at depths above 2 km. The fault core is sandwiched by a 400-m-wide zone with weaker velocity reductions. Q values within the fault zone are 10-60, with the lowest value within the fault core at shallow depth. (b) 3-D finite-difference synthetic seismograms (red lines) and fit to data (blue lines) recorded at the cross-fault dense array for a M2.1 near-fault aftershock occurring at depth of 16.5 km and ~25 km from the array. Seismograms are <3Hz filtered. Prominent fault-zone trapped waves (FZTWs) appear at stations within the fault core. Red bar denotes the time duration of FZTWs. (c) Observed and synthetic seismograms for a M2.3 on-fault aftershock at 7-km depth near the mainshock epicenter show prominent FZTWs with large amplitudes and long wavetrains at stations BAJ, MZP and LYZ located close to the main surface rupture, but short wavetrains after S-arrivals at station ZDZ away from the surface rupture.

A Study of Fault Damage and Healing at the Longmen-Shan Fault That Ruptured in the 2008 M8 Earthquake in China

Li documents the extent of rock damage on the Longmen-Shan fault (LSF) caused by the M8 Wenchuan earthquake and the healing rate after the mainshock by measuring fault-zone trapped waves (FZTWs). They focus on 300 aftershocks recorded at 8 Sichuan Seismological Network stations and a linear seismic array deployed across the LSF after the 2008 Wenchuan earthquake in the source region of the M8 mainshock. They observed prominent fault-zone trapped waves

characterized by large amplitudes and long wavetrains after S-waves at station MZP located close to the main rupture along the LSF, but only brief wavetrains at station GHS located on the hanging-wall and away from the LSF for the same events. The wavetrains of FZTWs envelopes increase in duration as traveltimes between station MZP and the aftershocks increase, indicating a low-velocity waveguide that extends at least 25 km along the fault strike and to 10 km depth.

They used a 3D finite difference code to investigate the geometry and material properties along and across strike of the Longmen-Shan fault. Preliminary simulations of FZTWs observed at the southern LSF suggest that the cross section of the fault zone consists of a ~200-m wide fault core sandwiched by the surrounding ~400-m wide damage zone (Figure 6). The damage zone velocities range between 65-75% of wall-rock velocities, while those of the fault core are reduced by 50% compared to intact rock. The width and velocity reduction of the damage zone of the LSF at the shallow depth delineated by the FZTWs are similar to the results from fault zone drilling in the Wenchuan earthquake source region. Preliminary results suggest that seismic velocities within the LSF zone were co-seismically reduced by ~15% or even more due to the rock damage caused by the 2008 M8 mainshock on May 12, 2008. Some healing of the fault zone is observed in the 1.5 years following the mainshock.

Effects of Off-Fault Inelasticity on 3D Dynamic Interaction of En Echelon Strike-Slip Faults

Extensive observational and theoretical studies have focused on the fault zone structure for strike-slip faults. A low-velocity fault zone embedded in the surrounding medium has been identified, which is likely due to repeated damage by historic events on fault. The recent 3D dynamic rupture models incorporating pressure-dependent off-fault yielding have confirmed the ‘flower-like’ fault zone structure (e.g., Ben-Zion et al., 2003; Rockwell and Ben-Zion, 2007; Cochran et al., 2009) and widespread near-surface inelastic response (e.g., Schaff and Beroza, 2004). The fault zone structure for dipping faults, however, has received much less attention. Very few fault-zone trapped wave studies have been carried out for dipping fault and few theoretical studies have investigated the inelastic off-fault response for dipping faults and explored the distribution of rupture-induced irrecoverable deformation. Here, Ma et al. explore the distribution of inelastic strain induced by rupture propagation on a 30° reverse fault and a 60° normal fault by simulating 2D inelastic dynamic ruptures with a Mohr-Coulomb yield criterion.

Ma (2009) explored the distribution of inelastic strain for reverse and normal faults (Figure 7). For the reverse fault, the hanging wall and footwall is in the compressional and extensional regime of rupture propagation, respectively. The inelastic strain is seen in the footwall only at depth (below approximately 1.2 km depth). In the upper 1.2 km the inelastic zone broadens dramatically in both the hanging wall and footwall due to a smaller confining pressure. This leads to the formation of a highly skewed ‘flower-like’ structure bounded at the top by the free surface. The inelastic strain is larger and broader in the hanging wall than the footwall even though the hanging wall is in the compressional regime.

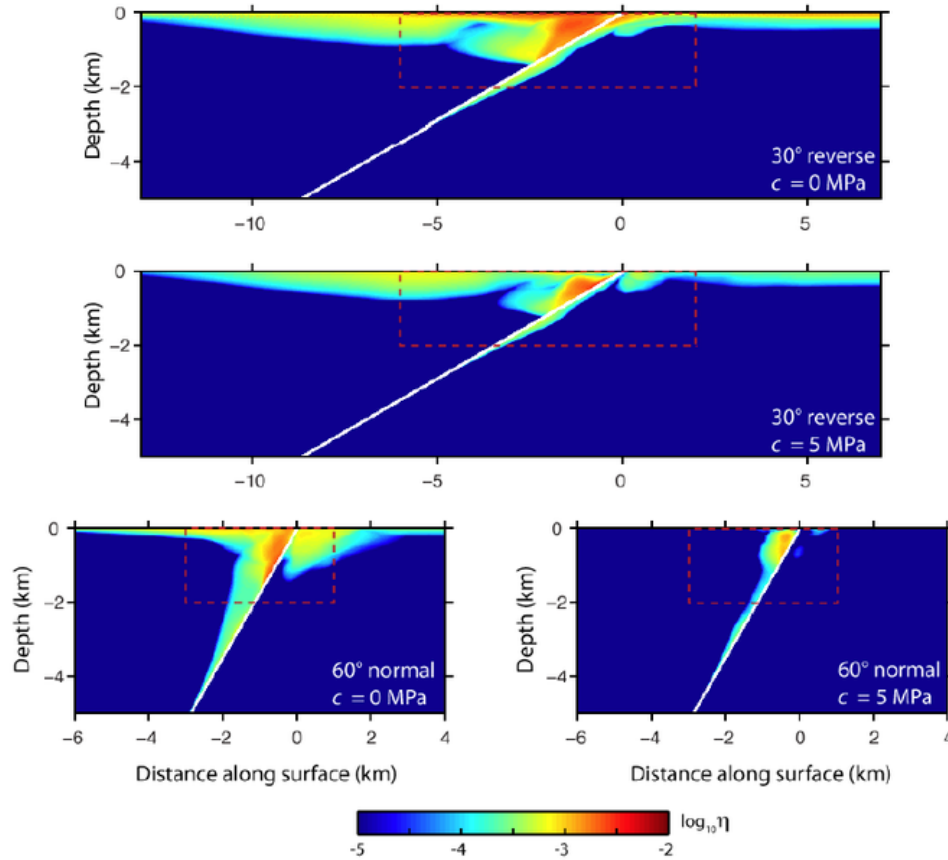


Figure 7. The inelastic strain η is mapped using a logarithmic scale. The inelastic zone widens as it moves up dip, forming a skewed ‘flower-like’ structure bounded at the top by the free surface. The ‘flower-like’ structure for the 30° reverse fault is more skewed than the 60° normal fault due to a smaller fault dip. The inelastic zone is larger with higher inelastic strain on the hanging wall than the footwall.

Distribution of Non-Volcanic Tremor Near Anza, California

Cochran and Wang examined surface and borehole seismic data from the region around Anza, California to begin searching for ambient and triggered tremor along the San Jacinto Fault near Anza, California. This region was chosen because there is a dense seismic network and tremor had been previously observed during the passage of the surface waves from the 2002 Denali earthquake. The stations were part of the Anza (AZ) network, the CISON network (CI), and the PBO network (PB). Initial data analysis included orientating the borehole stations and creating an Antelope database of the continuous waveforms.

Data from 2001 to 2008 was examined for tremor triggered by surface waves from teleseismic earthquakes near the Anza gap section of the San Jacinto Fault. Forty-one large earthquakes with magnitudes equal or greater than 7.5 and at a range of back-azimuths were examined. Because of the relatively small amount of data the search was done manually to ensure no episodes of tremor were missed. They found that only the Denali earthquake had triggered tremor (Figure 8), but did find a number of local earthquakes occurred during the passing surface waves of many of the events. Analysis of the fault parallel, fault perpendicular,

and vertical teleseismic surface wave amplitudes indicated that Denali earthquake had the highest surface wave amplitude compared to the 40 other events. The period around peak amplitude of Denali surface wave lies within the average of 40 other teleseismic events and is not significantly different.

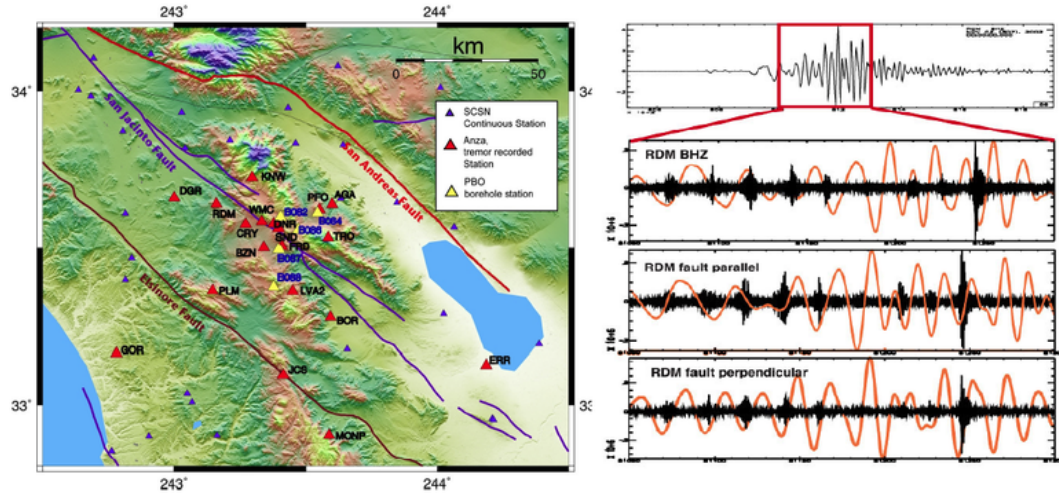


Figure 8. (Left) Map of SCSN and borehole seismic stations (red, blue and yellow triangles, respectively). Selected stations used in constrained tremor detection are shown as red and yellow triangles. (Right) Waveform examples of Denali tremor on station RDM that is triggered by the passing surface waves of the Denali earthquake. The upper panel shows the Denali earthquake recorded on the vertical component of RDM. The region that is expanded in the lower panels is highlighted in red. The lower panels span 250 seconds and show all three components (vertical, fault parallel, and fault perpendicular). The orange curves show the surface waves of the earthquake in nm/sec and the black curves show the data filtered between 2-8 Hz (amplitude is exaggerated by 20,000).

Systematic Analysis of Non-Volcanic Tremor in Southern California

A systematic analysis of non-volcanic tremor in southern California could provide important new information on the fault mechanics on the deep extension of the crustal faults and may shed new light on the predictability of large earthquakes. Zhigang Peng and his colleagues studied 30 large teleseismic events with $M_w \geq 7.5$ since 2001, and found that only the 2002 $M_w 7.8$ Denali Fault earthquake triggered tremor in all these regions, including the San Gabriel Mountain (SGM) where neither triggered nor ambient tremor has been observed before. These results suggest a relative lack of widespread triggering in Northern and Southern California (Figure 9), which is in contrast with the finding of multiple events that triggered tremor in Central California, Japan, Cascadia, and Taiwan.

Recently, Aguiar et al. (2009) and Brown et al. (2009b) have detected several cases of triggered tremor by regional and teleseismic events around the SJF and the Calaveras fault based on the waveform matched filter technique (Brown et al., 2008, 2009a). The difference between their results and ours mainly lie in the fact that we are using visual inspection to detect triggered tremor. Hence, we may omit weak triggered tremor signals that are close or below the

background noise levels. The tremor observed near the Calaveras fault and SJF appears to be initiated by Love waves, and becomes intensified during the large amplitude Rayleigh waves. The tremor triggered in Simi Valley and SGM only shows weak correlations with the Rayleigh waves. Peng's research group suggests that variability in the background tremor rate or different tremor triggering threshold could be the main cause of the different behaviors.

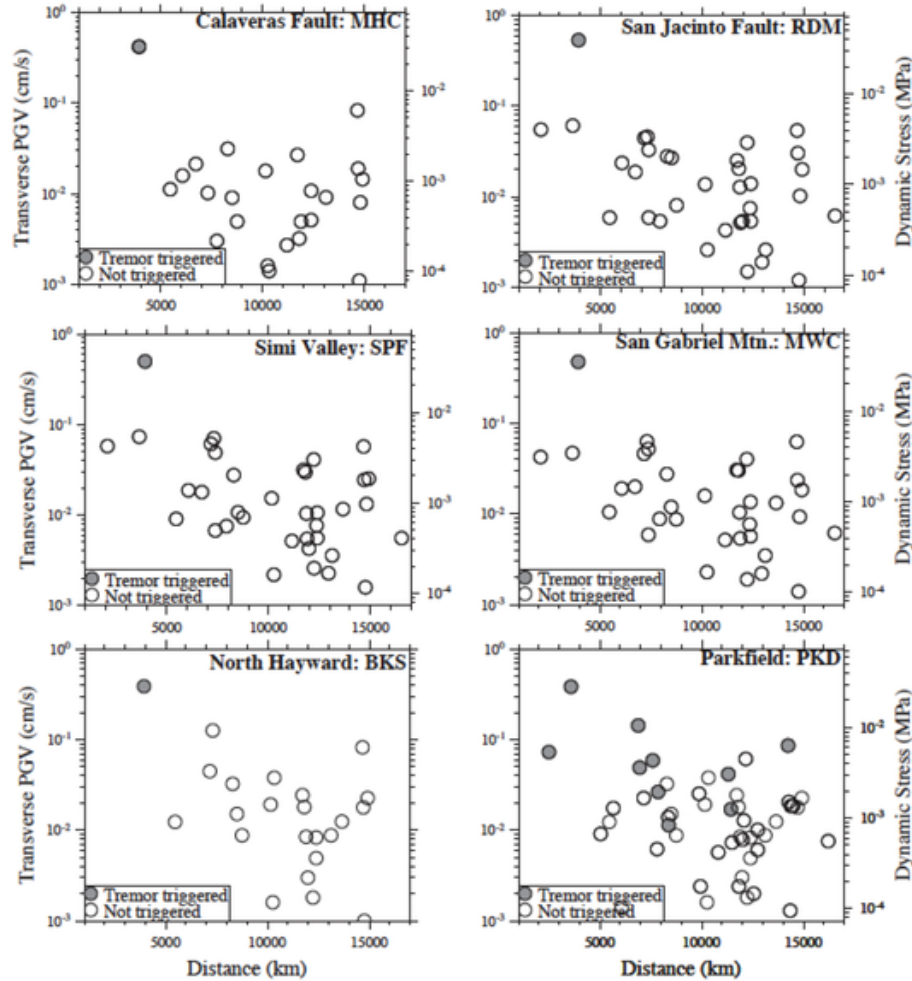


Figure 9. Peak ground velocities (left vertical axis) and related dynamic stresses (right vertical axis) for the transverse components measured at broadband stations in each studied region of California, plotted against the distance from the event to the station specified on plot label. Gray circles are events that caused tremor to be triggered in that area, open circles are events that did not trigger tremor.

Triggering Effect of the 2004 M6 Parkfield Earthquake on Earthquake Cycles of Small Repeating Events

A repeating earthquake sequence (RES) is a group of events that ruptures the same patch of fault repeatedly with nearly identical waveforms, locations, and magnitudes. The recurrence properties of RES are suggestive of a renewal process taking place on the repeatedly rupturing fault patches and thus provide crucial information about the nature of the earthquake cycle and

the physics of earthquake rupture. After the 29 September 2004, M 6.0 Parkfield, California earthquake, a large number of postseismic repeats of small earthquakes are observed.

Burgmann et al. analyze a subset of 34 M -0.4 ~ 2.1 repeating earthquake sequences (RES) from 1987-2009 at Parkfield to examine the variation of recurrence properties in space and time. Many of the repeating events strongly accelerated following the Parkfield earthquake with greatly reduced recurrence intervals (Tr) that increase systematically with time following Omori's law (Chen et al., 2010). They find systematic changes in seismic moment (Mo), where many sequences experienced an immediate increase in Mo and subsequent decay as Tr approaches pre-2004 durations (Figure 10). The RES at shallower depth tend to have a larger range in both Tr and Mo , whereas deeper RES shows small variation. These sequences reveal large variation in Tr but small variation in Mo . Earthquake simulations with rate- and state-dependent friction show that slip of velocity weakening asperities surrounded by a velocity strengthening fault is increasingly aseismic as the asperity patch size and loading rate decrease. These models predict that the degree of postseismic variation in Mo and Tr is a function of event size, consistent with the observation of decreasing Mo with increasing Tr for small RES. With a smaller percentage of aseismic slip during rupture, a small asperity appears to grow in Mo under high loading rate, which is contrary to the view that Mo should decrease due to a reduced healing time.

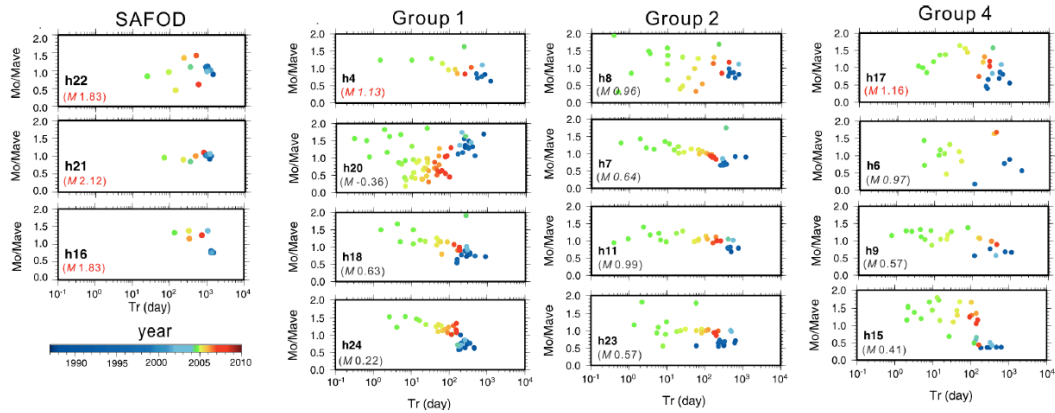


Figure 10. Relative moment as a function of recurrence interval for several groups of repeating earthquake sequences, color coded by the time of repeating events. Blue and green-to-red dots indicate pre- and post- Parkfield events, respectively.

Towards Strong Ground Motion Prediction Using Amplitude Information from the Ambient Seismic Field

Beroza et al. use the ambient seismic field for several aspects of ground motion prediction, including: validation of the ambient-field response against moderate earthquakes, developing a library of Green's functions for improving southern California velocity models, and developing a preliminary attenuation model for the southern California crust. The approach was validated by comparing the amplification effects in sedimentary basins using several well-recorded earthquakes and the ambient seismic field. They use the inter-station complex coherence derived through deconvolution and stacking to extend the analysis that we performed previously for Rayleigh waves on vertical components (Prieto et al., 2009) to all three components, and hence to Love waves. They are currently refining a library of Green's functions to refine crustal

wavespeed models in southern California. In addition, they observed some paths with strong sensitivity to sedimentary basins and developed a preliminary laterally varying model of attenuation by quantifying these observations (Figure 11).

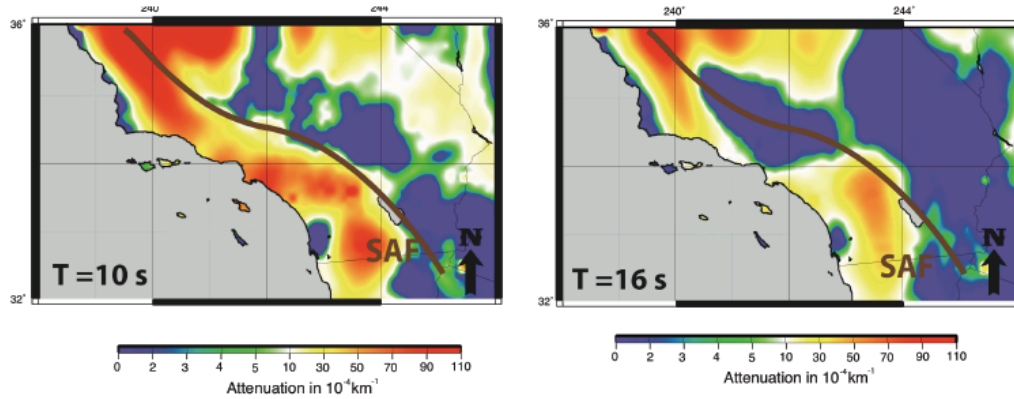


Figure 11. Preliminary maps of attenuation based on analysis of ambient noise vertical component data at periods of $T = 10$ and $T = 16$ s.

Using Seismic Noise for the Purpose of Improving Shallow S-Wave Velocity Models

Seismic noise provides important information for shallow S-wave velocity structure. Some parts of noise consist of high-frequency Rayleigh waves (0.1-0.4 Hz) whose properties are sensitive only to shallow depths and thus contamination from deep structure can be avoided without any problems. For the determination of shallow structure, this is an advantage over approaches based on body waves because use of body waves inherently leads to trade-offs between shallow and deep structure.

Tanimoto et al. are combining two analysis methods for seismic noise in order to improve shallow S-wave velocity structure in Southern California: the first is the noise correlation method, which yields Rayleigh-wave phase velocity maps for frequencies 0.1-0.2 Hz. The other is the Z/H method (H/V) for 0.1-0.4 Hz, which is particularly useful for constraining even shallower structure. By performing a joint inversion the aim is to obtain an improved, detailed structure for the upper crust (depth 0-10 km). A merit of inverting the two types of data is that depth ranges of sensitivity for phase velocity and ZH ratios complement each other and both are essential to determine S-wave velocity structure in the crust. The S-wave velocity maps at shallow depths show reduced velocities in the Los Angeles Basin and along the Newport-Inglewood fault (Figure 12).

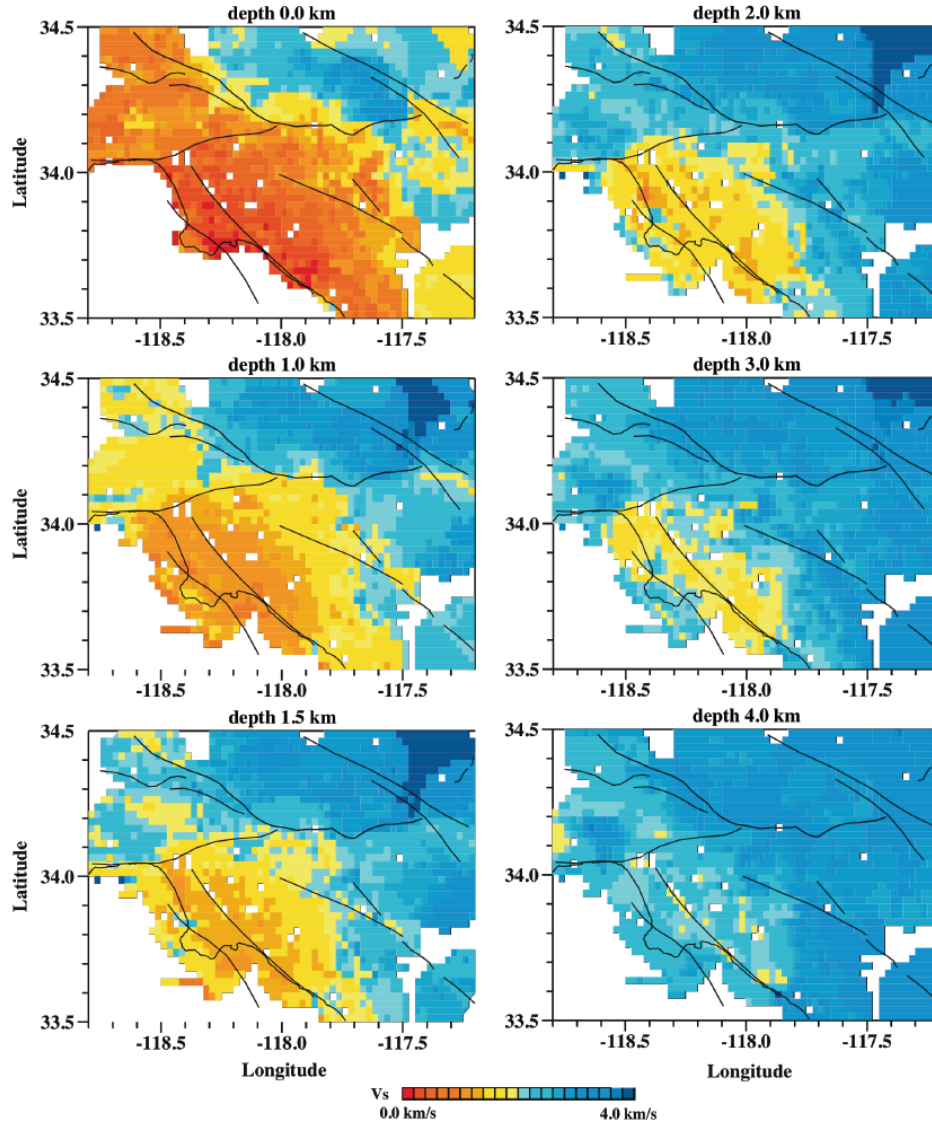


Figure 12. Preliminary results for the seismic noise joint inversion. Slow S-wave velocity in the basin is obvious. In particular, a prominent low-velocity anomaly can be seen along the Newport-Inglewood fault.

What can we learn about the greater Los Angeles Basin from the 2008 July 29 Mw5.4 Chino Hills Earthquake

Lin et al. developed three-dimensional P- and S-wave velocity models for the 2008 Mw5.4 Chino-Hills earthquake region in the greater Los Angeles basin, southern California by using the double-difference tomography algorithm (Zhang and Thurber, 2003). A checkerboard resolution test is used to assess the robustness of the model. They obtain first-arrivals for all local events in the study area from the Southern California Seismic Network (SCSN) and select 2870 events above magnitude 1.0 with more than 8 P and 2 S picks as the master events for the seismic tomographic inversion. In order to improve resolution in the seismically active areas where the differential data provide dense sampling, they also include catalog differential times and assembled P arrival times for 15 active-source data (from the Los Angeles Regional Seismic

Experiment (LARSE, Murphy et al., 1996; Fuis et al., 2001b) in order to constrain absolute event location and shallow crustal structure. They start with a one-dimensional (1D) velocity model derived from the layer-average values of the 3D CVM-H model to solve for new Vp and Vs models.

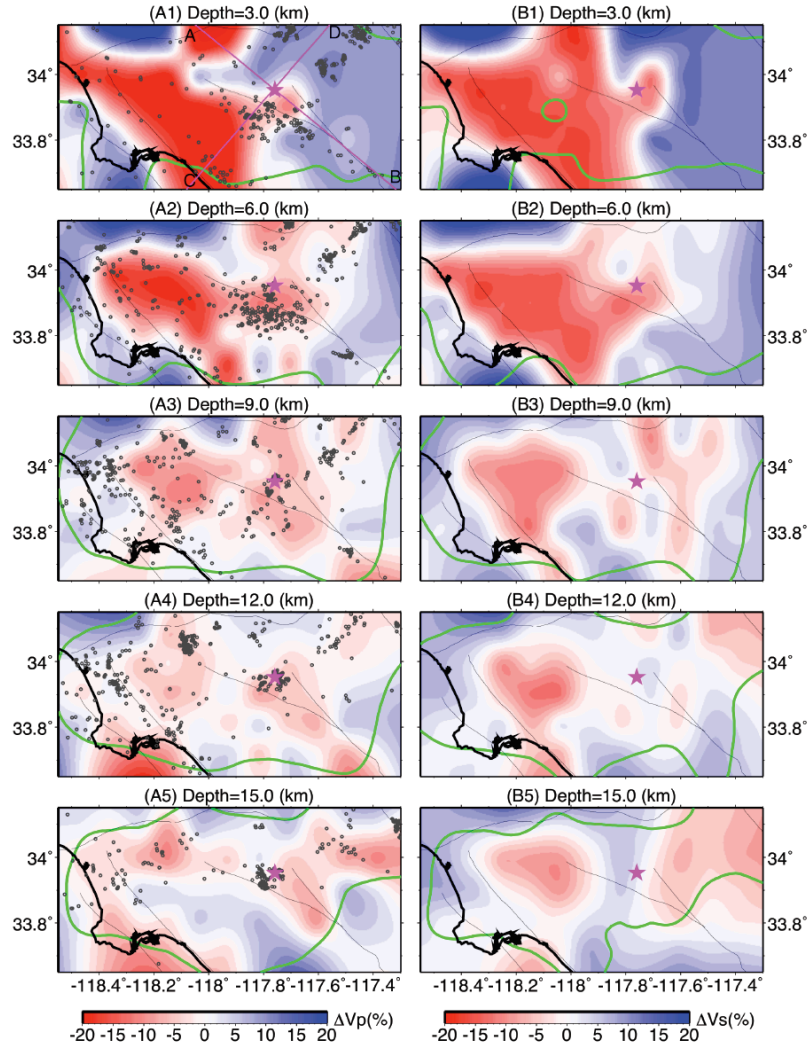


Figure 13. Map views of velocity perturbations relative to layer average at different depth slices. (A1)-(A6): Vp model; (B1)-(B6): Vs model. Black lines denote coastline and surface traces of mapped faults. Black dots represent relocated earthquakes, pink star epicenter of the 2008 Chino earthquake. The green contours enclose the well-resolved area.

The new P and S-wave velocity models, determined from both absolute and differential times, shows strong velocity contrasts around the 2008 Chino Hills mainshock. Figure 13 shows the map view slices of the P-velocity model at different depth slices between 3 and 15 km. The most significant difference between Lin et al.'s model and the CVM-H model is a local velocity contrast around the 2008 mainshock area. The CVM-H model shows a high velocity anomaly starting at 9 km depth from north near the junction between the Hollywood Fault and the Sierra

Madre fault zone to the southern section of the Newport-Inglewood Fault. This anomaly cuts the northwest end point of the Whittier Fault, leaving the 2008 earthquake area relatively smooth. Similar high velocity anomalies are also seen in the Lin et al. model, but start at the deeper layer of 12 km, extending toward the east side and stopping at the location of the 2008 Mw 5.4 Chino Hills mainshock.

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Tectonic Geodesy

Transient Detection

The transient detection exercise supported through most of SCEC 3 has the goal of identifying promising algorithms for the detection of temporal fluctuations in the geodetically measured strain field. This effort began with a short workshop in the summer of 2008, and has continued with an exercise involving the analysis of synthetic data by a number of groups pursuing a wide range of detection strategies. A second workshop, where participants presented methodologies and results, was held at the SCEC annual meeting in September, 2009.

Part of the effort involved funding for Duncan Agnew to generate realistic synthetic data sets, a process that has evolved over the course of the three test phases to date, as participants request progressively more sophisticated synthetic data. The most recent iteration of the freely available code for generating this data (FAKENET), includes secular velocities, data gaps, white, flicker and random-walk noise, common-mode seasonal noise dependent on the distance between stations, and tectonic transients that have temporal and spatial variability (i.e., that can propagate along the fault).

All groups detected the transients in Phase I and Phase II group A when the signal was large and had a short timespan relative to the length of the time series. One category of approaches encompasses those involving only characteristics of the signal, such as principle component or multi-trend time series analysis (Ji and Herring, Kreemer and Zaliapin) and the use of wavelets to model spatially or temporally coherent patterns in displacement data (McGuire and Segall, Simons and Zhan). Another category requires some model of the physics driving ground deformation (e.g., Meade, Segall et al.).

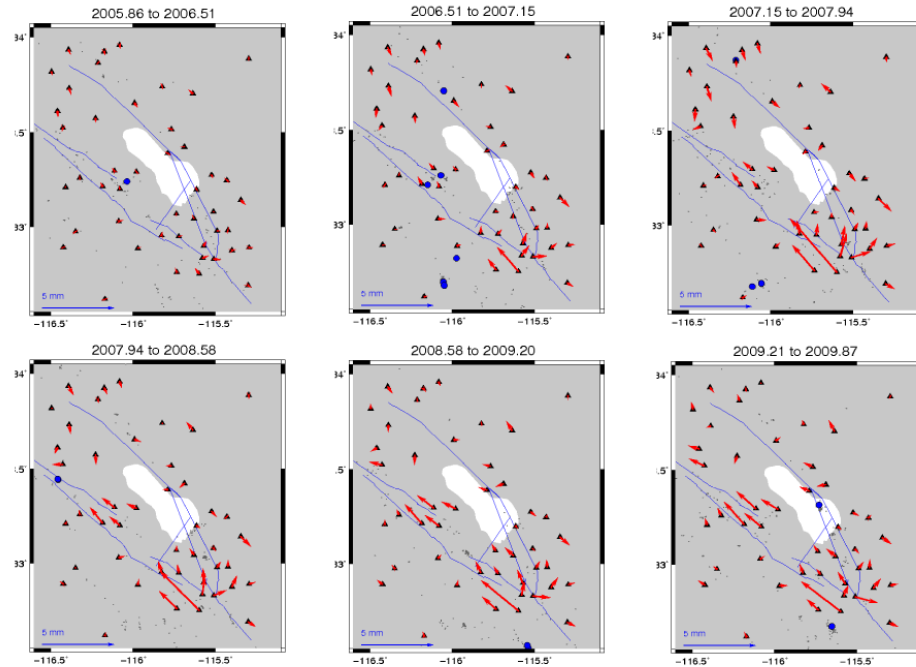


Figure 14. Transient displacement field detected by the Network Strain Filter from 2006-2009 using SCIGN+PBO data.

Advances for this year include McGuire and Segall's application of their Network Strain Filter, which now includes regularization, to real data (Figure 14). They detect several-month-long signals along the Superstition Hills and San Jacinto faults, as well as 1-2 mm offsets associated (but not co-located) with the 2009 Bombay Beach earthquake swarm and the 2008 Cerro Prieto earthquake swarm. In addition to the Network Strain Filter, Segall et al. further developed two other approaches to identify transients. The first detects changes in the time-variable fault slip estimated using a Kalman filtering approach (the Network Inversion Filter). The second uses a Monte Carlo Mixture Kalman Filter (MCMKF) and identifies transients at times when the size of the random walk parameter controlling fault slip exceeds a threshold to a statistically significant degree. Meade developed an alternative to the computationally expensive MCMKF, named the Covariance Candidate Filter, which tracks the statistical behavior of particles rather than having to store the exact behavior of each particle as it runs through the filter. Simons and Zhan extended earlier work to develop an event detector based on detection of transient signals in time series followed by multi-scale wavelet analysis of the transient trends to identify spatially-coherent signals. Herring and Ji continued work on an approach which applies principal component analysis to time series from which trends and seasonal terms have been removed using a first-order Gauss-Markov smoothing algorithm. Kreemer and Zaliapin focused on refinements to their multi-trend analysis detection algorithm.

Other groups have explored facets of the problem of detecting transients with geodetic data without participating in the official exercise. Thurber and colleagues developed a workflow for inverting for slip on faults and identifying whether the error bounds on the signal were larger than the data noise, and applied their approach to data spanning postseismic deformation associated with the 2004 Parkfield earthquake. Lohman worked on developing a synthetic test

that would assess whether the addition of InSAR observations from a dense temporal stack of SAR imagery can improve Kalman Filter-based analyses of continuous GPS data.

The next phase of work involves the use of a more realistic synthetic data set and real data provided by Tom Herring. Some effort was put into making it not immediately obvious which of the test datasets used real vs. synthetic data, although it is likely that most of the groups were able to figure out which was which. The results will be unveiled at the SCEC annual meeting in September 2010.

A related effort involved the generation of GPS time series products that merge all of the available data from PBO and SCIGN under a uniform processing scheme. This is of key importance to the ultimate goal of the transient detection exercise, which involves implementing a transient detector on real data.

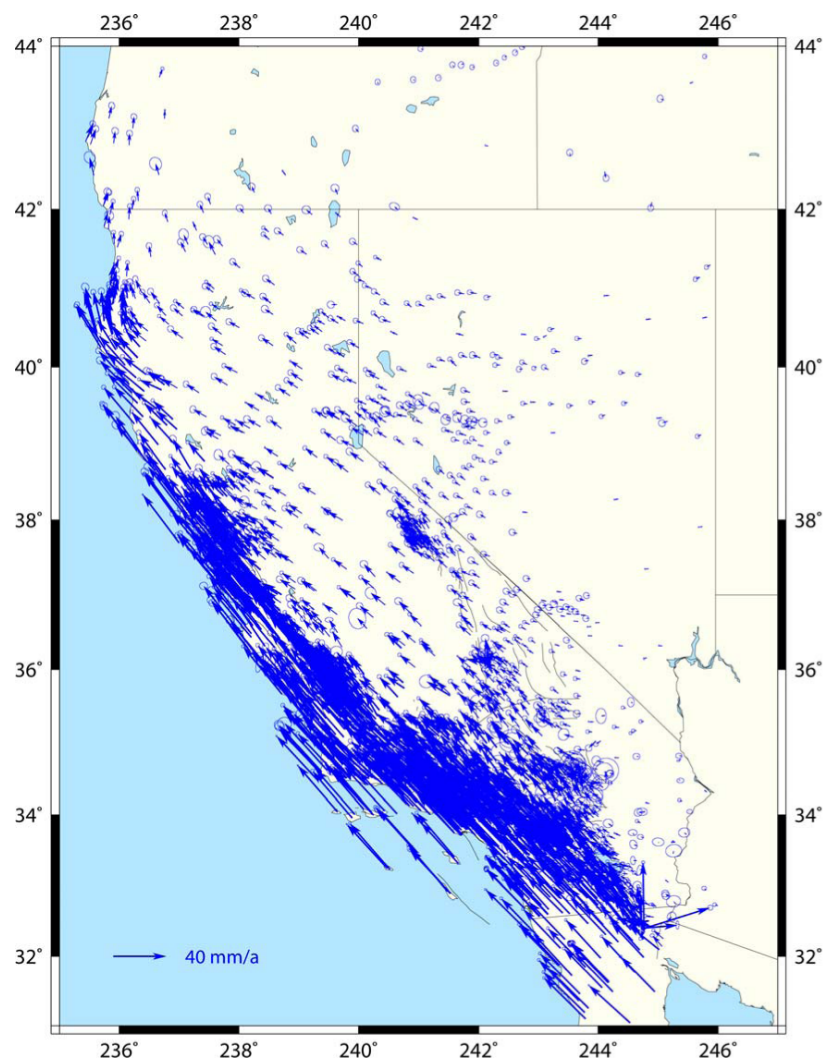


Figure 15. Crustal Motion Map. GPS horizontal station velocities with respect to the SNARF reference frame. Error ellipses represent 95% confidence.

Acquisition and Interpretation of New Data

Shen et al. completed the compilation of a new velocity field which they have named the Southwest US Crustal Motion Map version 1.0 (SWUS CMM1) (Figure 15). This data product covers an area spanning from 31° to 44°N and 114°-125°W and includes all survey-mode GPS data collected between December 1986 and March 2009. These data were reprocessed and the solutions merged with the SOPAC solutions for continuous GPS sites in this region. Velocities were estimated using a Kalman filter and accounting for the effects of major earthquakes.

Fialko and colleagues expanded the spatial and temporal coverage of their analysis of SAR data for the Coachella Valley-San Bernardino-Mojave segments of the southern San Andreas Fault and Eastern California Shear Zone. By stacking the data to reduce atmospheric noise they have produced line-of-sight time series useful for studying secular deformation. Using these data they have estimated the rate and depth-extent of creep on the Superstition Hills Fault and observed a slow slip event that occurred there in 2006.

The Tectonic Geodesy group participated actively in the SCEC response to the El Mayor-Cucapah earthquake of April 4, 2010, helping to coordinate geodetic data collection conducted by several groups. A number of PIs are currently conducting investigations related to this earthquake as noted below.

This year, SCEC continued support of the strainmeters at Piñon Flat observatory. 2009 proved to be an interesting year with a long-term fluctuation across the three strainmeters that may be consistent with slip on the San Jacinto fault. The laser and borehole strainmeters also captured offsets (on the BSMs) and dynamic strains from the El Mayor-Cucapah earthquake.

Data from the B4 lidar project received additional attention this year, with Lynch, Hudnut and Bevis combining field projects with use of the lidar data set, and Oskin, Cowgill and Kreylos developing a tool that identifies fault offsets with cross-correlation approaches. They are currently applying their approach to data spanning the El Mayor-Cucapah earthquake in Baja California.

Sandwell and colleagues are continuing their campaign surveys of geodetic benchmarks within the Imperial Valley, exploring both the deformation associated with the 2008 seismic swarm at Obsidian Buttes, and new monuments across the Imperial fault near Mexicali. They also responded to the El Mayor-Cucapah earthquake.

Modeling of Deformation (Crustal and Uppermost Mantle)

SCEC continued support of the summer workshop on numerical modeling of crustal deformation. The workshop includes two days of intensive tutorials on meshing packages and numerical modeling approaches, followed by three days of scientific talks, which help motivate discussions of where the modeling efforts should focus in the future. SCEC also funded several studies that explore what models of ground deformation can tell us about the relative importance of various driving forces, why fault slip rates inferred from geodetic data are often significantly different from geologically-constrained rates, and how geodetic data can be used more fully in hazard assessments such as UCERF3.

Becker and colleagues developed visco-plastic, 3D models for regional deformation modeling that incorporate the effects of gravitational potential energy and buoyancy forces due to density variations, viscous flow in the lower crust and uppermost mantle and edge driving

forces. Their work explores whether regions such as the Transverse Ranges would be expected to be under tension or compression in various regimes where they vary the strength of surrounding fault zones and compare buoyancy forces due to crustal and mantle topography with those expected from mantle flow. They find that mantle flow is a secondary effect given the range of parameters examined in their study.

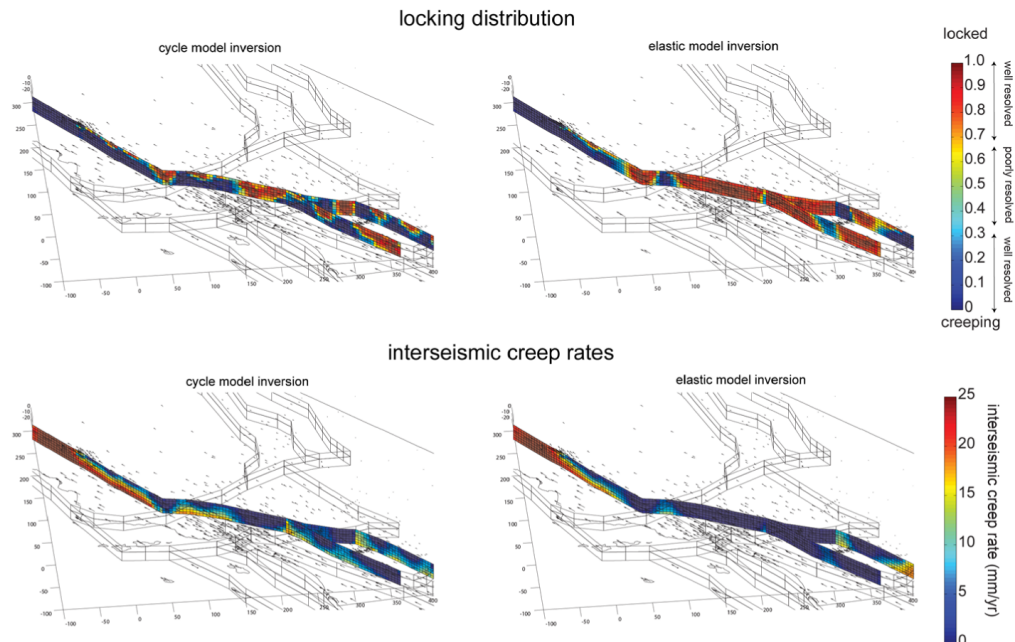


Figure 16. Distribution of locked and creeping patches and interseismic creep rates for viscoelastic cycle model and elastic half space model. Locking/creeping values and interseismic creep rates are the mean values from many thousands of Monte Carlo samples.

Johnson and Chuang explore a similar question and assess the impact of ignoring mantle flow on block models based on geodetic data. Their model with an elastic crust overlying a Maxwell viscoelastic lower crust and mantle does a good job of reproducing fault slip rates that are compatible with geologic estimates. They also find that the elastic-only models typically predict deeper locking depths than their viscoelastic model (Figure 16).

Smith-Konter and colleagues validated their stress accumulation model, both by compiling a more complete archive of slip models, and comparing their fault geometry to other data sets. They are also preparing for efforts to combine GPS and InSAR observations.

Charles Williams applied the Pylith finite element code to a 3000-year history of simulated earthquakes, after improving the computational efficiency of the code to the point where such an exercise became feasible. He has now compared the response of heterogeneous and homogeneous elastic and Maxwell viscoelastic spaces using the SCEC community velocity and fault models when appropriate. They identify regions where the geodetic velocities would differ significantly for ten years or more after an 1857 event, depending on the constitutive properties applied during their modeling.

Steven Ward continued development of methods for including geodetic data in earthquake simulators by developing the software infrastructure for, and conducting a joint inversion of, geodetic and geological data.

Earthquake Geology

The SCEC geology disciplinary group coordinates diverse field-based investigations of the Southern California natural laboratory. The majority of Geology research accomplishments fall under two categories: (1) focused studies of the southern San Andreas and San Jacinto faults in coordination with the SoSAFE (Southern San Andreas Fault Evaluation) special project; and (2) studies of other portions of the southern California fault network aimed at a better understanding fault system behavior. Geology also continues efforts to characterize outstanding seismic hazards to the urban region, and supports field observations related to several focus-group activities (e.g., USR, WGCEP, FARM, GMP, LAD, CDM). Additional goals include longer-term slip rates and deep-time, multi-event paleoseismologic records that have a high impact on seismic hazard assessments. In support to these efforts the Geology group coordinates geochronology infrastructure resources that are shared among various SCEC-sponsored projects.

Southern San Andreas Fault Evaluation (SoSAFE)

The primary goal of the Southern San Andreas Fault Evaluation (SoSAFE) project is to document the timing of large paleoearthquakes and amount of slip released by the southern San Andreas and San Jacinto faults over the past 2000 years. Additional goals include examination of longer-term slip rates and modeling studies that directly impact seismic hazard assessments. SoSAFE is funded by SCEC, leveraging funding from the USGS Multi-hazards Demonstration Project. Research includes earthquake trenching studies, radiocarbon dating supported through the geochronology infrastructure funding, geomorphic studies using lidar and other aerial imagery data in tandem with field measurements, and examination of new methods for analyzing and incorporating neotectonic data. A workshop, led by Kate Scharer and Tom Rockwell, highlighting the 2008-2009 accomplishments was held during the SCEC Annual Meeting in September, 2009 and attracted ~125 attendees. The workshop ended with a discussion aimed at generating new ideas for integrating paleoseismic data along the fault and use of such models in formal earthquake hazard assessments (e.g. UCERF).

SCEC researchers made significant advances at several sites along the northern San Jacinto Fault in 2009 and 2010. Intriguing new results from trenches excavated Nate Onderdonk and Rockwell across an ephemeral sag at Mystic Lake revealed six paleoearthquakes on the Claremont fault since ~300 A.D. Three of these events are of similar age to earthquakes documented at the Hog Lake site, raising the possibility of fault interaction between the Claremont and the Clark fault. At the Quincy site, Sally McGill and Onderdonk excavated an offset paleo-channel that provides a new slip rate of 9.5 to 23 mm/yr; the preferred offset of 17 \pm 2 mm/yr is consistent with the displacement of five nearby channels. Two additional offset landslides have been mapped and upcoming 10Be dating should provide slip rates for this part of the fault.

Farther south, on the Clark strand of the San Jacinto fault, field and B4 lidar measurements of 55 offset features reveal the slip distribution of past ruptures to the north and south of Anza. These measurements suggest that the Clark fault experiences average displacements of ~3 m, and may have generated the 1918 M6.9 earthquake. A study of longer-term slip rate variability along

the Clark fault based on ^{10}Be and U-series dating of offset alluvial fans shows decreasing slip on the Clark fault towards its southern end, and a sum rate of slip on the Clark and Coyote Creek faults of 10 to 14 mm/yr (Blisniuk et al., 2010). Work in progress on the Clark fault suggests that its late Holocene slip rate may be faster than the average Pleistocene rate. Similar temporal variations on the Coyote Creek fault suggest that both faults have experienced a concomitant change in the loading rate at depth.

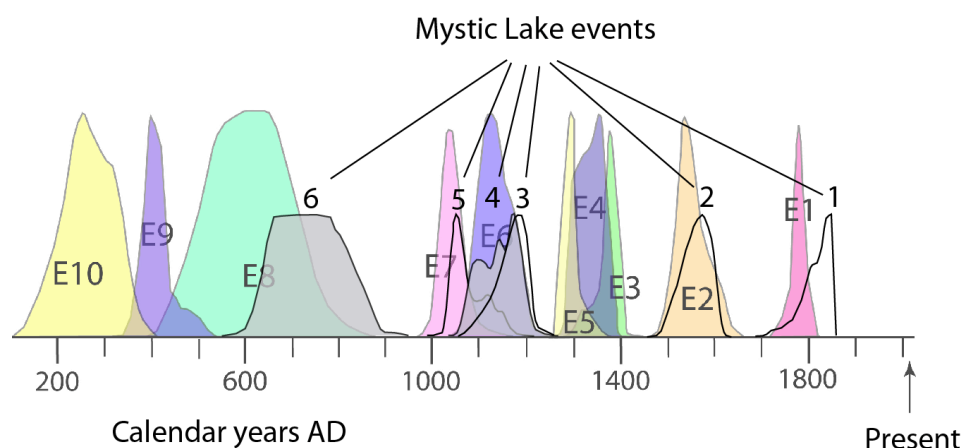


Figure 17. This figure compares the earthquake rupture record from Mystic Lake and Hog Lake along the San Jacinto fault (SJF). The two sites are separated by the Hemet Step-over, a several km-wide releasing step that has been attributed as the segmentation point along the northern SJF, with the Claremont strand to the NW and the Casa Loma-Clark strand to the SE. In other words, the Hemet Step-over has been interpreted as the likely structural barrier to rupture that segments the central and northern SJF zone. The new Mystic Lake observations suggest that, for the past 1200-1500 years, as many as five earthquakes may have ruptured through the step, whereas at least four did not. These new data suggest that the entire central and northern SJF may rupture together in some events, resulting in a surface rupture of as much as 175 km. Combined with the new B4 LiDAR observations of displacement per event along the Clark fault, which suggest 3-4 m of slip per event, these new data suggest that earthquakes as large as Mw7.5 have occurred along the north-central SJF during the late Holocene.

Several SoSAFE research projects on the San Andreas fault were published this year. For example, a study to examine recurrence patterns showed that the published Wrightwood series is statistically more periodic than would be expected to arise from a random (Poisson) series (Scharer et al., 2010). A new study using AMS-derived radiocarbon dates from the Pallett Creek site showed a similar coefficient of variation (0.68), suggesting that the Mojave section of the fault is weakly time-dependent and not clustered; this paper will be submitted in the fall of 2010. Three important papers on fault offsets and earthquake ages in the Carrizo Plain were published (Akciz et al., 2010; Grant Ludwig et al., 2010, and Zielke et al., 2010) and have generated significant discussion and renewed interest in this section of the fault. Collectively, these results have significantly revised our understanding of the behavior of this key portion of the San

Andreas, suggesting that great earthquakes on this part of the fault may be more frequent, and generate less surface slip, than had been thought previously.

Fault System Behavior

The second major emphasis of the Geology group has been to characterize patterns in fault system behavior that could significantly affect earthquake hazards. As a part of this effort, SCEC researchers continue to tease out the record of long-term earthquake clustering in southern California. The eastern California shear zone and the conjugate Garlock fault offer the most compelling examples of clustered earthquake behavior and its potential relationship to anomalously elevated fault loading (Dolan et al., 2007; Oskin et al., 2008; McGill et al., 2009; Ganey et al., 2010). New work by James Dolan and Eric Kirby on the Panamint Valley fault, a dextral-normal fault that lies just to the north of the Garlock fault, suggests that it has ruptured twice in the last ~1000 years, concurrent with the well-documented cluster of activity on dextral faults in the Mojave Desert (Rockwell et al., 2000). The antepenultimate event occurred 3,300-3,700 years age, during a quiescent period in the Mojave. This event, however, overlaps with the age of the penultimate earthquake on the Owens Valley fault, though the paleoseismologic record on dextral faults north of the Garlock fault is not yet sufficient to address possible clustering isolated to this section of the eastern California shear zone.

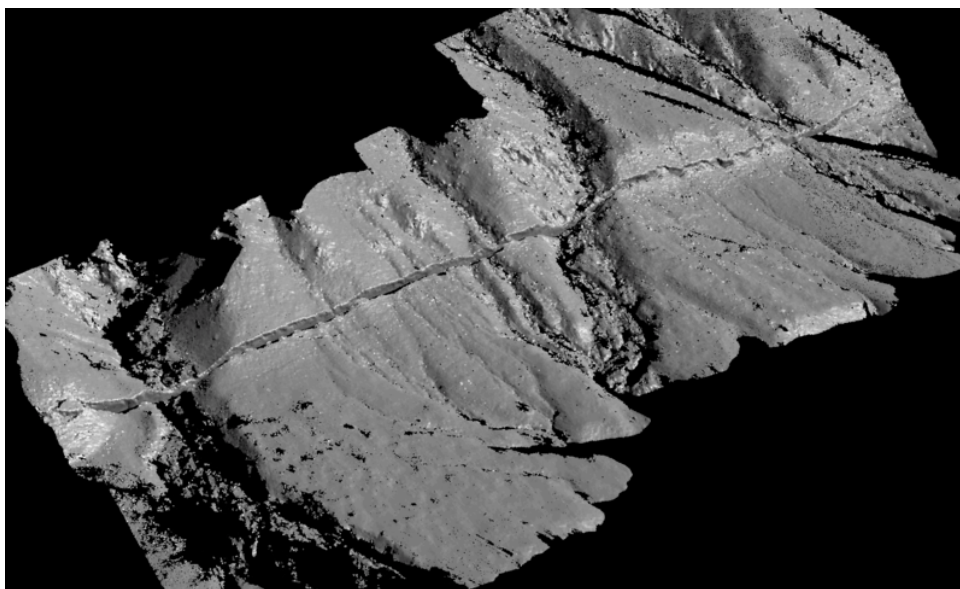


Figure 18. Oblique view of an ultra high-resolution terrestrial lidar scan of a 250 meter-long section of the Borrego fault rupture formed during the 4 April 2010 El Mayor-Cucapah earthquake. A total of 1 km of rupture were scanned immediately after the earthquake, capturing fine, ephemeral details of the rupture including abundant secondary faulting and warping. Data resolution approaches one point per square centimeter on the fault plane, sufficient to resolve striations on its surface.

As this report is being written, high-resolution seismic reflection data are being acquired by Dolan, John Shaw, and Tom Pratt across the zone of most recent folding above the Ventura Avenue anticline, as well as the blind western strand of the San Cayetano fault. These data will provide targets for borehole and potential trench studies to determine Holocene-Pleistocene slip

rates, slip-per-event, and earthquake age data. These observations will be critical for testing the possibility that these large thrust-fault ramps can sometimes connect together to produce great (M~8) earthquakes beneath the central and western Transverse Ranges.

Earthquake Response

The occurrence of the 4 April 2010 El Mayor-Cucapah earthquake in northernmost Baja California gave SCEC the opportunity to exercise its post-earthquake scientific response plan. A geology field team, led by John Fletcher from CICESE (Ensenada, Baja California) and Tom Rockwell commenced mapping of this complex earthquake rupture within a day of its occurrence. This was yet another unusual magnitude 7+ earthquake. As during the Landers (1992) and Hector Mine (1999) earthquakes, the 2010 event connected smaller fault segments to produce a large, complex rupture. The 2010 rupture was also unusual in that it ruptured a fault immediately adjacent (<1 km distant) to the 1892 Laguna Salada earthquake (Mueller and Rockwell, 1995; Hough and Elliott, 2009). Understanding the relationship between these two closely spaced earthquakes may lead to new understanding of the stress state and post-seismic reloading of faults. This earthquake presents the first opportunity to gather a comprehensive high-resolution topographic image of a fault rupture. Within two weeks of the earthquake, teams from UC Davis led by Mike Oskin, and from UNAVCO/University of Kansas/UCLA led Mike Taylor, were gathering ultra-high-resolution scans of portions of the surface rupture with ground-based lidar, revealing subtle and highly ephemeral features of the surface rupture in unprecedented detail. An airborne lidar survey of the entire surface rupture and the 1892 scarps will be acquired in mid-August 2010 (the day after this report was submitted). This survey is supported through an NSF RAPID grant to Mike Oskin and Ramon Arrowsmith, and augmented by additional funding from SCEC. Once completed these data will provide a permanent archive of the rupture for future study and comparison to field measurements. Pre-event low-resolution lidar gathered by INEGI (the Mexican cartographic agency) will enable the first-ever fine-scale analysis of distributed vertical motions surrounding the rupture.

Interdisciplinary Focus Areas

Within the new SCEC structure, the focus groups are responsible for coordinating interdisciplinary activities in six major areas of research: *Unified Structural Representation, Fault and Rupture 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.

Unified Structural Representation

The Unified Structural Representation (USR) Focus Area develops models of crust and upper mantle structure in southern California for use in a wide range of SCEC science, including strong ground motion prediction, earthquake hazard assessment, and fault systems analysis. These efforts include the development of Community Velocity Models (CVM & CVM-H) and Community Fault Models (CFM & CFM-R), which together comprise a USR. The Focus Area also seeks to evaluate and improve these models through ground motions simulations, 3D waveform tomography, earthquake relocations, and fault systems modeling in partnership with other working groups in SCEC.

This past year's accomplishments include:

1. Development of a new version of the SCEC Community Velocity Model (CVM-H 6.2), which directly incorporates 3D waveform tomographic results (Tape et al., 2009);
2. Development of a SCEC computational platform to evaluate the CVM and CVM-H models by comparisons of the recorded seismograms with synthetics, with demonstration for the 2008 Mw5.4 Chino Hills earthquake (Olsen and Mayhew, 2010);
3. Enhancements to the code that delivers the CVM-H, and optimized, parallel extraction software for CVM4 and CVM-H, in partnership with the SCEC CME group;
4. Development of a statewide Community Fault Model (SCFM); and
5. Improvement of the southern California Community Fault Model (CFM) using precisely relocated seismicity (Hauksson and Shearer, 2005; Shearer et al., 2005; Nicholson et al., 2008).

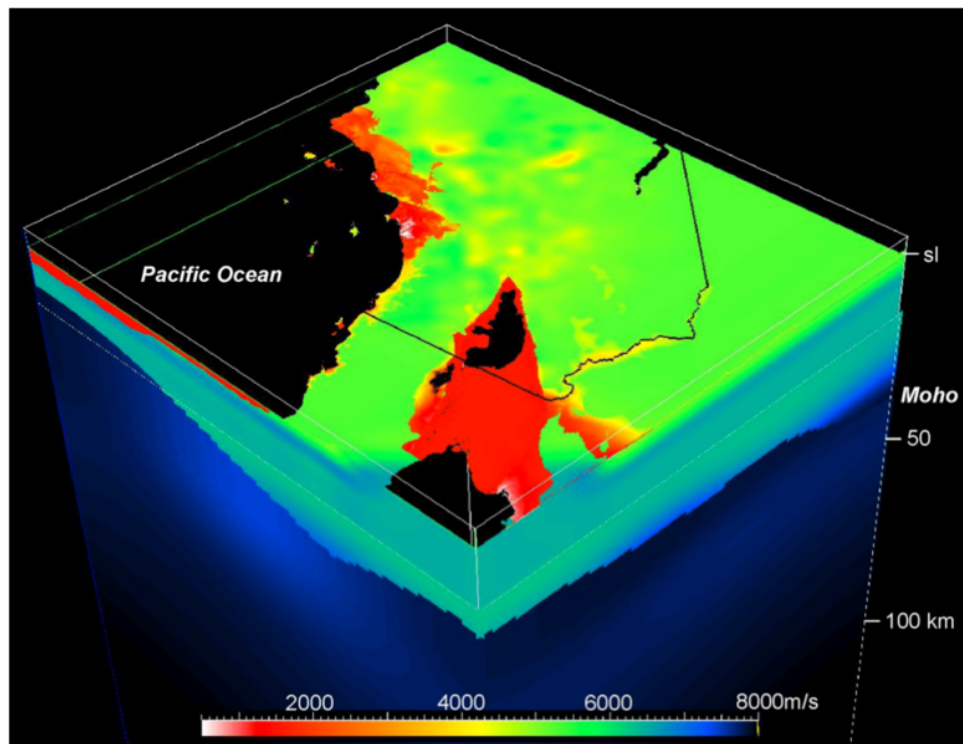


Figure 19. Perspective view of CVM-H 6.2, which includes basin structures embedded in a tomographic model that extends to 35 km depth, which is underlain by a teleseismic surface wave model that extends to a depth of 300km. This latest release of the model includes results from 3D tomographic waveform inversions (Tape et al, 2009). Vs is shown.

Community Velocity Models (CVM, CVM-H)

SCEC has developed two crust and upper mantle velocity models (CVM, Magistrale et al., 200; and CVM-H, Suess & Shaw, 2003) for use in strong ground motion simulation and seismic hazard assessment. The community velocity models consist of basin descriptions, including

structural representations of basin shapes and sediment velocity parameterizations, embedded in regional tomographic models.

The latest release of the CVM-H (6.2) is an important milestone for SCEC, as it represents the integration of various model components, including fully 3D waveform tomographic results (Plesch et al., 2009). The CVM-H consists of basin structures defined using high-quality industry seismic reflection profiles and tens of thousands of direct velocity measurements from boreholes (Plesch et al., 2009; Süss and Shaw, 2003). These basin structures were then used to develop travel time tomographic models of the crust (after Hauksson, 2000) extending to a depth of 35 km. This model was then used to perform a series of 3D adjoint tomographic inversions that highlight areas of the model that were responsible for mismatches between observed and synthetic waveforms (Tape et al., 2009). Sixteen tomographic iterations, requiring 6800 wavefield simulations, yielded perturbations to the starting model that have been incorporated in the latest model release (Figure 19). CVM-H 6.2 also incorporates a new Moho surface (Yan and Clayton, 2007) and a series of other upgrades to the basement geotechnical layer and the V_p -density scaling relationship.

Comparisons of observed and synthetic waveforms for earthquakes in southern California demonstrate that the SCEC Community Velocity Models (Magistrale et al., 2000; Süss and Shaw, 2003; Plesch et al., 2009) perform much better than simple 1-D velocity models (Figure 20) (e.g., Komatitsch et al., 2004; Chen et al., 2007; Olsen and Mayhew, 2010). Furthermore, the new 3D waveform tomographic inversion methods offer a comprehensive way to evaluate and iteratively improve velocity models. For example, the adjoint tomographic results included in the CVM-H 6.2 include significant changes ($\pm 30\%$) from the starting models based on travel-time tomographic methods. Such strong perturbations resulted in dramatically improved fits to full-length three component waveforms (Tape et al., 2009, 2010).

Coincident with the release of the latest CVM-H model, we also worked in partnership with the SCEC CME group to enhance the code that delivers the model to users. Specifically, we added the capability to extract velocity values below the topographic land surface or relative to a sea level datum. This change helps facilitate the different needs of finite-difference- and finite-element-based wave propagation codes. We also made a number of additional modifications to the code that help facilitate parameterizing grids and meshes, and summarized these enhancements in an updated instruction manual that includes training datasets.

Optimized code for delivering the CVM'S

During the past year, the SCEC CME group (Small, Ely, Maechling) made important progress on speeding up the process of delivering extractions of the CVMs to the ground motion modelers. The developed C/MPI code is called `cvm2mesh` and is meant for fast mesh generation from either CVM4 or CVM-H. The program operates by partitioning the mesh region into a set of slices along the z-axis as illustrated in Figure 21. Each slice is assigned to an individual core for extraction from the underlying CVM. The partitioning and extraction is an embarrassingly parallel operation as the cores do not need to communicate with each other, and they only indirectly interact through the file system when the slices are merged into the final mesh file. Each core contributes its slice to the final mesh by computing the offset location of the slice within the greater file, and uses efficient MPI I/O file operations to seek to that location and write the slice data.

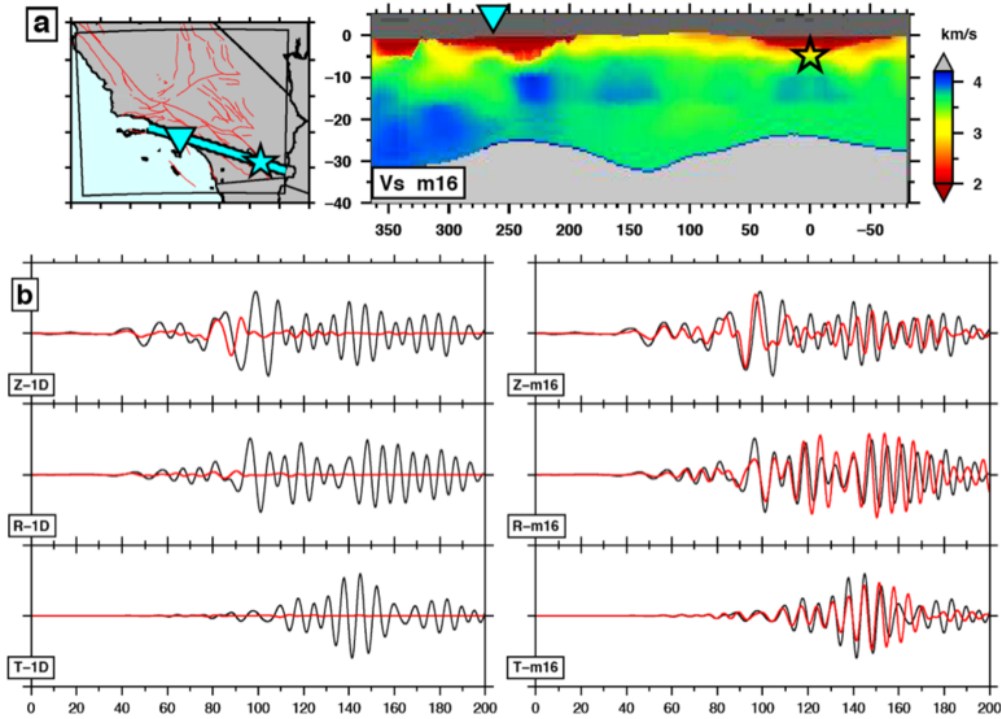


Figure 20. The influence of 3D velocity structure on the seismic wavefield based on the 3D adjoint tomographic analysis of Tape et al. (2009, 2010). (a) Cross section of the final 3D V_s crustal model (m16), containing the path from event 14179736 (I; Mw 5.0, depth 4.9 km), beneath the Salton trough, to station LAF.CI (∇ ; distance 263.5 km), within the Los Angeles basin. (b, left column) Data (black) and 1D synthetics (red). (b, right column) Data (black) and 3D synthetics for model m16 (red). The seismograms are bandpass filtered over the period range 6–30 s. Z, vertical component, R, radial component, T, transverse component.

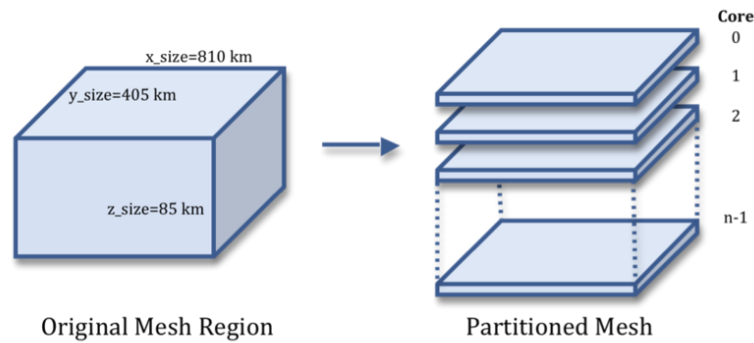


Figure 21. The 3-D mesh region is partitioned into slices along the z-axis. Each slice is assigned to a core in the MPI job, and each core queries the underlying CVM for the points in its slice only.

Using this procedure, *cvm2mesh* extracted input mesh for the M8 simulation (Cui et al., 2010, finalist for the Gordon Bell Prize 2010) from CVM-4 with ~436 billion points in under five hours while running on 2125 cores. The equally-sized input mesh extracted from CVM-H was generated in under one hour on 425 cores. The *cvm2mesh* program can scale up to a maximum of n cores, where n is defined by the relationship: $n = z_size (m) / spacing (m)$. Thus, the maximum parallelism that can be achieved for the M8 mesh extractions is $85000 m / 40 m = 2125$ cores.

The parallel code applied to CVM-H has also been extended to allow for ‘topography flattening’, used by the ground motion modelers omitting surface topography in their simulations. Querying can be done using either (lat, lon) or UTM coordinates. Finally, the code allows for a user-defined 1-D background model for CVM-H. Derivation of a Vs30-based near-surface velocity model.

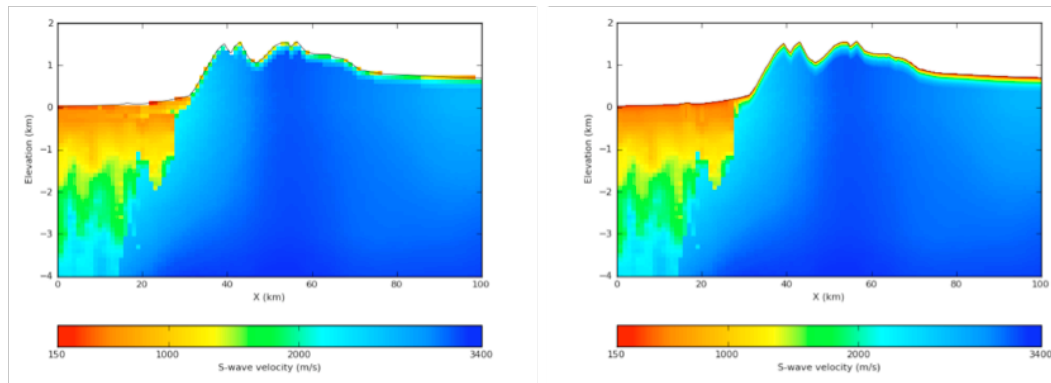


Figure 22. Cross sections from CVM-H (left) without and (right) with the proposed Vs30-based near-surface velocity model.

Additional efforts are ongoing from SCEC CME (Geoff Ely and Phil Maechling) to derive a Vs30-based near-surface velocity model for the CVMs (Ely and Maechling, 2010). The approach generates a supplementary geotechnical layer (GTL) model derived from available maps of VS30 (the average shear-velocity down to 30 meters). The approach also minimizes rasterization artifacts in the near-surface due to sample depth dependence on local topographic elevation (nearly 50 percent of CVM-H does not reach the ground surface at all) (Figure 22).

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

The SCEC CME group initiated development of a platform to examine systematically the goodness-of-fit (GOF) between seismic data and synthetics generated from CVM4 and CVM-H (Small and Maechling, 2010). Current status for the platform includes an estimate of the bias between observed and simulated response spectral accelerations for all included stations, demonstrated for 60+ records of the 2008 Mw 5.4 Chino Hills event. Planned use of the platform includes GOF estimates for future updates of the CVMs, as compared to previous versions. Future efforts will consider adaptation of the GOF method by Olsen and Mayhew (2010), which includes a set of user-weighted metrics such as peak ground motions, response spectrum, the Fourier spectrum, cross correlation, energy release measures, and inelastic elastic displacement ratios.

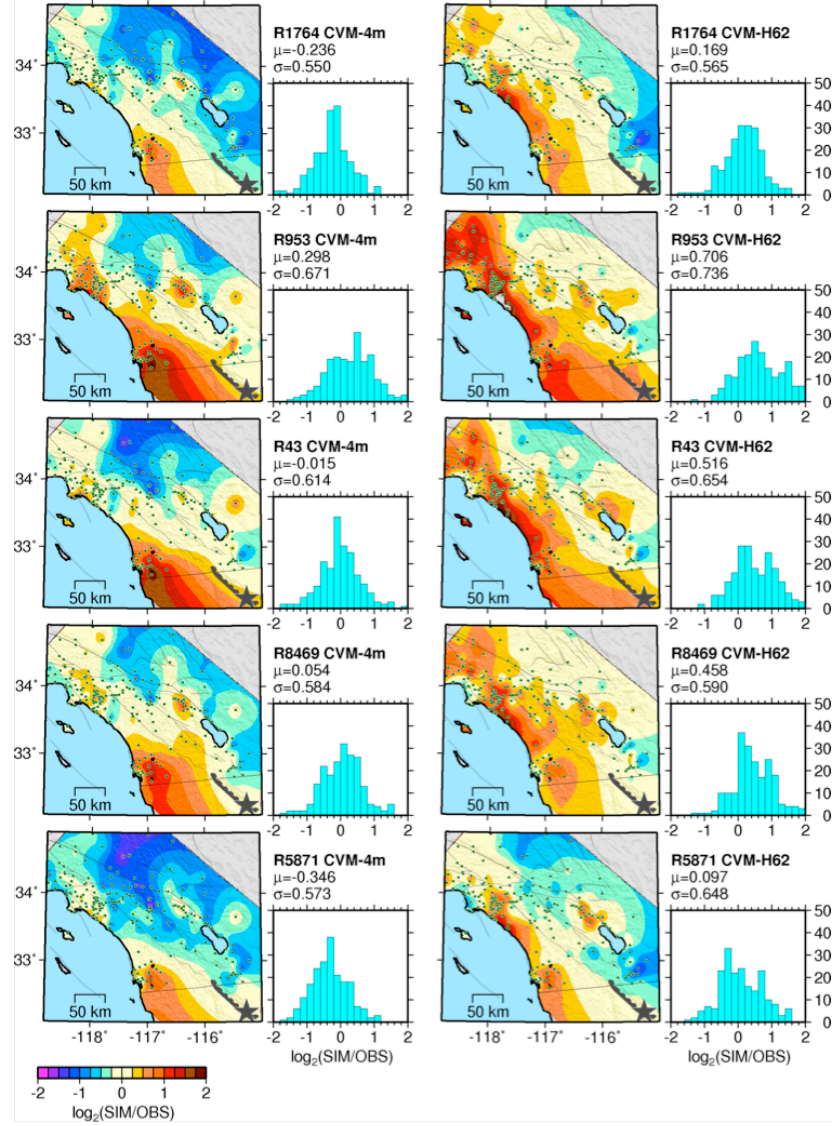


Figure 23. Residuals of simulated and observed PGV for the five rupture scenarios of the Mw 7.2 El Mayor-Cucapah event, using seismic velocity models CVM-4m (left column) and CVM-H62 (right column). For each case, results are displayed as the base 2 logarithm of the ratio of the simulated to observed value computed for each recording site in both map view and histogram, with the mean (μ) and standard deviation (σ) of the residuals indicated above the histogram. From Graves and Aagaard, 2010).

Additional comparisons of CVM-H and CVM-S were carried out by Robert Graves and Brad Aagaard (2010), using 5 long-period ($>2s$) kinematic rupture descriptions of the 4 April 2010 M7.2 El Mayor Cucapah earthquake (Figure 23). While the details of the motions vary across the simulations, the median levels match the observed motions reasonably well with the standard deviation of the residuals generally within 50% of the median. Simulations with the CVM-4m model yield somewhat lower variance than those with the CVM-H62 model. Both models tend to over-predict motions in the San Diego region and under-predict motions in the Mojave Desert. Within the greater Los Angeles basin, the CVM-4m model generally matches the level of

observed motions whereas the CVM-H62 model tends to over-predict the motions, particularly in the southern portion of the basin. Future work will analyze the causes of these differences, and use the aftershocks of the El Mayor-Cucapah event to explore the predictive capability of the two CVMs.

Community Fault Model (CFM)

The SCEC Community Fault Model (CFM) is an object-oriented, 3D representation of more than 140 active faults in Southern California, and includes direct contributions from more than twenty SCEC investigators (Plesch et al., 2007). The model consists of triangulated surface representations (T-surfs) of major faults, which are defined by surface geology, seismicity, well logs, seismic reflection profiles, and geologic cross sections. These 3D fault representations are intended to support SCEC research efforts in fault system modeling and earthquake rupture propagation, as well as to serve as a basis for regional seismic hazards assessment.

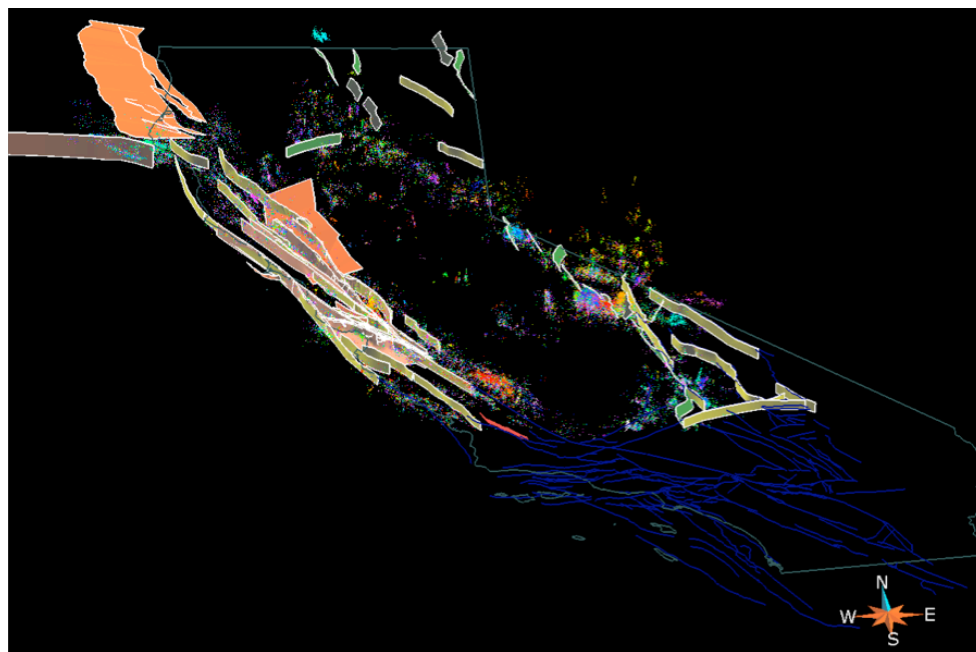


Figure 24. Perspective view of the Statewide CFM (SCFM 1.0), which includes the SCEC CFM 4.0 (Plesch et al., 2007), and the USGS San Francisco bay region fault model (Brocher et al., 2005). New faults added to the model this past year are highlighted in colors.

This past year, we completed a major expansion of the CFM by developing the first generation Statewide Community Fault Model, SCFM 1.0. The statewide model is comprised of the southern California CFM 4.0 and more than 150 additional fault representations for northern California (Figure 24). Geologic models of the greater San Francisco Bay area, developed largely by the U.S.G.S. (Menlo Park), serve as the basis for most representation in that area of northern California (e.g., Brocher et al., 2005). The remainder of the new fault representations was developed by integrating geologic maps and cross sections, seismicity, well and seismic reflection data using the approach of Plesch et al. (2007). Each of the faults are defined by triangulated surface representations, with separate patches that distinguish between interpolated

and extrapolated regions of the fault surfaces. This allows users to clearly distinguish portions of the fault representations that are directly constrained by data from those that are inferred or extended from better known parts of the fault. In addition, the model contains alternative representations of many faults. These cases arise when two or more fault interpretations have been made that involve substantial differences in 3D representation (i.e., in dip direction, fault type), and all of them are seemingly consistent with the available data.

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 the latter part of 2010, we plan to facilitate evaluation of the SCFM 1.0 by the SCEC working group, in order to establish preferred and alternative fault representations, assign quality rankings to faults, and identify areas where further improvements to the model are needed.

In a related effort, the CFM in southern California is being systematically re-evaluated using new re-located earthquake catalogs developed by SCEC (Hauksson and Shearer, 2005; Shearer et al., 2005). These new catalogs provide significantly improved resolution of many faults, and are being used to refine interpolated fault patches for many of the representations in the CFM (Nicholson et al., 2008). These updates, which include critical model components such as the San Andreas fault in San Geronio Pass, will be incorporated in a new release of the CFM and SCFM.

Community Velocity Models (CVM, CVM-H)

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Fault Rupture and Mechanics

A large number of projects were funded as part of the Fault and Rupture Mechanics focus group this past year reflecting the continuing need for, and strong community interest in, this area of research. These projects address a broad spectrum of SCEC3 goals that overlap the other SCEC focus and disciplinary group activities. FARM-related research continued to emphasize several critical topics, including understanding the relative importance of different dynamic weakening mechanisms, characterizing the properties of fault cores and damage zones, formulating constitutive laws for use in dynamic rupture models, and comparing the results with

both repeatable computer simulations, and laboratory and field observations to assess their impacts on crustal, fault-zone, and earthquake behavior. This section only provides a brief summary of some of the accomplishments and research-related activities reported during 2009 and the early months of 2010. Additional related accomplishments are reviewed in other sections of this report. For a complete review of all FARM-related activities please see the individual PI annual reports posted on the SCEC website.

Frictional Strength of Faults During Earthquake Slip

The concept that most earthquake slip seems to occur in extremely thin zones, suggesting intense thermal effects during rupture, continues to drive laboratory experiments that investigate physical effects at realistic earthquake slip rates. These laboratory studies have revealed a rich array of new physics of dynamic fault zone weakening, including flash heating, thermal pressurization of native fluids or of volatiles liberated by decomposition reactions, possible silica gel lubrication, and as yet poorly understood, nano-particle weakening. A SCEC-led workshop, convened by Dunham and Chester, and with 127 participants, was devoted to reviewing recent experimental results concerning fault friction at coseismic slip rates and associated modeling efforts. Most experiments presented show extreme weakening of friction at speeds exceeding ~ 0.1 m/s for a wide variety of rock types. Some experiments show friction to be proportional to the inverse of slip velocity, consistent with the theoretical flash heating model, while others show less velocity dependence. Di Toro presented a compilation of results for a variety of rock types showing how universal dynamic weakening is, even though most of the experiments reviewed were run at either low normal stresses or at slip rates just approaching the coseismic range. Prakash presented data produced at much higher normal stresses and velocities that show extremely low friction coefficients. A topic of discussion is occurrence of oscillations often attributed to machine compliance and Goldsby illustrated how changing machine stiffness influences the amplitude of these oscillations. Reches and Lockner reported results from a new high-speed friction apparatus that show weakening of friction down to ~ 0.3 at ~ 0.01 m/s followed by strengthening to ~ 0.7 at ~ 0.1 m/s. In addition to fault weakening due to flash heating, distributed high strain-rate plastic flow at asperity contacts (Brown) and the production of nanoscale particles that adhere to the sliding surfaces were offered as alternative mechanisms. Establishing a theoretical understanding of experimental results and identifying distinguishing characteristics of dynamic weakening that can be mapped in the field both remain top research priorities.

Although thermal pressurization is becoming more widely used in the modeling community, this mechanism has yet to be documented in laboratory experiments under carefully controlled conditions. Kitajima et al. (in press) links the onset of dynamic weakening to the development of distinct structural units within the sheared layer. The microstructure evolves as slip-rate and temperature increase from distributed shearing flow at low temperatures to fluidized flow associated with the formation of an extremely localized slip zone and dynamic weakening at high temperature. Thermal-, mechanical-, and fluid-flow-coupled FEM models, based on the temperature-dependent friction constitutive relation and that treat thermal pressurization of pore water, successfully reproduce the frictional response in all experiments (Figure 25). Kitajima et al. (2010) hypothesize that thermal pressurization is important at high slip rates and small displacements as temperature rapidly increases. The critical displacement for dynamic weakening is approximately 10 m or less, and can be understood as the displacement required to form a localized slip zone and achieve a steady-state temperature condition. The observed

relationship between steady state friction and slip rate is consistent with predictions from micro-mechanical models of flash heating.

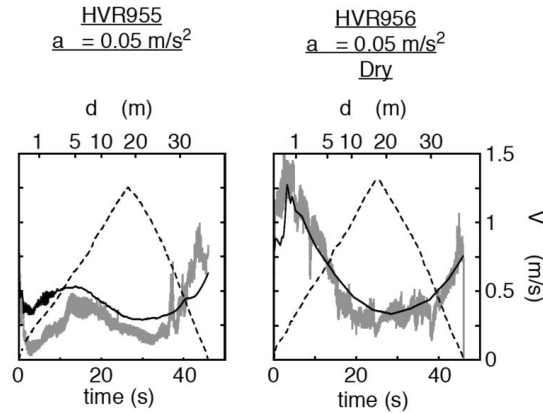


Figure 25. Results of thermal-, mechanical-, and fluid flow-coupled FEM models for constant acceleration experiments on wet gouge, HVR955gb, and on room-dry gouge, HVR956gb. The reduction in strength of the wet gouge relative to the dry gouge, particularly at small displacement, reflects weakening by thermal pressurization. The magnitude of the pore fluid pressurization diminishes with slip because pore fluid escapes (the gouge layer is not sealed) and the rate of temperature increase is reduced. Black and gray solid lines represent the model-calculated torque and the measured torque, respectively, plotted as a function of time. The dashed black lines represent the equivalent velocity.

At the workshop, constitutive equations discussed describing dynamic weakening ranged from physics-based descriptions of melting and shear of viscous melt layers at asperity contacts (Rempel) to more empirical formulations capturing a broad set of experimental results (Beeler). Rice presented results of numerical simulations of rupture propagation with flash heating and thermal pressurization using parameters derived directly from laboratory measurements. While computational constraints limit the analysis to very small earthquakes, the resulting stress drop and scaling of slip with propagation distance appear to be consistent with natural events, lending support to the dynamic weakening model of fault mechanics. Lapusta and Noda's work on earthquake cycle simulations with rate-and-state friction and thermal pressurization, showed how dynamic weakening from thermal pressurization can permit ruptures to propagate on rate-strengthening portions of the fault. Using numerical simulations, Joe Andrews suggested that efficient thermal pressurization in the shales at the north end of the Chi-Chi earthquake might explain the low levels of spectral acceleration relative to spectral velocity observed in strong ground motion records.

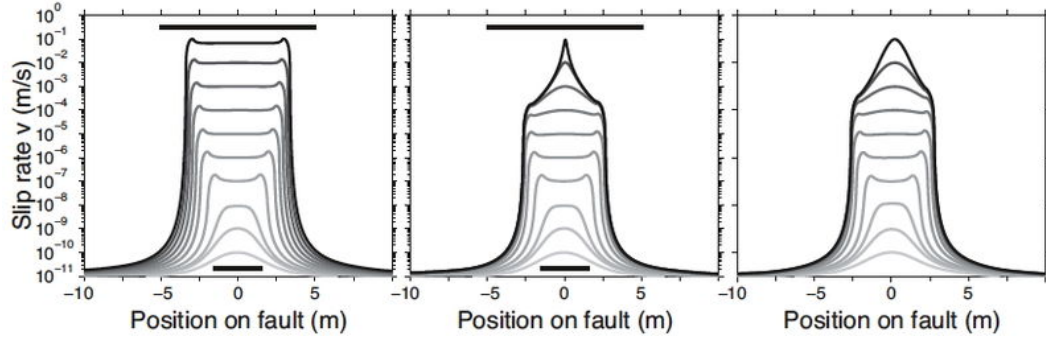


Figure 26. Results from aging law simulations in the isothermal (left) and thermal pressurization (middle and right) cases. In these simulations, $a/b = 0.8$, $d_c = 100 \mu\text{m}$, and $(\sigma - p_0) = 140 \text{ MPa}$. Lines are snapshots of slip speed for each tenfold increase in maximum slip speed. (a) Snapshots of slip speed for isothermal, drained, aging-law nucleation. Bottom scale bar shows $2L_{\text{min}}$ [Dieterich, 1992]; top scale bar shows $2L_{\infty}$ [Ampuero & Rubin, 2008]. (b) Snapshots of slip speed with thermal pressurization, with $\alpha = 0$. Comparing to (a), note that at early times (low slip speeds) the profiles are similar to the isothermal simulation. At about 10^{-5} m/s , the profiles start to diverge. By about 10^{-4} m/s , the profiles have distinctly different forms. The sharp peak at higher slip speeds indicates how slip is evolving toward a singularity of high slip over a zero-width area. (c) Snapshots of slip speed with thermal pressurization and the Linker & Dieterich [1992] effect with $\alpha = \mu_0 = 0.6$. The inclusion of this effect prevents the development of a slip singularity.

Exploring the notion that thermal pressurization also can be significant during slow slip, Segall and others are extending their earlier models of a 2D elastic, diffusive system with a 1D fault to include a finite-width shear zone. To date, using a zero-width shear zone approximation, they have demonstrated that thermal pressurization is significant during the late stages of earthquake nucleation following a period dominated by rate- and state-dependent friction. For an aging friction law they find that thermal pressurization is an important process at slip-speeds of $0.02\text{--}2.0 \text{ mm/s}$, and for pulse-like slip it dominates at speeds of $1\text{--}100 \text{ mm/s}$ (Figure 26).

To understand and characterize the effects of elastic-plastic interaction with pore fluids and determine the pore pressure along the rupture plane, Viesca et al. (2009) and Viesca and Rice (2009, 2010) have extended previous models to include the poro-elastic-plastic response. The interaction between dynamic rupture, inelastic deformation, and changes in the near-fault pore fluid pressure, permeability and storage coefficients predicts a different pore pressure evolution on each side of a planar fault surface, a greater degree of plastic straining behind the rupture front along one side of the slip-weakening zone, and a narrow lobe of plastically active material that extends outward into the surrounding material (Figure 27). With plastic deformation, changes in permeability and compliance modify the magnitude of pore pressure at rupture (Figure 28).

Where plastic straining occurs

The strongest plastic straining occurs behind the rupture front and lies within the slip-weakening zone.

Below are superimposed contours of plastic strain rate taken at the same moments and regular intervals for $\Psi=14^\circ, 56^\circ$.

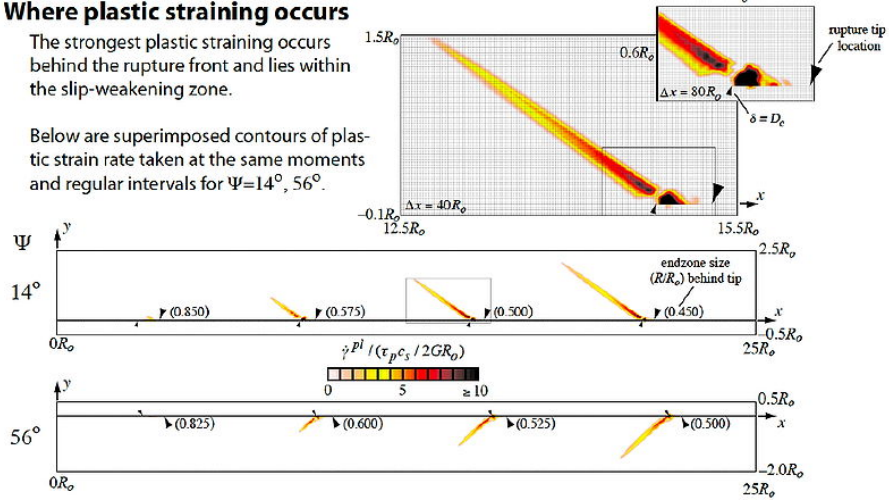


Figure 27. Fine resolution poro-elastic-plastic solution (based on procedures of Viesca et al., [JGR, 2008]) for dynamic shear rupture propagation in a fluid-infiltrated Drucker-Prager material. Note that the most intensive plastic straining occurs along one side of the slip-weakening zone in these examples.

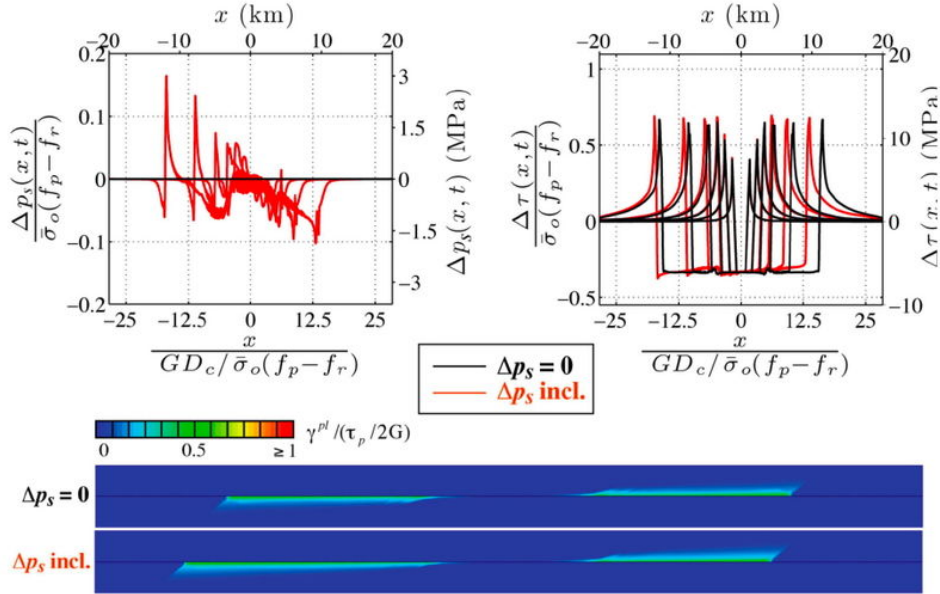


Figure 28. Example of poro-elastic-plastic rupture, with (curves in red) and without (in black) inclusion of procedure for calculation pore pressure changes at the slip surface and including it in the fully coupled dynamic analysis, with undrained conditions assumed everywhere except in the diffusive boundary layer along the slip surface.

Geometric Complexity, Off-fault Damage, and Earthquake Rupture Dynamics

An emerging focus of SCEC in 2009 was directed at understanding the geometric complexity of faults and the implications for earthquake phenomenon. In an attempt to quantify the geometric heterogeneity in California faults over a range of spatial and temporal scales, Wechsler et al (2010) characterized the surface expression of fault displacement accumulated

over tens of thousands of years and found that frequency-size statistics of all fault segment lengths can be fit well by an exponential function. To characterize geometric heterogeneity as a function of seismogenic depth, Bailey et al (2010) used focal mechanism data from 0 to 15 km depth for the period of 1983 to 2004 and illustrated a clear link between the long term evolution of the fault and its seismic behavior over a 20 year interval, and that the partitioning of faulting styles suggests that focal mechanism heterogeneity is primarily controlled by the structural characteristics of the fault.

In the same way that SCEC is pushing the development of advanced experimental techniques to investigate microscale physics and constitutive behaviors, SCEC is making progress testing and advancing computational methods and efficiency for modeling rupture propagation, and incorporating the geometric roughness of faults into modern rupture dynamics simulations to provide insight on high-frequency ground motion and aftershock localization. These community-wide advances have been catalyzed by dedicated workshops and annual meeting topical sessions over the past year.

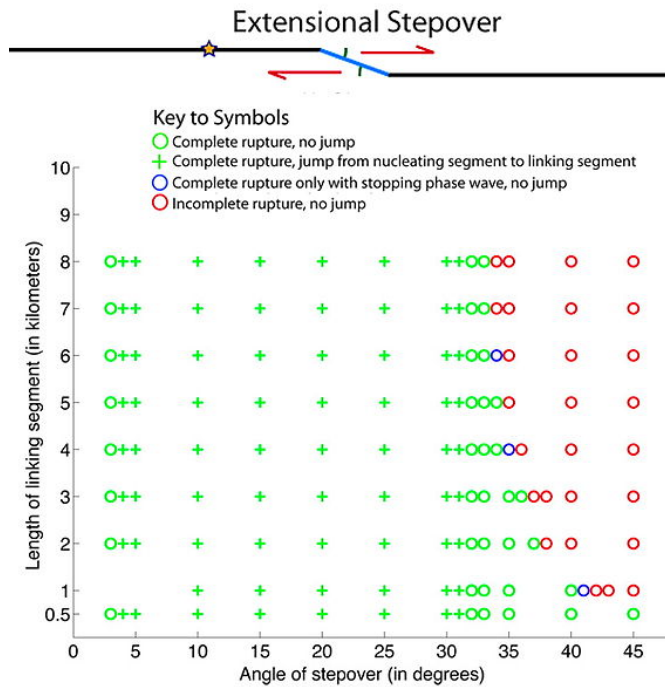


Figure 29. Cartoon of fault geometry and results for an extensional stepover. The blue line represents the linking segment, which is variable in length. The green arcs show the stepover angle, taken relative to the strike of the parallel end segments; this angle also is variable. The red arrows represent the direction of slip. The star marks the nucleation point, 7 km along the nucleating segment of the fault. The lengths of the nucleating and far segments, in black, are constant at 10 km each.

An approach to understand the effects of geometric complexity of fault surfaces, on rupture propagation, is to identify and examine specific classes of geometric features. For example, in 2009, Oglesby and Wesnousky examined double-bends (linked stepovers) in strike-slip faults (Figure 29). They found that for very long linking-faults, the likelihood of a simulated rupture propagating through a stepover is determined by the static favorability of the linking segment

(i.e., static stress change due to the main rupture, on the linking segment). They also found that for smaller linking fault lengths, it is possible for simulated ruptures to propagate even though the linking faults might seem to be ‘unfavorable’. This study provides insight into the relative contributions of dynamic versus static changes in stress on rupture propagation through geometric complexities.

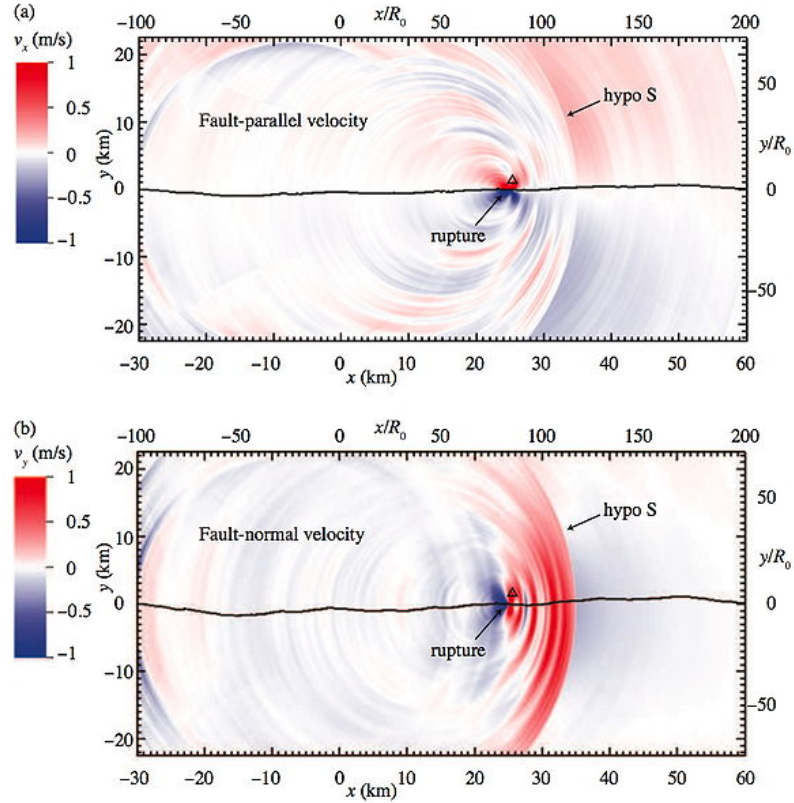


Figure 30. Snapshots of the velocity field radiated by a rupture on a band-limited self-similar fault. a) fault-parallel (v_x); (b) fault-normal (v_y). The hypocentral shear wave is marked as hypo S.

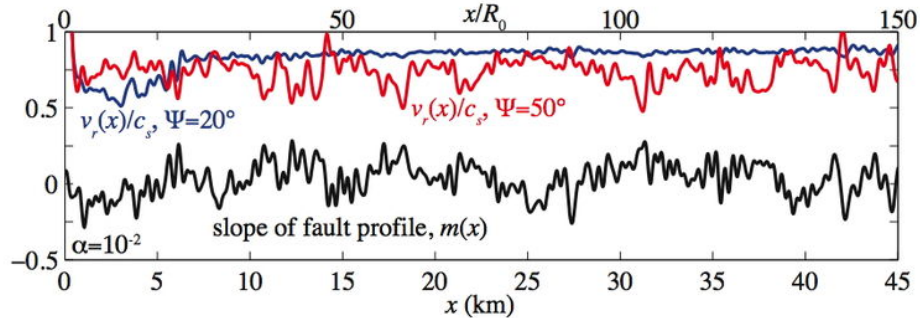


Figure 31. Influence of the orientation of the initial stress field on fluctuations in rupture velocity for self-similar rough faults. Slope of fault profile for amplitude to wavelength ratio of 10^{-2} for orientation of the initial stress field at 20 and 50 degrees. The orientation specified by the angle between the maximum compressive stress and the plane defining the average surface of the fault.

While Oglesby and Wesnousky looked at larger scale geometrical features and their effects on the propagation of earthquake rupture, Dunham and Brodsky looked at smaller scale features and their effects on ground motion. Decades ago, U.S. and Japanese researchers hypothesized the effects of small scale fault heterogeneity on high-frequency ground motions, but the computational capabilities to explore this were not yet available, and so most studies assumed flat faults with heterogeneous stresses and slip distributions. Now, with more field-based observations available, along with impressive computational platforms, these calculations are viable. Dunham and Brodsky did 2D numerical simulations assuming strong rate-weakening friction laws. They showed that the radiated velocity field is affected when assuming rupture on a band-limited self-similar fault, rather than a simple planar fault, and that high-frequency shear waves are emitted every time the simulated rupture accelerates or decelerates (Figure 30 and Figure 31). These studies, which will likely continue in 2010, are an important step towards including not only stress heterogeneity on faults, but also including geometrical complexity.

Significant advances also have been realized in understanding the origin of fault-bordering damage zones, the characterization of their properties by field geologic studies and by seismic analysis of fault-zone trapped waves (including post-rupture time-dependence of their speeds as a window on healing), and understanding how they interact with rupture propagation (e.g., with their inelastic response putting a limit on maximum local slip velocity at the rupture front, compared to modeling which assumes elastic off-fault response). Shallow drilling and coring of the pulverized zone adjacent to the San Andreas Fault at Little Rock is the first attempt to distinguish rock damage caused by near-surface weathering from fracture generated by repeated earthquakes (Wechsler et al., 2009). Although addressed theoretically for some time, Biegel et al. (in press) and Bhat et al. (in press) demonstrate in laboratory experiments that the presence of damage adjacent to the rupture surface has a significant effect on dynamic rupture characteristics.

Multi-Investigator Collaborative Projects

A highlight of SCEC is its dedication to multi-investigator collaborative studies (referred to as "Technical Activity Groups" or TAGs in the SCEC4 proposal) that help organize, catalyze, and focus diverse research groups in the earthquake science community. The SCEC workshops are a critical part of this collaborative interaction, and for FARM, the workshop described earlier in this section demonstrates the clear advances in understanding that can be made only in a group event setting. In addition, SCEC hosts large multi-PI science projects. Among these are the computational exercises where a number of researchers agree to tackle a mutually agreed upon science problem to make sure that their science is repeatable. Here we highlight some recent group efforts, as well as the multi-year dynamic rupture code validation computational exercise.

A SCEC collaborative group project that is making much progress is the Transient Detection collaboration (described in detail under the Geodesy section of this report), led by Murray-Moraleda and Lohman. In addition, a new SCEC group in 2009, with goals that will help FARM better understand the physics of coseismic rupture, is the Source Inversion Validation Exercise (SIV), led by Mai, Page, and Schorlemmer. Although tackling the difficult earthquake-source inverse problem that is inherently non-unique, the SIV exercise is showing much promise, and its success would lead to improved views of the earthquake source that are critical to our science overall and especially important for FARM, Ground Motion Prediction, and Seismic Hazard Analysis groups.

Another collaborative exercise in SCEC is the earthquake simulator exercise. Led by Tullis, the simulator group aims to compare computer codes that simulate multiple earthquake cycles on multiple faults, with the dynamic rupture process and dynamic wave propagation simplified to a quasi-static form. In 2009 group progress included meetings to decide on specific benchmarks to run and discussions about appropriate formats for comparison of results. In 2010 the group aims to finalize decisions about implementing a statewide fault geometry, in addition to finalizing decisions about comparison metrics.

In 2009, Harris and co-PI's continued the SCEC dynamic earthquake rupture exercise of computer code validation. The multiple spontaneous-rupture codes used by SCEC PI's and other interested international researchers are tested to determine if the results produced by the different codes are consistent. In particular, the on-fault rupture evolution and simulated ground motion results from the different codes are compared. In 2009, two normal-fault benchmarks designed by Joe Andrews were implemented; both benchmarks were designed to test hypotheses by Andrews et al. (2007) about extreme ground motion near the nation's formerly-proposed nuclear waste repository at Yucca Mountain (see Figure 32 for the regional setting and idealized fault geometry). The normal-fault benchmarks consisted of 2D and 3D extreme-stress drop, supershear, dynamic-rupture scenarios, that were simplifications of the scenarios presented in 2D in Andrews et al. (2007). For one benchmark (TPV12), the off-fault response was assumed elastic; in the second benchmark (TPV13), the off-fault response was assumed inelastic. Good agreement was found for the simulated ground motions (see Figure 33 for some examples) and fault-rupture evolution among most of the participant codes that conducted the benchmarks, and the findings verified the hypothesis of Andrews et al. (2007) that 2D numerical simulations produce higher extreme-ground-motions than 3D calculations. In addition, the elastic simulations generally produced higher ground motion values than those that assumed inelastic off-fault response. In 2010 the code validation group will move into non-planar fault geometry benchmarks, starting with a study of branched strike-slip faults. A spinoff project occurring in 2010, that is based on the results of the 2009 normal-fault benchmarks, is the '100 runs' exercise, with three code-validation participants whose 3D codes agreed well in TPV12 and 13, running cases of heterogeneous initial stresses to generate scenario M6.5 events on a normal fault.

In work related to both the Extreme Ground motion project and FARM, in 2009, dynamic rupture code-validation participants Duan and Day wrapped up a project where they investigated the physical limits to ground motion near Yucca Mountain when off-fault yielding is included for the Solitario Canyon fault. Rather than assuming the simplifications of the TPV12 and TPV13 code verification benchmarks mentioned above, Duan and Day more fully incorporated the Andrews et al. (2007) assumptions, and in addition investigated sophisticated variations on the Andrews et al. (2007) parameters. All of this was done in 2D with the goal of checking the sensitivity of the ground motion results to possible variations in the actual faulting behavior during 'extreme ground motion' events. Duan and Day found that 1) if there is a shallow dip at depth, as earlier studies by Brocher et al. (1998) indicated there might be, and if the cohesion near the Earth's surface is higher than that used by Andrews et al., (2007), then the simulated peak velocities in the ground motion can be larger than those calculated in Andrews et al. (2007), 2) inclusion of a 100-m wide symmetric low-velocity damage zone has little effect on the 'extreme, complete stress drop calculation', and 3) inclusion of time-dependent pore-pressure has little effect on the ground motion calculations (Figure 34 and Figure 35; Duan and Day (2009)).

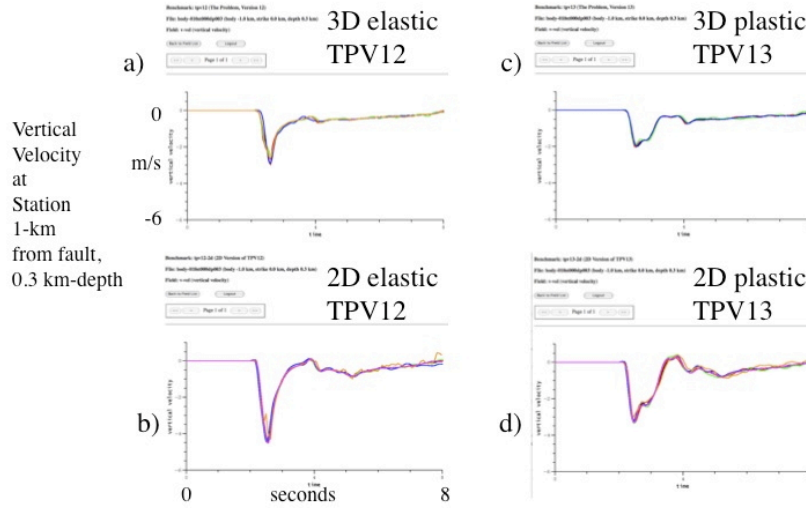


Figure 33. Ground motion simulation results for the Harris et al. TPV12 (elastic) and TPV13 (inelastic) rupture dynamics code verification benchmarks. For each simulation, the filtered vertical velocity results for just one site are presented, with the site located 1-km from the fault, at 0.3km depth. For more results, and a complete benchmark description, please visit the SCEC code verification website. a) TPV12-3D case. b) TPV12-2D case. c) TPV13-3D case. d) TPV13-2D case.

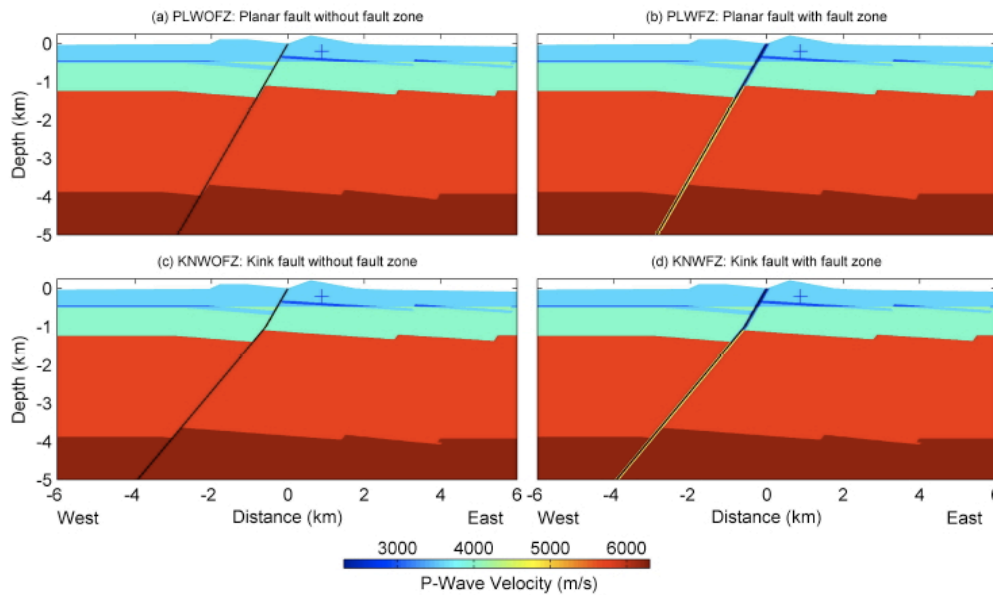


Figure 34. Different fault models to examine effects of fault geometry and fault zone structure of the Solitario Canyon fault (black line) on ground motion at the site (plus sign). A) PLWOFZ and b) PLWFZ are planar fault models, while c) KNWOFZ and d) KNWFZ are kinked fault models with a change in dip from 60 degrees to 50 degrees at a depth of 1 km. The fault zone is absent in a) and c), while a 100-m wide fault zone bisected by the fault is present in b) and d). In the fault zone, seismic wave velocities (both P and S) of the rock are reduced 20 percent relative to those of lateral surrounding wall rock. (From Duan and Day, 2009).

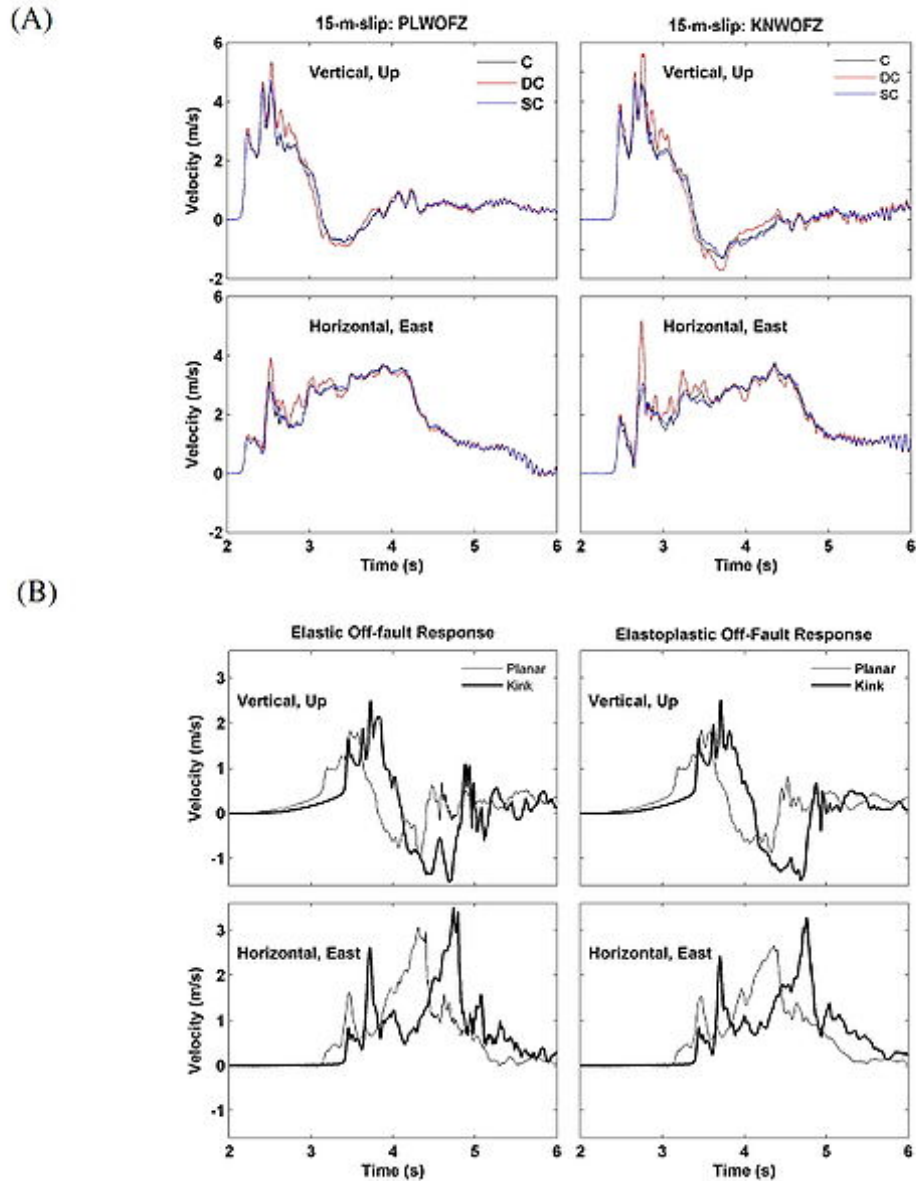


Figure 35. Effects of fault geometry and material strength on ground motion at the site. A) A shallower dip of the Solitario Canyon fault at depth and doubled cohesion values at shallow depth (red on right panel, DC) results in considerably higher peak ground velocities at the site, compared with the reference case (black on left panel, C) in the nearly complete stress drop scenario. B) Effects of a shallower dip (kink) of the Solitario Canyon fault at depth on ground motion with elastic (left panel) or elastoplastic (right panel) off-fault response, compared with the reference fault (planar).

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Crustal Deformation Modeling

This past year, several Crustal Deformation Modeling Group (CDMG) researchers have used detailed 3D viscoelastic models incorporating the SCEC CFM to address first-order scientific questions. Other CDM researchers have continued to focus their investigations on problems involving earthquake-cycle models with single faults, or postseismic deformation. Below, we showcase some exciting, representative results from various research groups in both categories. This is not meant to be a comprehensive overview of the full range of CDMG research activities, rather it is meant to highlight some of the last year's progress on important issues.

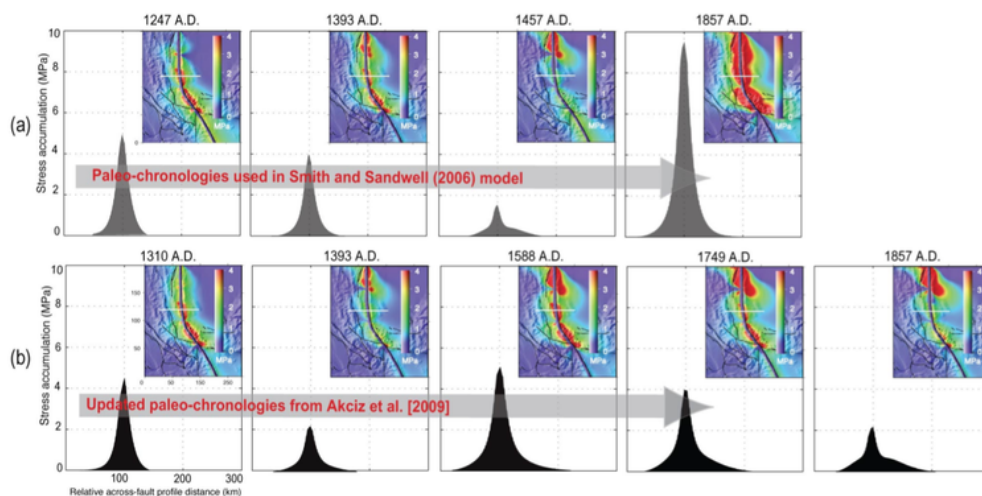


Figure 36. Comparison of hindcast stress accumulation models based on historical and prehistorical earthquake activity of the Carrizo section of the SAFS. Profile locations are represented by the solid white line in each panel. (a) Pre-event stress model results from Smith and Sandwell (2006) based on paleoseismic data (slip events at 1247, 1393, 1457, and 1857 A.D.) available at the time of publication. Each panel represents a snapshot of the accumulated stress field 1 year prior to the estimated slip event. (b) New stress model results calculated from updated data provided by Akciz et al. (2009) (slip events at 1310, 1393, 1588, 1749, and 1857 A. D.)

Multiple-fault models

Bridget Smith-Konter (UTEP) and David Sandwell (Scripps) have used semi-analytical models to investigate how differences in earthquake chronologies can affect estimates of stress accumulation, focusing on the Carrizo Plain, Imperial Valley, and Mojave sections of the SAF. This is an important point to address because: (1) revised earthquake chronologies are available

for several southern California faults (e.g., Acsiz et al., 2009) and (2) it has been demonstrated that timing of earthquakes, even prior to the ultimate large event, can influence surface velocities predicted with viscoelastic models (Hetland and Hager, 2005). Even though Smith-Konter and Sandwell's models assume a simple viscoelastic structure (50 km thick elastic plate over a uniform viscoelastic halfspace), this is the first investigation of its kind to incorporate multiple faults and competing earthquake chronologies. The models show that large differences in slip history scenarios can result in large uncertainties (1 to 5 MPa) in interseismic stress accumulation estimates (Figure 36). This underlines the need for a comprehensive and conclusive paleoseismic database. Smith-Konter and Sandwell's modeled Coulomb stress accumulation rates range from 0.5-7 MPa/100 years vary as a function of fault locking depth, slip rate, and fault geometry, and are inversely proportional to earthquake recurrence intervals.

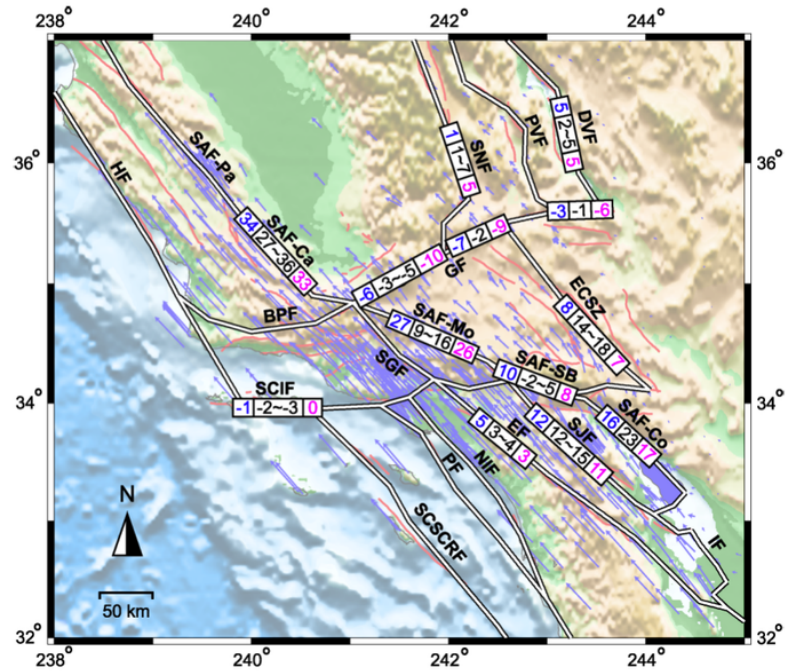


Figure 37. Comparison of geologic fault-slip rates (blue, mm/yr) used in the model, the range of the estimates from elastic block models (black) of Becker et al. (2004) and Meade and Hager (2005), and estimates from our block model (purple) along major faults. Light red lines are surface fault trace, and white thick lines are model blocks. Fault segments and geometry are constructed according to SCEC CFM-R. Blue arrows are crustal deformation velocities from SCEC CMM 3 with respect to the stable North America. BPF: Big Pine fault; DVF: Death Valley fault; ECSZ: eastern California shear zone; EF: Elsinore fault; HF: Hosgri fault; IF: Imperial fault; NIF: Newport – Inglewood fault; PF: Palos Verdes fault; PVF: Panamint Valley fault; SAF: San Andreas fault, Pa: Parkfield segment, Ca: Carrizo segment, Mo: Mojave segment, SB: San Bernardino segment, Co: Coachella segment; SCIF: Santa Cruz Island fault; SCSCRF: Santa Cruz – Santa Catalina Ridge fault; SGF: San Gabriel fault; SJF: San Jacinto fault; SNF: Sierra Nevada fault.

Kaj Johnson (Indiana) and his PhD student Ray Chuang have continued to apply 3D, viscoelastic block models to the interpretation of the southern California GPS velocity field. These models incorporate earthquake chronology information for each fault segment, including repeat time and time since the most recent large earthquake (Figure 37). They have shown that when viscoelastic relaxation is incorporated into these block models, GPS-inferred slip rates on the SAF, ECSZ faults, and the Garlock Fault change dramatically relative to values inferred from elastic block models. In many areas, incorporating viscoelasticity brings the GPS-inferred rates closer to the geological estimates (Figure 38). A grid search suggests that the optimal value of effective viscosity for the lower crust throughout the modeled region is 2×10^{20} Pa s, an estimate which is consistent with recent studies (e.g., Bürgmann and Dresen, 2008). Johnson and Chuang also show that inferred locking depths for some faults are lower when viscoelasticity is incorporated in block models (so locking depths inferred from elastic models may be biased upward). Currently, Johnson and Chuang are addressing whether their findings hold true for a range of admissible lithosphere-asthenosphere viscosity profiles.

Figure 38. Summary of geologic rates, recurrence interval (T), and time since last earthquake (teq) in southern California used in our models. Blue numbers are geologic rates from WGCEP (2008) and red numbers are rates from other paleoseismology data. The color of each rupture segment represents the ratio of time since last earthquake and recurrence interval. Hot colors show segments are in early earthquake cycle, and cold colors show late earthquake cycle. Light grey lines are surface fault trace.

particularly apparent after large earthquakes (e.g. the 1857 SAF event). For a similar model incorporating a Burger's rheology with two Maxwell times (one the same as before, and another a factor of ten lower) the long-wavelength deformation component is greater. Together, these results suggest that "ghost transients" associated with viscoelastic relaxation from large earthquakes could pollute the southern California GPS velocity field, and that if two relaxation times are present, Maxwell viscoelastic models incorporating just the slower relaxation time may underestimate the magnitude of viscoelastic contributions to the GPS velocity field. Work on a wider variety of viscosity models is underway, as well as an effort to address whether power-law flow may be adequately mimicked with linear rheologies. The latter project is important because FE models incorporating power-law flow run very slowly, and semi-analytical or block models do not incorporate power-law flow.

We also note that our past funding has borne fruit: at the 2010 CFEM workshop in Golden, Colorado, Williams, Brad Aagaard, and their colleagues distributed a version of PyLith that incorporates frictional faults and Drucker-Prager plastic rheology. This allows us to accurately model long sequences of earthquakes (large deformations) in areas with geometrically complex and kinematically imperfect fault systems, and to compute absolute crustal stresses.

Single-fault models

Yuri Fialko (Scripps) and his PhD student Sylvain Barbot improved their semi-analytical deformation code for modeling postseismic deformation, by adding stress-driven afterslip and power-law viscoelastic relaxation. They applied their technique to model coseismic stress-driven afterslip following the 2004 Parkfield earthquake. Their calculations show that the geodetic data are best explained by a rate-strengthening model with frictional parameter $(a - b) = 7 \times 10^{-3}$ and afterslip in areas of low coseismic slip and low seismicity. This is broadly consistent with past findings from Parkfield (Johnson et al., 2006), which were obtained using a different approach.

Elizabeth Hearn (UBC) and PhD student Ali Vaghri modeled the effects of lateral contrasts in viscosity structure on surface deformation around a strike-slip fault. For models with a plate thickness contrast across the fault or a contrast in viscosity below the elastic plate, they found that the sense of asymmetry in surface velocity profiles reverses during the interseismic interval, allowing the integrated interseismic displacement profile to be symmetric about the fault, like the coseismic displacements (Figure 39). For moderate to high substrate viscosity values, which are required for strain to localize around a fault late in its interseismic interval, asymmetry in surface velocities is modest. This suggests that strongly asymmetric surface deformation around major strike-slip faults cannot be explained in terms of viscosity contrasts or plate thickness variations. Models of fault formation and evolution by PhD student Yaron Finzi, which incorporate a brittle damage rheology, show that asymmetric interseismic surface velocity profiles may result from viscosity contrasts. In these models power-law viscosity is assumed and the creeping fault zone at depth develops at a position which is offset from the material (or plate-thickness) contrast. Damage occurs preferentially in the weak (or thin-plate) side, resulting in asymmetric deformation relative to the fault. The UBC group's findings, and bounds on admissible, large-scale elasticity contrasts in crustal rocks, suggest that asymmetric deformation around strike-slip faults may reflect geometrical effects (e.g., offsets between the surface trace and the creeping fault at depth, perhaps due to deviations from vertical fault orientation) rather than material contrasts.

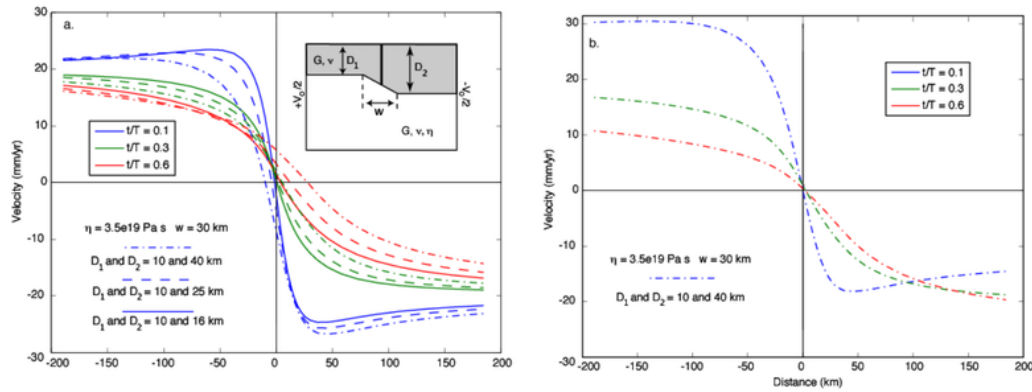


Figure 39. Earthquake-cycle models with a contrast in elastic plate thickness across the fault. (a) Results at three times in the earthquake cycle ($t/T_{\text{cycle}} = 0.1, 0.3, \text{ and } 0.6$) for three models. (b) Velocity profiles plotted relative to a point on the fault for the model with the most extreme plate thickness contrast. Note the change in the sense of asymmetry with time. $T_{\text{cycle}} = 200$ years, $T_{\text{Maxwell}} = 50$ years, $G = 40$ GPa, and Poisson's ratio = 0.25.

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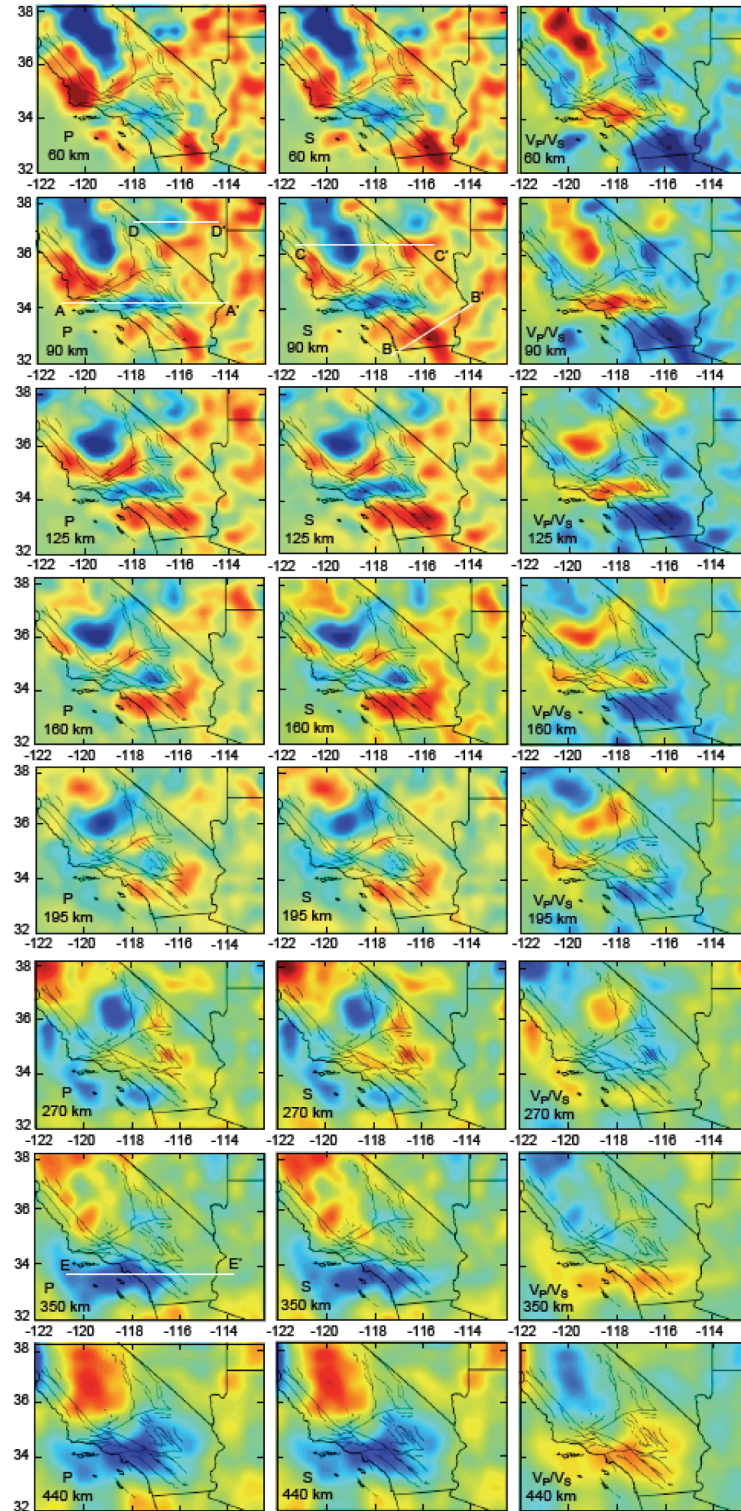


Figure 40. Map-view finite frequency P and S velocity model and V_p/V_s ratios (from Schmandt and Humphreys, 2010).

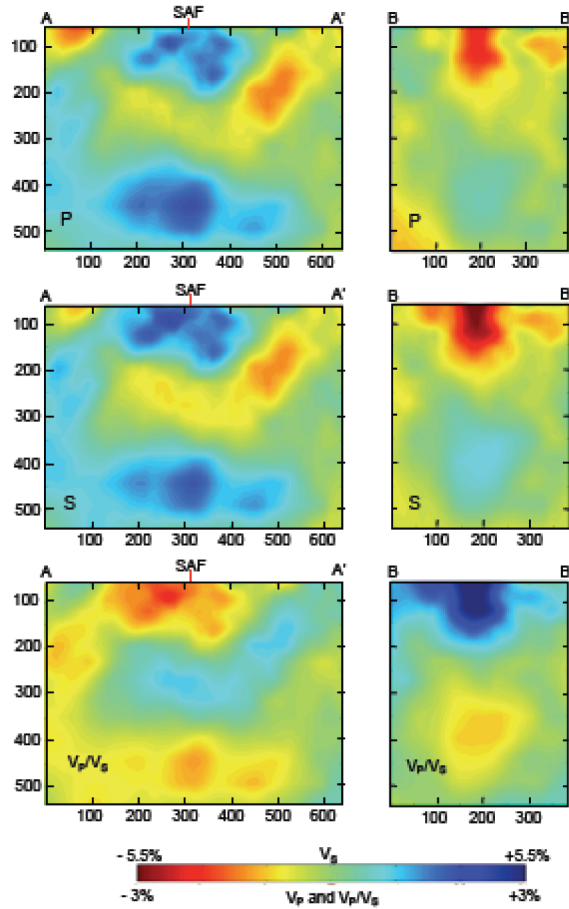


Figure 41. Finite frequency P and S velocity model cross-sections at depth (km) along profiles across the Transverse Ranges (LHS) and Salton Sea (RHS) (from Schmandt and Humphreys, 2010).

Lithospheric Architecture and Dynamics

Three Dimensional V_p V_s V_p/V_s Structure

Gene Humphreys' group has accomplished a long-standing goal of constructing a tomographic image of southern California upper mantle using modern methods and data, including use of: (1) finite-frequency sensitivity kernels, (2) all available P and S wave data (to hundreds of kilometers from southern California), (3) the SCEC crustal velocity model (crustal velocities and Moho depths), and (4) spatially variable meshing of tomography nodes. The results were published in G-Cubed (Schmandt and Humphreys, 2010). Together, these improvements contribute to a significantly better resolved and accurate upper mantle P-wave model, which in turn provides better constraints for geodynamic and tectonic models. Beyond improved resolution of the geometry and amplitude of the P-wave structure, other important results include: a companion S-wave tomography model (of resolution better than the previous P-wave model); a well-behaved V_p/V_s model, from which partially molten mantle is inferred beneath the Salton Trough to depths of ~ 125 km; resolution of high velocity structures within the transition zone that reasonably are fragments of previously subducted ocean lithosphere. Results

are shown in map view in (Figure 40) and selected cross-sections beneath the Transverse Ranges and Salton Sea in (Figure 41). The regional tomography shows that the Transverse Ranges high velocity anomaly extends to a depth of 200 km but the southern Sierras anomaly is significantly stronger.

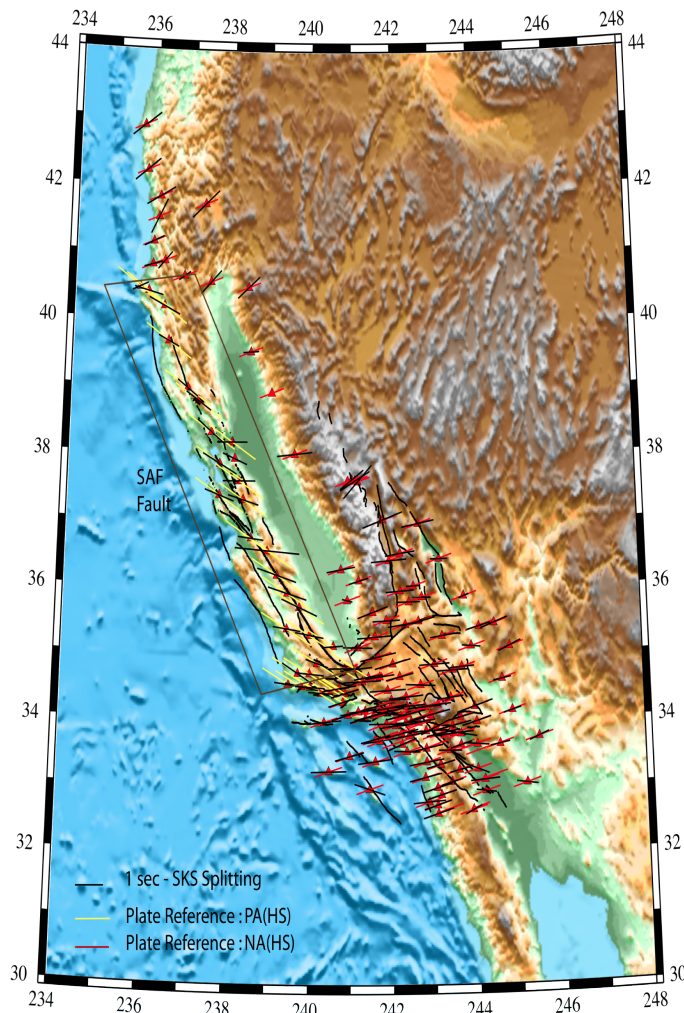


Figure 42. Comparison between APM (absolute plate motion) and splitting variations of the SKS phase for California Stations. Yellow lines give Pacific plate APM from the Nuvel 1A model (Gripp and Gordon, 2002). Red lines denote North American APM and black lines are SKS splitting fast directions. The brown box shows stations that have splitting directions that are rotated towards Pacific plate APM consistent with the 400-500 km of relative motion across the San Andreas Fault system that has occurred after plate capture. In southwestern California the onshore relative motion west of the SAF has been less than half this amount, insufficient to rotate the fast directions.[Kosarian et al., 2010].

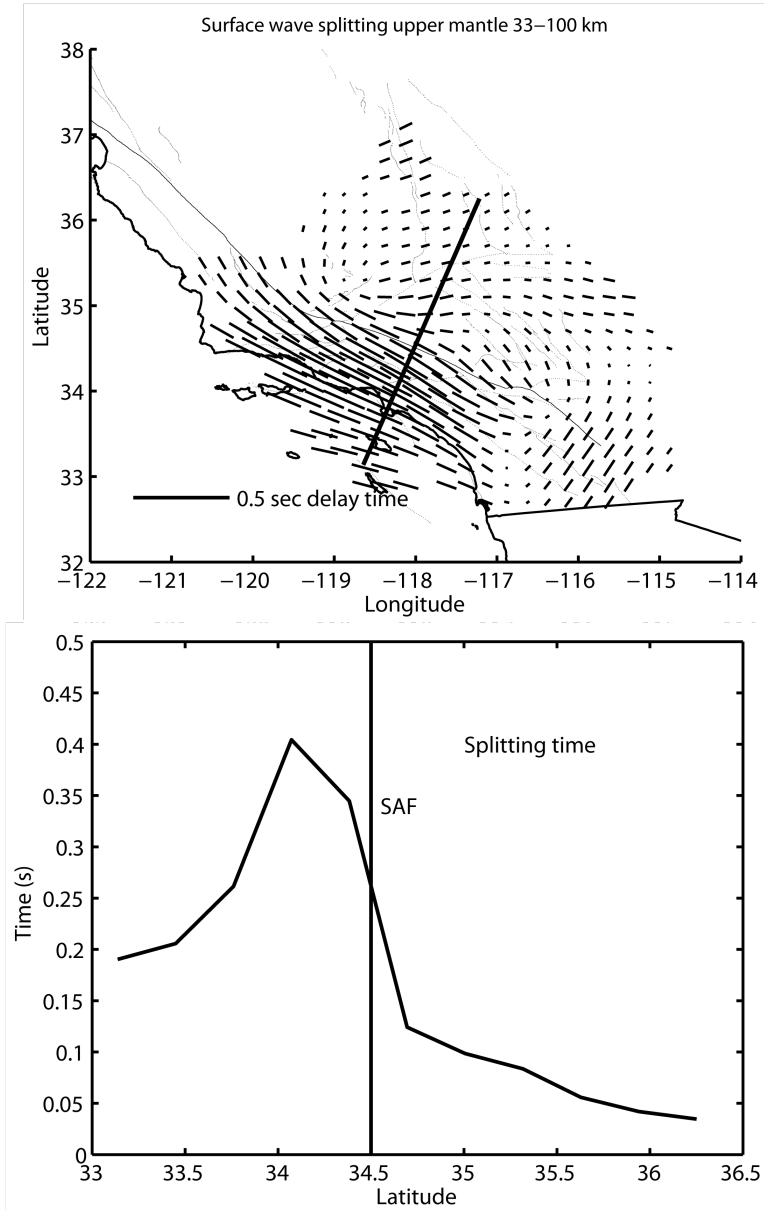


Figure 43. Predicted splitting times from surface wave analyses from mantle lithosphere (33-100 km). The other layers ([0-33, 100-150] km) give negligible effects. The surface waves fast axes are parallel to the San Andreas Fault (curved dark line) and obtain maximum values in the region of high topography associated with the Big Bend south of the fault. A cross-section illustrating this is shown in the lower panel along the line in the upper panel.

SKS Splitting

A paper on SKS splitting and surface wave comparison is under revision (Kosarian et al., 2010). SKS splitting parameters were calculated for all available data from the California Integrated Seismic Network. In southern California, where the density of stations is greatest, azimuthal anisotropy in the upper 100 km was estimated using surface waves. The inferred

splitting from surface waves in the mantle lithosphere is small (on average 0.2 sec) compared with SKS splitting (1.5 sec) and obtains a maximum value (0.4 sec) in the transpressive region of the Big Bend, south of, and aligned with, the San Andreas Fault. In contrast, the SKS splitting is aligned approximately E-W and is relatively uniform spatially on either side of the Big Bend (Figure 42 and Figure 43). These differences suggest that most of the SKS splitting is generated deeper, perhaps in the asthenosphere. Fast SKS directions align with absolute plate motions (APM) in northern and southeastern California but not in southwestern California. The authors interpret the parallelism with APM as indicating the SKS anisotropy is caused by cumulative drag of the asthenosphere by the over-lying plates. The discrepancy in southwestern California is interpreted as arising from the diffuse boundary there compared to the north, where relative plate motion has been concentrated near the SAF system. In southern California the relative motion originated offshore in the Borderlands and gradually transitioned onshore to the SAF system. This has given rise to smaller displacement across the SAF (160-180 km) compared with central and northern California (400-500 km). Thus, according to this view in southwestern California the inherited anisotropy from prior North American plate motion has not yet been overprinted by Pacific plate motion.

Receiver Functions (Lower Crust Anisotropy)

Zandt is examining receiver functions (RFs) in order to obtain seismic properties of the lower crust including anisotropy. He identified a lower crustal anisotropic zone, present in much of southern California (Figure 44). For this work he calculated teleseismic receiver functions for 38 broadband seismic stations in southern California and rotated the anisotropy measurements back to their orientations at 36 Ma. Results reveal a signature of pervasive seismic anisotropy in the lower crust that is consistent with the presence of schists emplaced during Laramide flat-slab subduction.

Anisotropy is identified in receiver functions by the large amplitudes and small move-out of the diagnostic converted phases. Within southern California, the similarity of data patterns on widely separated stations also supports an origin primarily from a basal crustal layer of hexagonal anisotropy with a dipping symmetry axis. Neighborhood algorithm searches (Frederiksen et al., 2003) for depth and thickness of the anisotropic layer and the trend and plunge of the anisotropy symmetry (slow) axis have been completed for the stations. The searches produced a wide range of results, but a dominant SW-NE trend of the anisotropy symmetry axis emerged among the station measurements.

When the results are divided into crustal blocks and restored to their pre-36 Ma locations using the reconstruction of McQuarrie and Wernicke (2005), the regional-scale SW-NE trend becomes even more consistent, though a small subset of the results can be attributed to NW-SE shearing that may be related to San Andreas transform motion. They interpret this dominant trend as a fossilized fabric within schists, created from a top-to-the-southwest sense of shear that existed along the length of coastal California during pre-transform, early Tertiary subduction. The mechanism is described in (Figure 45).

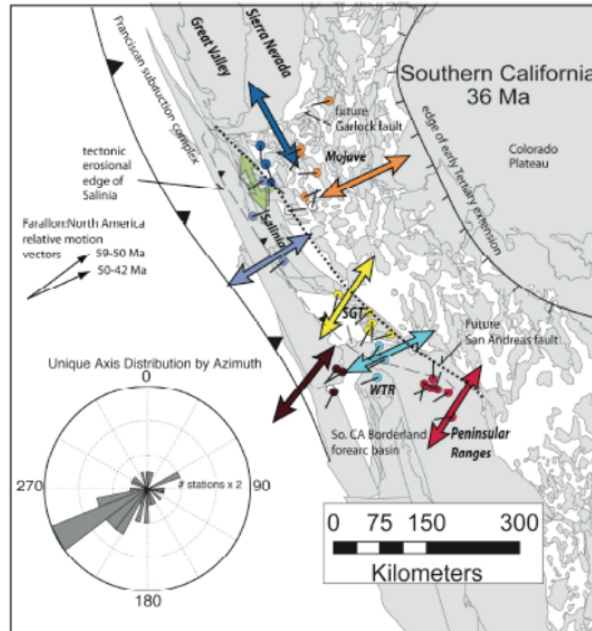


Figure 44. Map of station locations and unique lower crust anisotropy axis orientations at 36 Ma based on the reconstruction of McQuarrie and Wernicke (2005). Station color-coding corresponds to the crustal blocks. The large arrows show the best fitting block trend-lines rotated back to their orientation at 36 Ma. The rose diagram shows the number of stations with anisotropy trends within each 10° bin when rotated back to their 36 Ma orientations. Vectors show Early Tertiary Farallon-North America relative motion vectors from Saleeby (2003). [Zandt 2010].

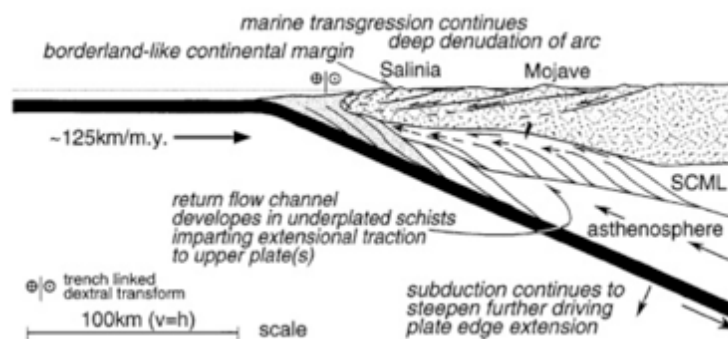


Figure 45. Interpretation of lower crustal anisotropy based on Saleeby model. Under-plated schist associated with relative motion of the Farallon slab and NA plate develops a fabric that can explain tangential energy in receiver functions.

Regional Surface Wave Analysis

The discrepancy between SKS splitting and anisotropy from surface waves in the upper 100 km still remains. The surface wave anisotropy is too small and in the wrong orientation to explain the splitting. Both Tanimoto and Davis groups are examining very long period surface

waves to see if the SKS anisotropy could be located deeper; however, achieving the required accuracy to detect anisotropy in (>150 s) long period waves is proving difficult. Tanimoto used a beamforming approach in order to completely remove complications and doubts on the surface wave results from complex wave propagation effects. The whole earthquake data sets from 190 events from 1999 to 2008 were reanalyzed by the beamforming method. Figure 46 shows some examples of beamforming for selected earthquakes. In order to determine anisotropy refractions must be taken into account that cause incoming waves to depart from great circle azimuths by as much as thirty degrees. They make phase velocity measurements from the maximum beam locations. In Figure 47, they show the azimuthal variations of Rayleigh wave phase velocities obtained from beams. One hundred ninety events were selected to cover the entire azimuth as uniformly as possible. There are some azimuths for which it is hard to find earthquakes. Two prominent results are (i) 4-theta variations are much smaller than 2-theta variations. This has been assumed since the beginning of this type of study in the mid 1980s but has never been shown directly from data. (ii) The fast axis is in the azimuth of 290-300 degrees, clockwise measured from north. The main results unequivocally show the azimuthal variation of Rayleigh-wave phase velocities. The dominant component is in the 2-theta component, as has always been assumed, but this is perhaps the first result that shows the 4-theta components are small. The fast axis is in the azimuth 290-300 degrees (Figure 48). The fast phase velocity axis for the surface wave analysis is basically in the direction of WNW-ESE. The azimuth is 290-300 degrees. Red lines give regional fast axis for different Rayleigh frequencies. Unlike SKS which has fast directions \sim E-W the surface wave fast directions are aligned with the San Andreas Fault (WNW-ESE).). Therefore, previous estimates (Prindle, 2006) for the fast axis is consistent with the current results.

In summary anisotropy in southern California can be separated into at least 4 layers (1) the upper crust with about 0.1 sec splitting with fast axis north-south, possibly associated with cracks and structures related to N_S compressive stresses, (2) lower crust with a similar splitting value oriented NE associated with underplaying of schists such as Catalina etc., at the time of subduction, (3) Mantle lithosphere with variable fast directions, but a coherent pattern in the Big Bend region aligned with structures caused by the transpression and (4) deeper asthenospheric values that amount to 1.5 s splitting and for most of the State are aligned with absolute plate motion, but in southern California is at a large angle to Pacific plate motion, for reasons we do not completely understand. The location of SKS anisotropy has not been found, but appears to be deeper than 150 km. Its parallelism to APM suggest it is upper mantle. The fact that is appears undetectable by surface waves of periods 100 sec and longer begs the question as to whether the strain associated with APM extends to depths of several hundred km.

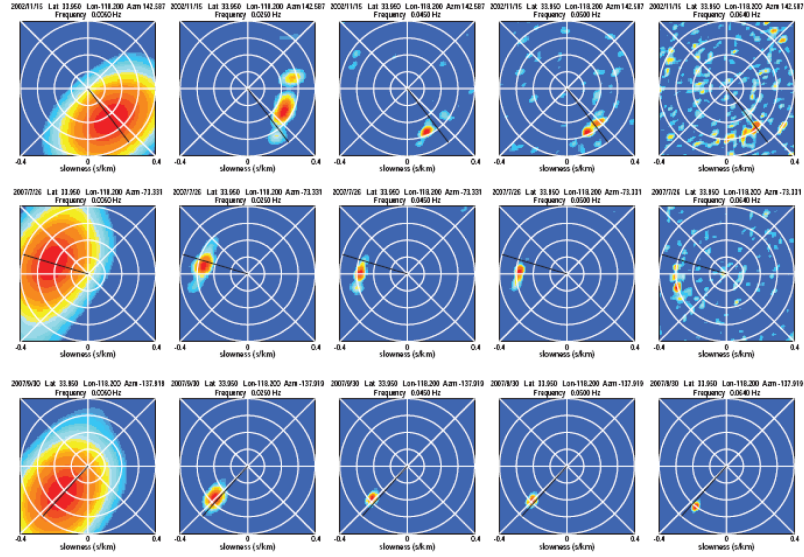


Figure 46. Beamforming analyses for three earthquakes (each row). From left to right, the results at frequencies 0.005 Hz, 0.025 Hz, 0.045 Hz, 0.05 Hz, and 0.064 Hz are shown. Black line from the center shows the (back-) azimuth of source location (along great circle path). At higher frequencies, systematic deviations between the beam locations (orange) and the black lines are obvious. Phase velocity measurements from the beam locations are free from such complications of surface wave refraction.

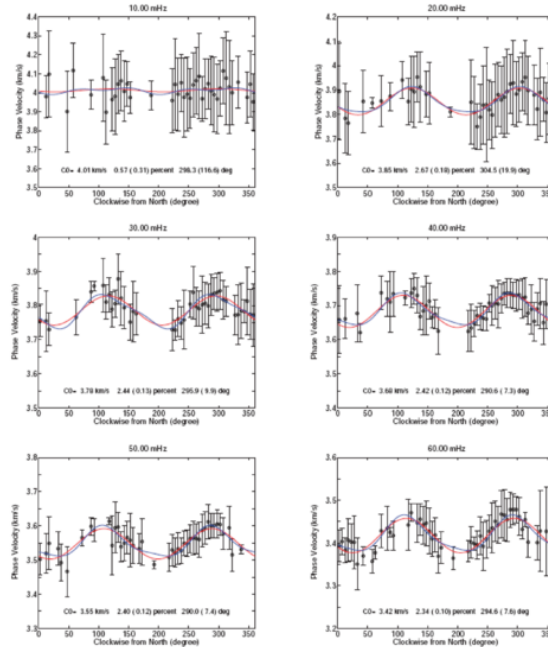


Figure 47. Azimuthal variations of Rayleigh wave phase velocity measurements from beam locations. Note the 100 sec waves indicate very low anisotropy, which is a puzzle when we try to explain SKS splitting.

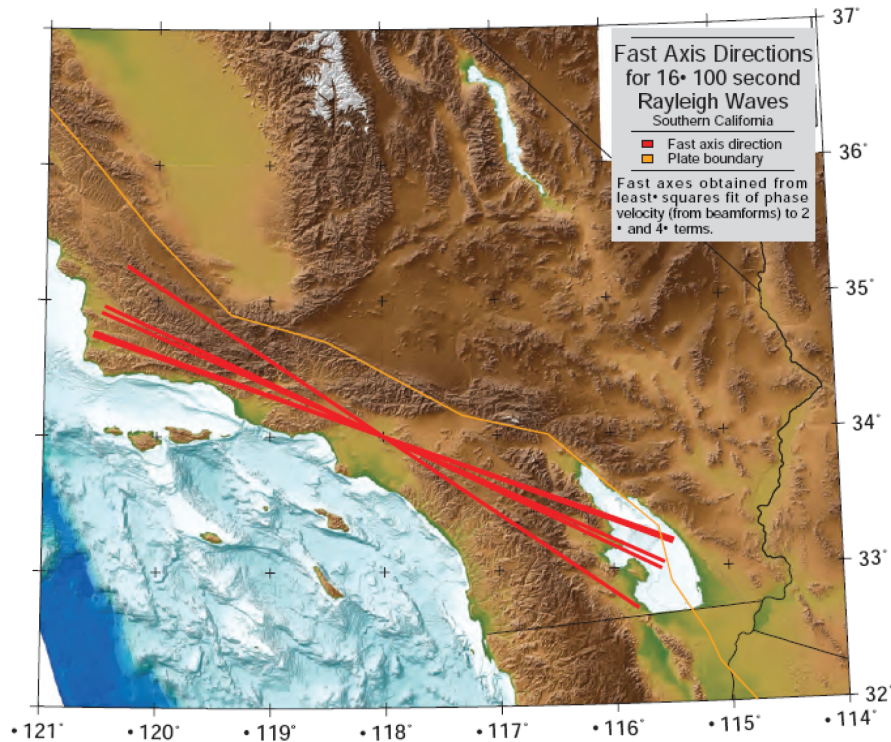


Figure 48. The fast phase velocity axis for the surface wave analysis is basically in the direction of WNW-ESE. The azimuth is 290-300 degrees. Red lines give regional fast axis for different Rayleigh frequencies. Unlike SKS which has fast directions ~E-W the surface wave fast directions are aligned with the San Andreas Fault (WNW-ESE).

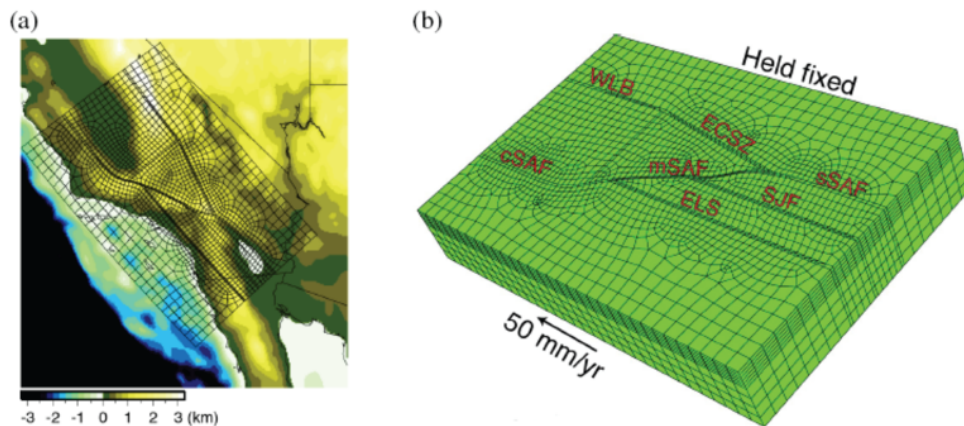


Figure 49. Map of the regional model study area (topography) with finite element domain overlain, focusing on southern California. (b) 3D perspective view of the finite element grid, major fault zones in southern California are marked. WLB: Walker Lane Belt; SAF: San Andreas Fault; cSAF: Central SAF; mSAF: Mojave section of the SAF; sSAF: southern SAF (Carrizo segment); SJF: San Jacinto Fault; ELS: Elsinore fault; Other abbreviations used in text: TR: Transverse Ranges; ECSZ: Eastern California Shear zone.

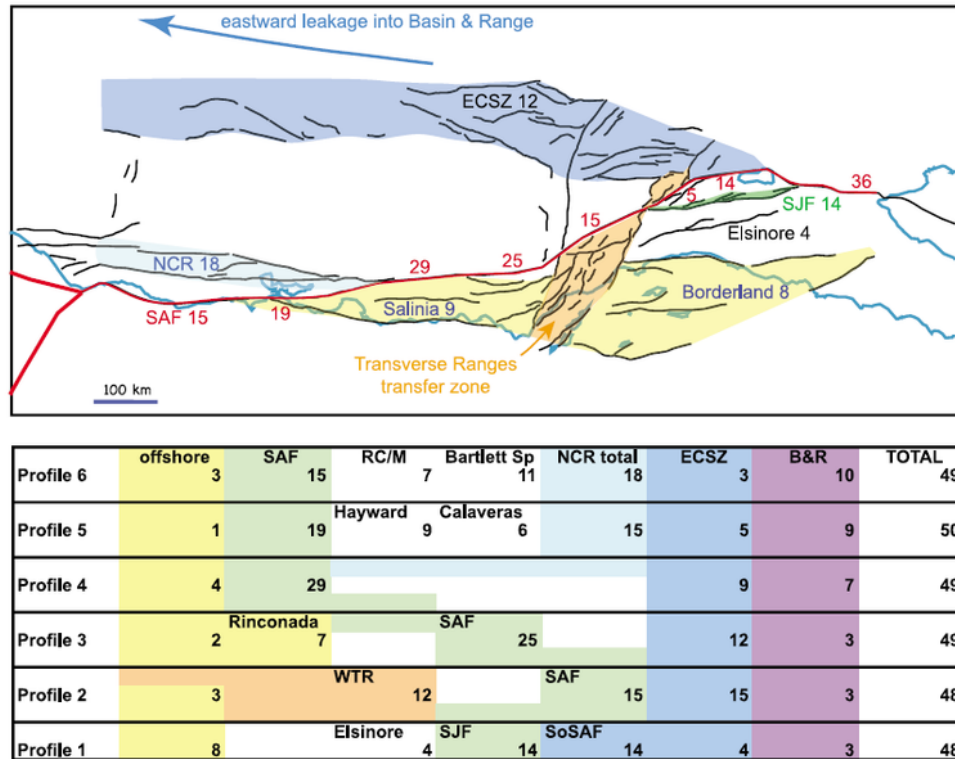


Figure 50. Slip rate budget for California, showing major faults and bands of grouped faults, with interpreted slip rates. (bottom) The slip rates in tabular form for each profile, including the additional slip rate at the ends of each profile needed to bring the total to the Pacific–North America relative plate velocity. The color bands show schematically how the slip is transferred along strike. (top) Map showing in simplified form how the slip is distributed among the different parts of the system, together with their linkages. [From Platt and Becker, 2010]

Dynamic Models of Lithospheric Deformation

Becker’s group is developing finite element models (SMOG3D) to understand driving forces, fault strength and rheology (Figure 49 and Figure 50). They model curved faults with large off-fault strain similar to that observed geodetically and the interaction of the San Andreas, San Jacinto (SJF) and Elsinore (ELS) faults and conclude that if only fault strength is varied to accommodate the geodetically observed distribution of slip-rates, the strength of the ELS must be larger than that of the SJF, which must be larger than that of the SAF Indio by at least a factor of 3 and 2, respectively. The results show that the models can be used to test several suggested forces acting upon southern California faults include in crustal as well as mantle tractions.

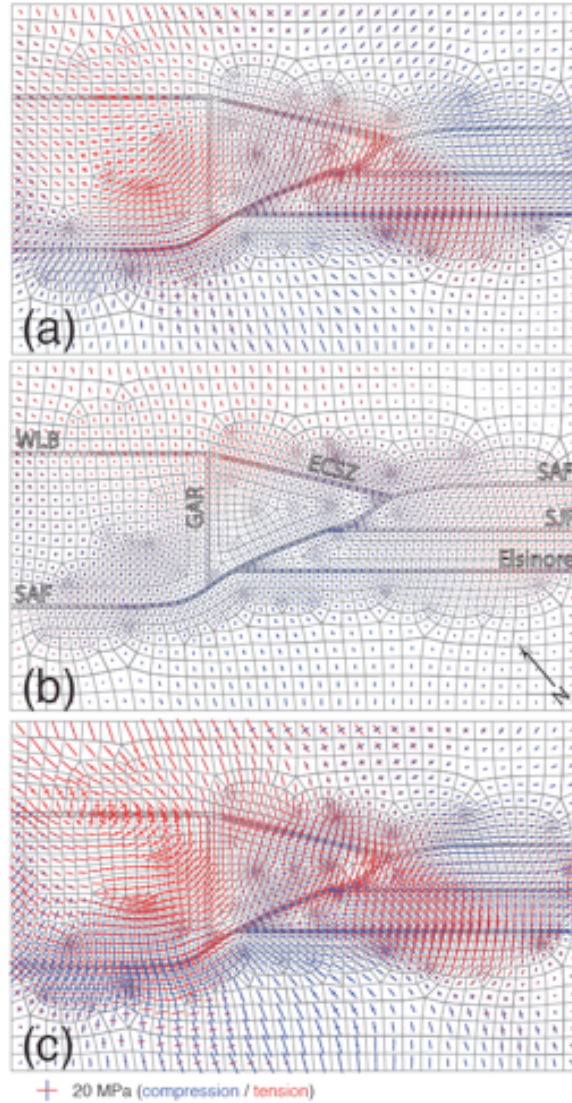


Figure 51. Estimated stress field, from body forces associated with topography, Moho variation and mantle loads inferred from tomography. Horizontal deviatoric principal stress field at 7.5 km depth caused by buoyancy heterogeneity. Blue bars indicate compression, red indicate tension. (a) Stress field caused by lateral variation in crustal thickness. Moho depth taken from receiver function studies [Zhu and Kanamori, 2000; Yan and Clayton, 2007] (b) Stress field caused by anomalous upper mantle density structure and tractions caused by density driven upper mantle flow [Fay et al., 2008]. SAF, San Andreas fault trace. (c) Total stress field ($c = a + b$) caused by crustal and upper mantle density variations. In the vicinity of the eastern and central Transverse Ranges the stress field is dominantly N-S compression and E-W tension [from Fay et al., 2009].

Analysis of geodetic velocities

Platt and Becker [2010] substantiate that the zone of highest geodetically defined strain rate in California does not everywhere coincide with the surface trace of the San Andreas Fault

(SAF). To determine whether this reflects the pattern of long-term, permanent deformation, they analyzed the velocity field on swaths across the transform, located so as to avoid intersections among the major fault strands. Slip rates and flexural parameters for each fault were determined by finding the best fit to the velocity profile using a simple arctan model, representing the interseismic strain accumulation. Their slip rates compare well with current geologic estimates (Figure 51), which suggests that the present-day velocity field is representative of long-term motions. Platt and Becker find that the transform is a zone of high strain rate up to 80 km wide that is straighter than the SAF and has an overall trend closer to the relative plate motion vector than the SAF. Most sections of the SAF take up less than half of the total slip rate, and slip is transferred from one part of the system to another in a way that suggests that the SAF should not be considered as a unique locator of the plate boundary. Up to half of the total displacement takes place on faults outside the high strain rate zone, distributed over several hundred kilometers on either side. Platt and Becker's [2010] findings substantiate previous suggestions that the transform has the characteristics of a macroscopic ductile shear zone cutting the continental lithosphere, around which stress and strain rate decrease on a length scale controlled by the length of the transform [e.g. Platt et al., 2008].

Tractions from Global Mantle Flow

To place the regional modeling for southern California into a broader context, and to check the consistency of the mantle loading that was explored in the regional finite element models, Becker's group also explores plate-wide models with high enough resolution to incorporate the western US. Earlier studies (Humphreys and Coblentz, 2007) have argued for the importance of shear tractions beneath the continent, but at a reduced amplitude from those predicted by Becker and O'Connell(2001); however, these tractions did not take into account the existence of lateral viscosity variations (LVVs) beneath North America, resulting from strong cratonic root and weak plate margin (cf. Conrad and Lithgow-Bertelloni, 2006; Becker, 2006). They evaluate the tractions and the resulting stresses over North America by incorporating LVVs in a global, high resolution, finite-element convection code, CitcomS (Zhong et al., 2000) (Figure 52). Since one of their goals is to match observables, such as plate motions and geoid, in addition to stresses, they perform a global inversion for both radial and lateral viscosity variations and choose the viscosity structures that yield a good fit simultaneously to both the global geoid and plate motions. They evaluate the tractions and corresponding stress field from those models. Recently they have also incorporated the effects of gravitational potential energy in their convection model by applying the GPE gradients as a stress boundary condition throughout the lithosphere. The GPE induced stresses from the flow model are benchmarked with vertically integrated deviatoric stresses obtained from a thin sheet model (Ghosh et al., 2009). They are in the process of refining the representation of plate boundaries (thinner weak zones), and intend to explore further the role of regional and global tomographic models for mantle tractions.

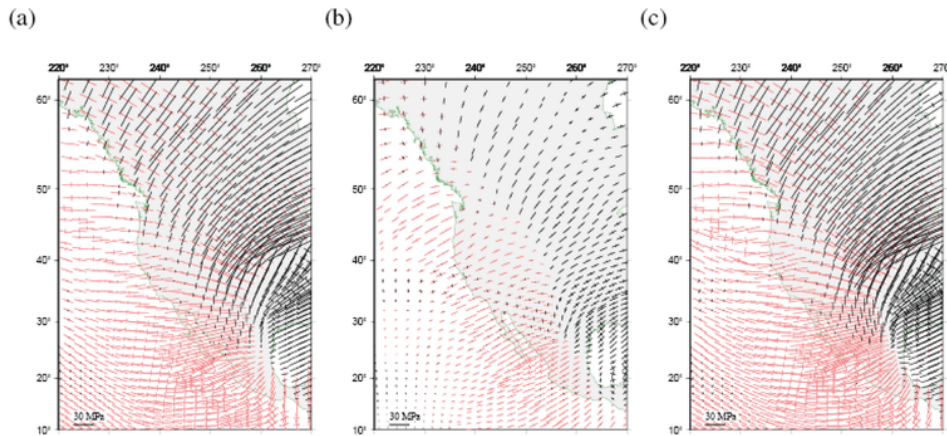


Figure 52. Lithospheric stress fields as predicted from a preliminary global, viscous flow computation (cf. Becker, 2006; Ghosh et al., 2009); red and black sticks indicate the orientation of the tensional and compressional axes, respectively. (Strike-slip style of stresses are correspondingly represented a pair of stresses.) (a) Deviatoric stress prediction from density driven flow model with lateral viscosity variations (LVVs). The tomography model used is the composite SMEAN (Becker and Boschi, 2002). LVV models are based on the best-fitting viscosity structure that matches both global geoid (correlation of 0.82) and plate motions (correlation of 0.85, both up to spherical harmonic degree 20) well (Ghosh et al., 2009). The LVVs are generated by weak plate boundaries (reduced viscosity), strong keels and temperature dependent viscosity. Most of the western US exhibits strike slip style of deformation, but note artifacts from the NW-SE trending weak zone which is at present too wide. (b) Deviatoric stresses from gravitational potential energy (GPE) differences. GPE is calculated based on the CRUST2.0 model of crustal structure, and the gradients of GPE are applied as traction boundary condition throughout the lithosphere. The resultant stress field is due to the instantaneous flow induced by these tractions alone. Tensional stresses mostly occur in the Great Valley and Sierra Nevada region where the GPE is relatively high, mainly due to topography. The stress field is dominated by either pure extension or compression. (c) Deviatoric stresses from GPE differences and density driven flow combined. Strike-slip stresses dominate in most areas except for the westernmost part.

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Earthquake Forecasting and Predictability

The Earthquake Forecasting and Predictability (EFP) focus group coordinates two types of research projects. The first type encourages the development of earthquake forecasting methods to the point that they can be moved to testing within the framework of the Collaboratory 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 Search for Earthquake Precursors

There is a long-standing question as to whether the seismicity prior to a large earthquake contains any precursory signals, such as rate changes over the future fault area or more foreshocks than would be expected from a simple earthquake clustering model. Shearer ("Analysis of Southern California Seismicity Using Improved Locations and Stress Drops") addressed these questions by stacking a large database of small earthquake locations. A subtle but significant signal was found, similar to the classic "Mogi doughnut", where more events occur in the day before a larger earthquake, at distances comparable to its source dimension (Figure 53). Comparing the rate of foreshocks to the rate of aftershocks also shows that there are relatively more foreshocks than would be expected from a self-similar process (Figure 54). These signals are too small to be useful precursors for earthquake forecasting, but provide significant insight into pre-earthquake processes, and highlight the limitations of simple self-similar earthquake clustering models.

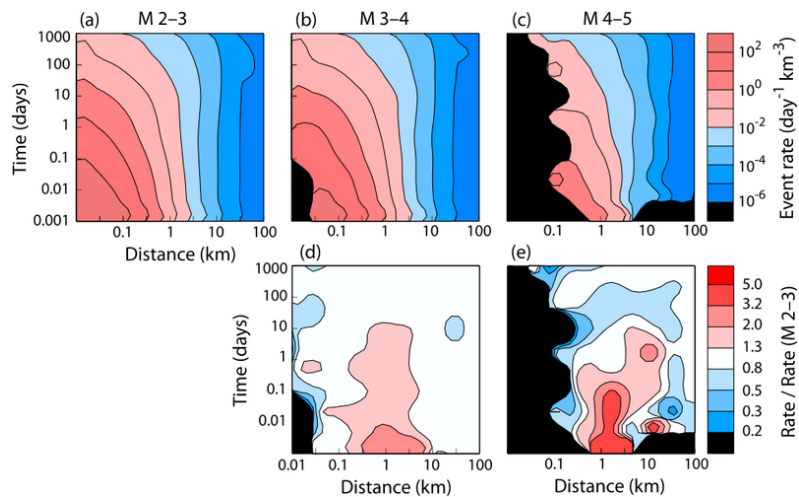


Figure 53. Space/time behavior of precursory seismicity in southern California. (top) The average event rate prior to target earthquakes of (a) M 2–3, (b) M 3–4, and (c) M 4–5, at times from 0.001 day (86 s) to 1000 days prior to the target events at distances from 10 m to 100 km. Contours are uniform in log event density (per day per cubic kilometer). Black shows regions of no data. (bottom) The ratio of precursory seismicity rate for the (d) M 3–4 and (e) M 4–5 target event bins compared to the M 2–3 bin (from: Shearer and Lin, JGR 114, B01318, doi:10.1029/2008JB005982, 2009.)

It has also been proposed that large earthquakes are preceded by a change in the frequency-magnitude distribution, commonly represented by the b-value. Zaliapin ("Investigating temporal changes in the earthquake magnitude distribution") tested for a change in b-value before large earthquakes, as well as changes in the relative number of medium sized earthquakes compared to the number of small earthquake, and changes in the number of earthquakes, fault area, and moment release rate. The ratio of medium sized to small earthquakes appears to increase prior to large earthquakes in California; however, the standard b-value had mixed results, decreasing before large events in northern California while increasing before large events in southern California. The other statistics were found to have better spatial resolution than temporal predictive power, reflecting spatial variations in earthquake rate. A smoothed seismicity model from this project has been submitted to CSEP testing.

SCEC also supports the operation of the strainmeters at Pinon Flat Observatory (Agnew "Pinon Flat Observatory: Continuous Monitoring of Crustal Deformation"), which are suited to capture precursory slip on the San Jacinto or southernmost San Andreas fault, or at least to constrain the maximum possible precursor if no strain signal is detected.

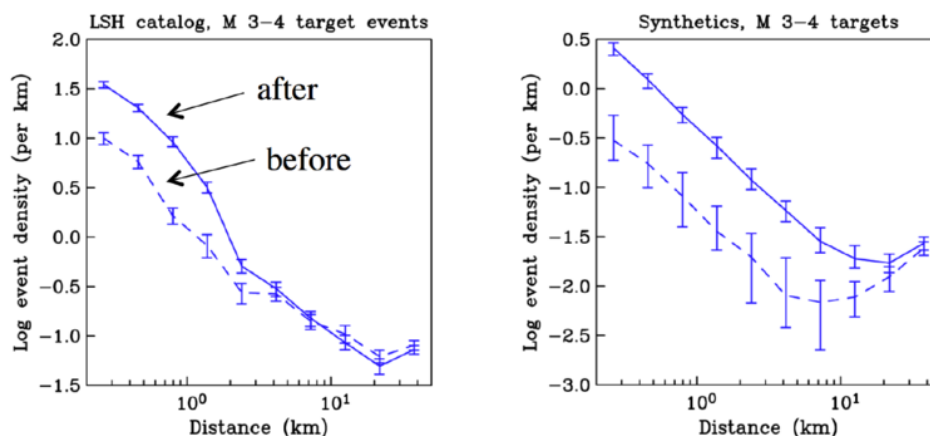


Figure 54. Event density as a function of distance in one-hour windows before and after M 3–4 target earthquakes, comparing the LSH catalog of southern California seismicity (left) with predictions of an ETAS-like triggering model (right). One-standard error bars are computed using a bootstrap resampling method. (From: Shearer, SCEC annual report.)

Testing Earthquake Forecasts

Zechar ("Parkfield microrepeater predictability experiments") attempted forecasts of repeating small earthquakes on the San Andreas Fault near Parkfield, based on the regularity of the events. While retrospective tests indicated that the forecasts based on recurrence times were better than random, the forward tests were unsuccessful. One problem may be the change in rate following the 2004 Parkfield earthquake. Burgmann ("Triggering Effect of the 2004 M6 Parkfield Earthquake on Earthquake Cycles of Small Repeating Events") studied the effect of the Parkfield earthquake on repeating events, and found that after Parkfield, the recurrence intervals decreased dramatically and then started increasing back towards their pre-Parkfield values (Figure 55). Interestingly, the magnitudes also increased for many sequences (Figure 55), a counter-intuitive change that can be explained by post-seismic slip and rate and state friction. For

a small velocity-weakening patch embedded in a velocity-strengthening (creeping) fault, at low slip speeds much of the patch slips aseismically, while at higher slip speeds more of the patch participates in stick-slip events. These two studies demonstrate the considerable complexities in the predictability of even the most apparently simple earthquake sources, and the importance of developing a physical basis for the understanding of earthquake behavior.

Several short-term and long-term forecast were submitted to CSEP testing, based on smoothed seismicity and spatial-temporal clustering. These models cover the California-Nevada region and the whole earth (Kagan, "Global and Regional Earthquake Forecasts"; and Jackson, "California Earthquake Forecasts".)

Several proposals supported the CSEP testing centers and implementation of CSEP tests. Gerstenberger's "Developing reference models for earthquake predictability experiments" addressed the important problem of producing appropriate reference models for testing in CSEP and other testing environments. Gerstenberger's "CSEP Forecast Test Methodology: Development and Participation" supported travel for collaboration and meeting participation for the New Zealand testing center. Wiemer's "Travel funds for CSEP integration & development" provided similar support for the testing center in Zurich.

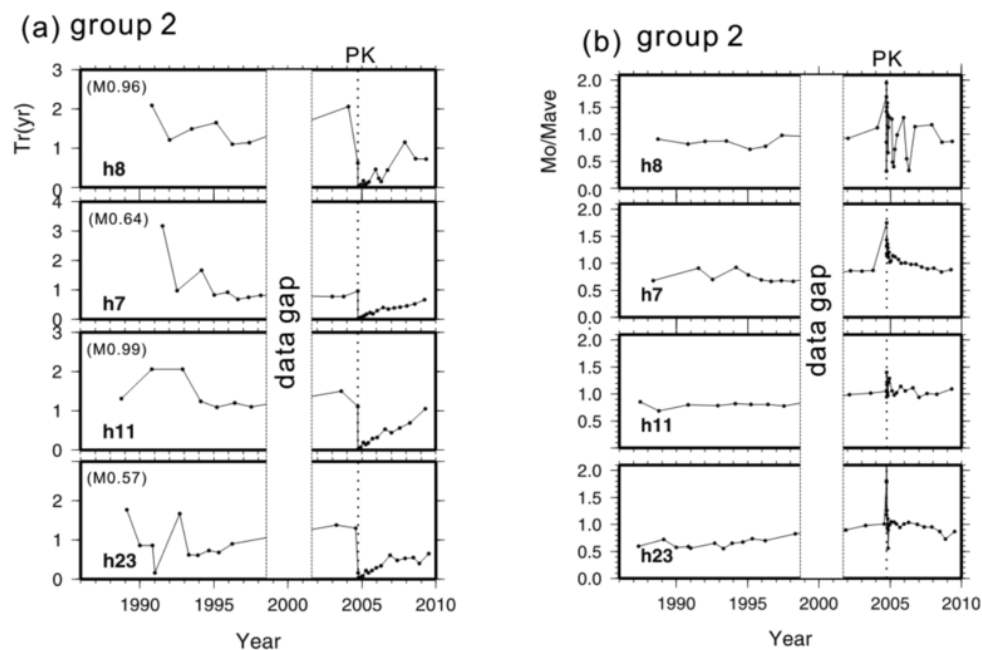


Figure 55. (a) Recurrence interval as a function of time and (b) relative moment variation (ratio of M_o and average M_o of the sequence) as a function of time for repeating sequences on the San Andreas Fault near Parkfield. (From: Burgmann et al., SCEC annual report.)

Observational Constraints

Earthquake forecasts often rely on accurate models of long-term earthquake rates. Zaliapin ("Time-dependent modeling of seismic moment release in San Andreas Fault -- Great Basin System") reconciled apparent differences in moment rate from earthquake catalogs and geodetic information. They demonstrate that moment rate deficits in earthquake catalogs are to be

expected due to sampling and clustering affects, and hence can be consistent with geodetic rates. McGill ("Late Quaternary slip rate of the northern San Jacinto fault") studied off-set features along the San Jacinto Fault to better constraint the long-term slip rate. Schärer ("Reducing uncertainties of paleoseismic event dates through critical examination of contributions to the COV") updated the slip history of the San Andreas fault at Pallett Creek using modern dating techniques, and used the revised estimates to better understand the variation of recurrence times.

The multi-disciplinary nature of EFP, and the recognition that certain tests required long-term measurements that may only be accessible through geology, led to support of several other geological studies. Stirling ("Age of precarious landforms near major plate boundary faults in New Zealand: Cross validation of western United States Studies") identified precariously balanced rocks near the Alpine Fault in New Zealand that appear to be old enough to have survived several earthquake cycles, hence potentially placing bounds on the near-field ground motions. Grant-Ludwig ("Constraining the age and renewal rates of precariously balanced rocks (PBRs) in southern California") studied precariously balanced rocks in southern California to constrain better their exhumation history, how this history may affect their apparent age, and how that would feed into their use in testing long-term ground motion predictions.

Earthquake Simulators

Several investigators have conducted research using Earthquake Simulators, including Ward's "ALLCAL -- An Earthquake Simulator for All of California", Tullis' "Quasi-Dynamic Parallel Numerical Modeling of Earthquake Interactions Over a Wide Magnitude Range Using Rate and State Friction and Fast Multipoles", and Dieterich's "Application of a Physics-based Earthquake Simulator to Southern California" and "Stress Heterogeneity and Its Effect on Seismicity". These simulators are numerical models aimed at generating catalogs of simulated earthquakes over a variety of spatial and temporal scales. The aim of these studies is to gain new insight into the behavior of real earthquakes by studying the behavior of simulated earthquakes. For example, one line of inquiry is to see if patterns of simulated seismicity in space and time occur that might also be discovered in real seismicity. If so, forecasting future earthquakes might be done by recognizing ongoing patterns in past and current seismicity. The Earthquake Simulator Comparison Project has recently focused on comparing scaling relationships found from different simulators, including the frequency-magnitude distribution, scaling of the earthquake length with slip and moment, and moment-area relationships (Figure 56).

There is currently much debate about whether the earthquake frequency-magnitude distribution follows the self-similar Gutenberg-Richter law at large magnitudes, or whether there is a relative surfeit of earthquakes at larger magnitudes. Modeling by Arrowsmith ("The effect of structural complexity and fault roughness on fault segment size and multi-segment rupture probability") demonstrated the effect of fault roughness on the frequency-magnitude distribution. Simulation results show that rough faults produce Gutenberg-Richter distributions, while smooth faults generate characteristic earthquakes, suggesting that both behaviors may be present, and depend on fault maturity (Figure 57).

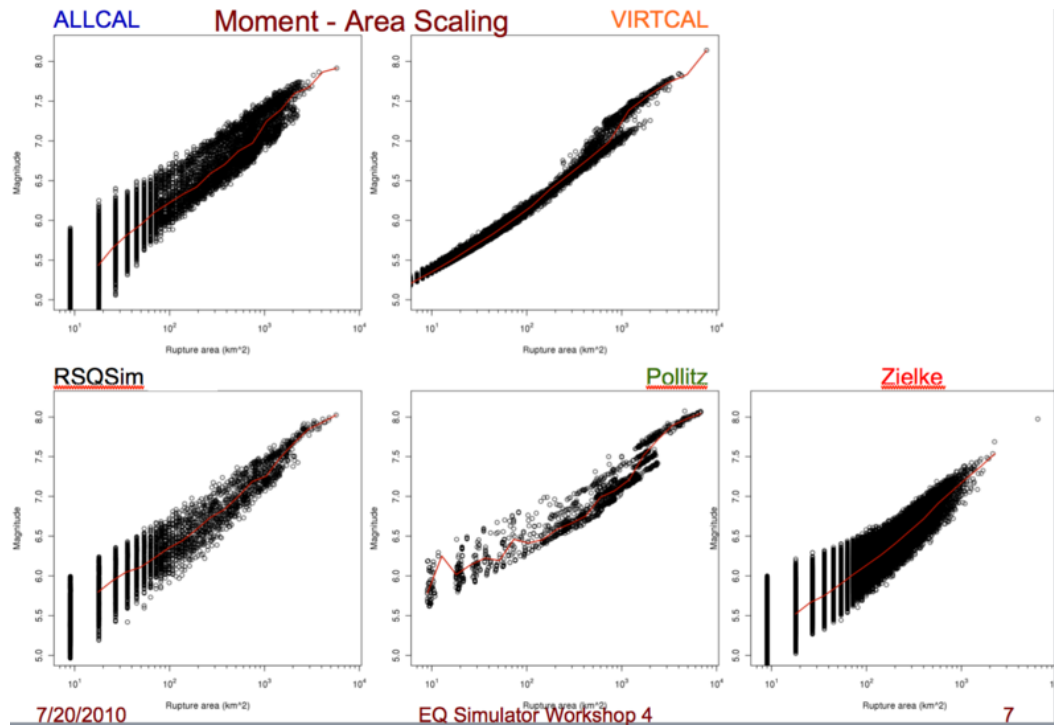


Figure 56. Comparison of moment-area scaling of model earthquakes for Northern California from five different simulators.

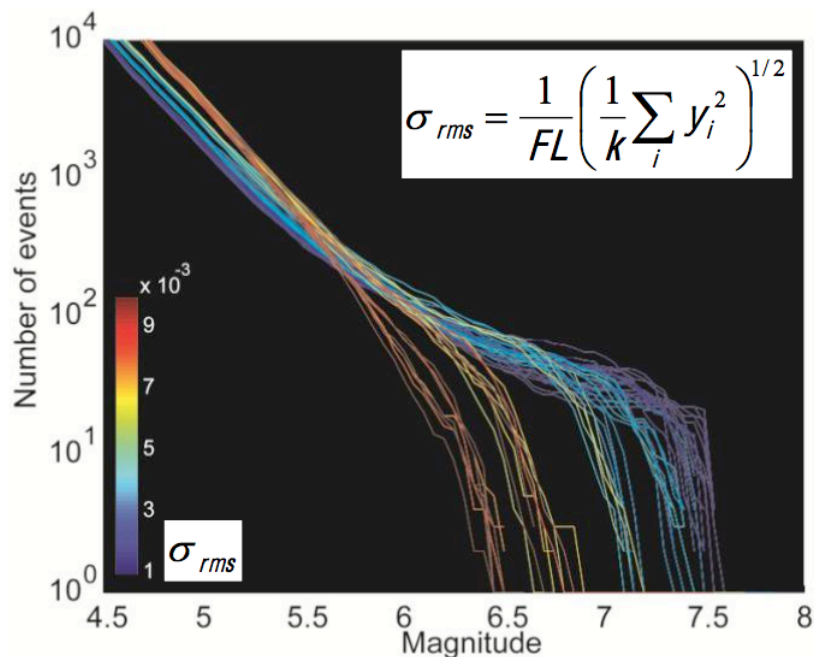


Figure 57. Cumulative magnitude frequency relationship for earthquake simulations along faults with different roughness values. Seismic behavior is becoming increasingly characteristic i.e., bimodal as the fault matures (indicated by decreasing roughness, in cold color.) (From: Arrowsmith and Zielke, SCEC annual report.)

Workshops

The "6th International Workshop on Statistical Seismology" was hosted by SCEC in April of 2009. This 3-day workshop, with approximately 100 participants, included a full day of talks and discussion focused on earthquake forecasting, predictability, and testing, in addition to related topics including earthquake recurrence, earthquake clustering, and earthquake stress interaction.

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 Earth 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.

Ground-Motion Simulations and Model Validation

Precariously Balanced Rocks. Grant-Ludwig and Rood engaged in collaborative research to develop, refine, and implement the use of precariously balanced rocks (PBRs) for validation of ground-motion studies and seismic hazard analysis. Their work focuses on constraining the age and exhumation or "renewal" rates of PBRs. In previous years they identified PBRs with good potential for cosmogenic nuclide exposure dating at sites that are important for PetaSHA validation and collected >35 samples from rocks at 6 sites. They have analyzed 30 samples for ^{10}Be concentration, obtained preliminary, model-dependent exposure ages of four PBRs near the southern San Andreas fault, and completed a full 3-D model dependent exposure age analysis of a PBR at Grass Valley near the San Andreas and Cleghorn faults as a "proof of concept" (Figure 58).



Figure 58. Sampling profile for Grass Valley Rock GV-2 and the 3D shape model. The 3D modeling effort for GV-2 demonstrates the value of this shape-based method for obtaining exposure ages.

Preliminary results indicate exposure ages correspond with marine isotope stage 2. They hypothesize a causal relationship between climate cycles and PBR formation. The Last Glacial Maximum may have increased soil erosion rates, which rapidly exhumed these PBRs. This hypothesis will be tested when exposure ages are obtained from remaining field sites. If true, regional climatic control on PBR formation would provide high resolution spatial control on unexceeded ground motions since the Last Glacial Maximum. Additionally, the age and location of the Grass Valley PBR is inconsistent with the 2% in 50 year PGA exceedance from the National Seismic Hazard Map. One possibility is that the Cleghorn fault does not have a 3 mm/yr slip rate, as assumed for UCERF-2. Similarly, the slip rate for the Pinto Mountain fault may have been overestimated because PBRs at Yucca Valley and Pioneer Town appear to be inconsistent with the National Seismic Hazard Map. Finally, the Grass Valley rock has experienced shaking from many San Andreas fault ruptures in the last ~18 ka. The enduring stability of this rock indicates persistent low ground motions from San Andreas fault ruptures at this site and suggests a preferred direction, or nucleation region, or upper bound magnitude for past earthquakes.

Ambient Noise Analysis. Beroza, Lawrence, Denolle and Prieto have extended their use of the ambient seismic field for several aspects of ground-motion prediction, including: validation of the ambient-field response against moderate earthquakes, developing a library of Green's functions for improving southern California velocity models, and developing a preliminary attenuation model for the southern California crust. Validation involves using several well-recorded earthquakes that occurred in the vicinity of continuously recording seismic stations to compare amplification effects in sedimentary basins from the ambient field to observed ground motions (Figure 59). Current work focuses on improving such comparisons by making corrections for earthquake depth and the radiation pattern. Previous analyses were limited to the vertical component (i.e., Rayleigh waves). Utilization of the inter-station complex coherence derived through deconvolution and stacking permits extending the analysis to all three components, and hence to Love waves. This process allows the development of a library of Green's functions that can be applied to refine crustal wavespeed models in southern California. Preliminary results indicate that the horizontal component waveforms appear to have more local noise than the vertical components, which will require an increase in the amount of data being used to construct the ambient-field response to extract the weakly coherent station-to-station signal. Prieto et al. (2009) reported strong differences between paths with strong sensitivity to

major sedimentary basins, and paths that have little sensitivity to basins. They have since quantified these observations to develop a laterally varying attenuation model for southern California. Current work focuses on using ambient noise Green's functions in the scattering integral approach for estimating velocity structure.

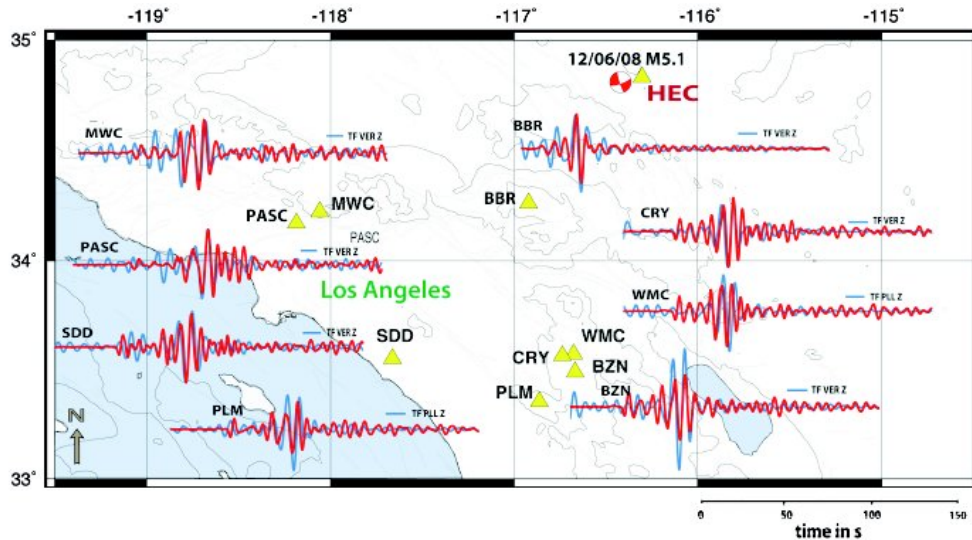


Figure 59. Comparison of vertical component ambient-field ground-motion prediction (blue) with recorded earthquake waveforms (red) for the Mw 5.1 6 December 2008 earthquake. The strong similarity of earthquake and "virtual earthquake" waveforms validates this approach.

Broadband Simulations. Recent work has focused on the development of a Broadband Simulation Platform. This is a collaborative project among Graves and Somerville (URS), Archuleta and Schmedes (UCSB) and Olsen and Mai (SDSU/ETH). Mai and Olsen (2010) developed a method to generate synthetic broadband ground motions by combining low-frequency ($f < 1-2$ Hz) deterministic simulations and high-frequency ($f > 1-2$ Hz) point scatterograms based on the theory by Zeng et al. (1991) and Zeng (1993). The two frequency bands are combined at a selected frequency that minimizes the error in both amplitude and phase between the deterministic and stochastic time series (Mai and Beroza, 2003). The scatterograms are generated from values of the elastic scattering coefficient, $Kappa$, $Vs30$, and high-frequency attenuation model. Mena et al. (2009) extended this method to distribute the moment of the event to that of a finite-fault and included a dynamically consistent source-time function. Validation has focused on the 1994 Mw 6.7 Northridge earthquake. Using low-pass filtered strong-motion data (to isolate the accuracy of the synthetic high-frequency portion), the method produces a very good fit between observed and synthetic peak ground accelerations, peak ground velocities, and spectral accelerations. Using synthetic low-frequency motions also produces a favorable fit; the broadband synthetics tend to slightly under-predict the strong-motion amplitudes between 2 and 10 Hz, primarily due to lack of complexity in the low-frequency rupture model between 1 and 2 Hz. The response spectra residuals are significantly smaller as compared to results for the Northridge earthquake using an early approach.

Mayhew and Olsen (2010) have developed a new goodness-of-fit method for the validation of broadband synthetics, consisting of a combination of commonly used metrics such as peak

values, Fourier and response spectra, cross correlation, and duration. Additionally, for structural engineering-specific applications, the algorithm includes a comparison of the inelastic/elastic displacement ratios. The method has been applied to broadband synthetics (0-10Hz) generated for the 2008 Mw 5.4 Chino Hills earthquake. The best fits are found for stations SRN and OGC just south of the epicenter, CHF and KIK toward the northwest, and HLL and SMS toward the west. Stations with goodness-of-fit values near or below the proposed acceptable threshold include STS (amplitude and duration under-predicted), and DEC, PDU and RVR (amplitude and duration over-predicted) (Figure 60). Average inelastic/elastic displacement ratios have been computed at short periods (0.2-0.5s), moderate periods (0.75-1.5s) and long periods (2.0-5.0s). At the shorter periods, about 1/3 of the sites (located primarily north of the epicenter, as well as STG, SMS, and WTT) produce inelastic/elastic displacement ratios below the proposed acceptance threshold. On average, the simulated ratios are under-predicting the recorded ratios at the short periods with a large variance. This is in agreement with the findings by Tothong and Cornell (2006) who showed that the inelastic/elastic displacement ratios for oscillators with a short natural period ($<0.6s$) are highly variable. At moderate periods and long periods, the synthetic ratios tend to have a very good to good fit, suggesting that these ground motions could be used in engineering and hazard analysis applications.

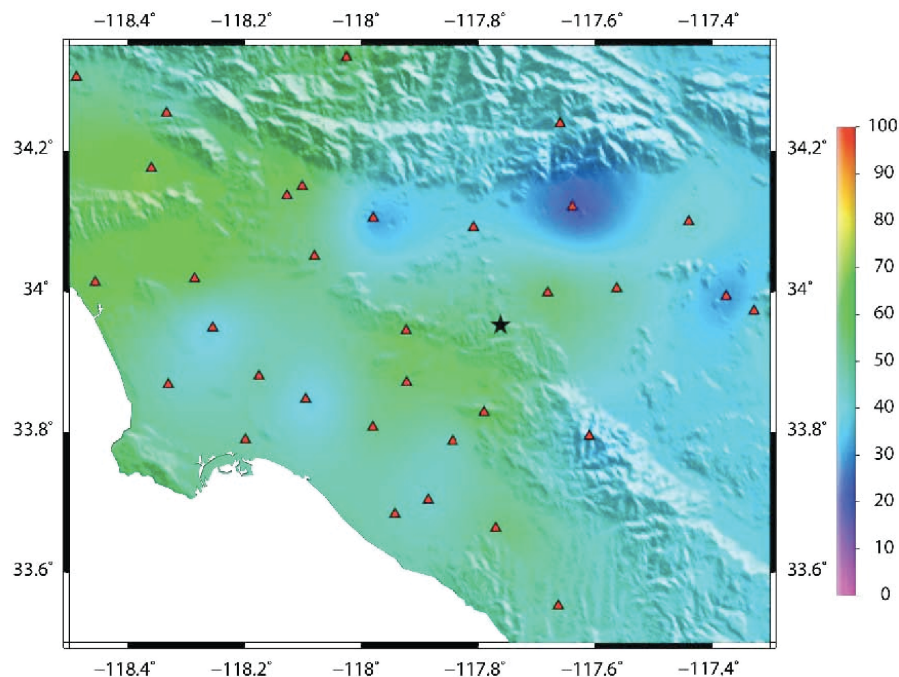


Figure 60. Map of average broadband (0.1-10 Hz) goodness-of-fit for the 2008 Chino Hills earthquake. Triangles depict stations used for comparison, and the star depicts the epicenter.

Seismic Hazard Characterization. As part of the Community Modeling Environment, Graves et al. (2010) are developing the CyberShake Platform, which explicitly incorporates deterministic 3D rupture and wave propagation effects within seismic hazard calculations. The process begins by converting the UCERF-2 rupture definition into multiple rupture realizations with different hypocenters and slip distributions, resulting in about 415,000 scenarios per site.

Strain Green tensors are calculated for the site of interest using the SCEC Community Velocity Model, Version 4 (CVM4), and synthetic waveforms are calculated for each rupture variation using reciprocity. Thus far, ruptures at over 200 sites in the Los Angeles region have been simulated for ground-shaking periods of 2 seconds and longer, providing the basis for the first generation CyberShake hazard maps. These hazard results are much more sensitive to the assumed magnitude-area relations and magnitude uncertainty estimates used in the definition of the ruptures than are the conventional, empirically based ground-motion prediction equation approach. This reinforces the need for continued development of a better understanding of earthquake source characterization and the constitutive relations that govern the earthquake rupture process.

Graves et al. constructed a first generation CyberShake hazard map for the Los Angeles region using the 200+ sites. Figure 61 illustrates the hazard calculated from the CyberShake ground motions with spatial interpolation based on residuals with respect to the Campbell and Bozorgnia (2008) ground-motion prediction equation. The map shows generally elevated hazard for many of the deep basin sites, and a generally reduced hazard level along the San Andreas fault. This highlights the importance of effects such as rupture directivity and basin response on the hazard levels, and demonstrates the potential of using the CyberShake approach for hazard characterization on a regional scale; however, the density of sites (nominally at 10 km spacing) does not provide the resolution needed for detailed interpretation of the results.

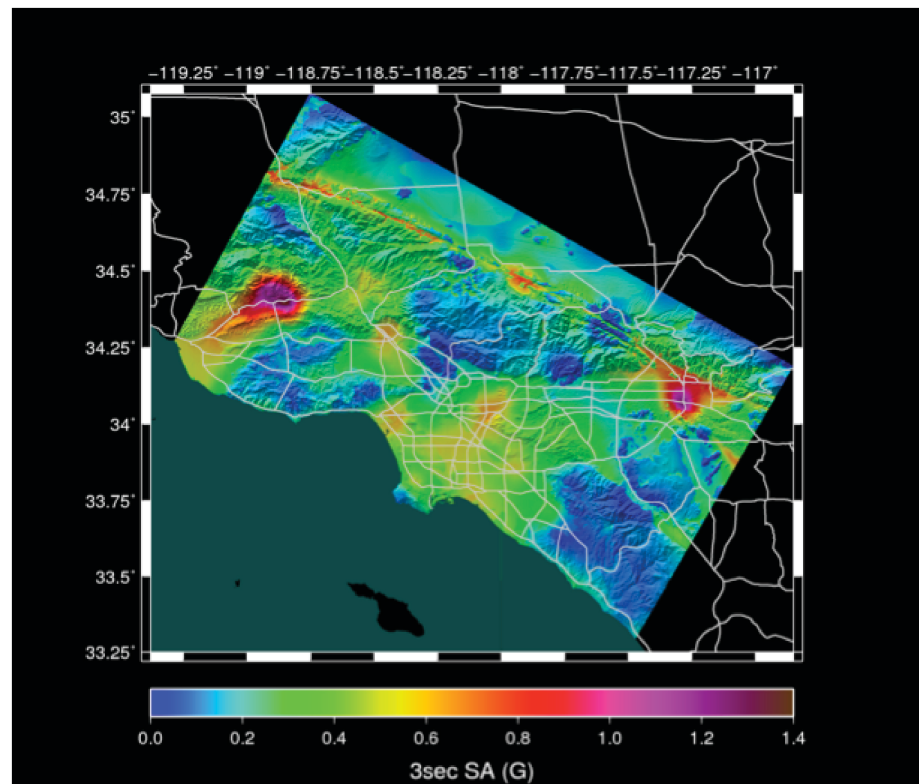


Figure 61. CyberShake hazard map for 3 second SA at 2% probability of exceedance in 50 years derived by interpolating the residual map onto the background map of Campbell and Bozorgnia (2008).

Large-Scale Simulations. Cui et al. (2010) simulated a Mw 8.0 earthquake rupturing the entire southern San Andreas fault (Cholame to Bombay Beach) at frequencies up to 2.0 Hz. The objective was to examine the ground motions over the 800 km by 400 km area, which is home to more than 20 million people and subjected to strong shaking in this scenario. The calculation used a uniform mesh of 400 billion cubes and ran for 24 hours on 223,074 cores of the NCCS Jaguar to compute waveforms with a duration of up to 360 s. The simulation shows that directivity effects for this scenario may generate similar levels of amplification in the Ventura basin as for southeast-to-northwest ruptures, despite the fact that the wave field enters almost perpendicular to the Ventura basin. Peak motions in the deeper Los Angeles basin are lower and reach about 120 cm/s with 40 cm/s in downtown Los Angeles. San Bernardino appears to be the area with some of the most severe shaking, due to rupture directivity effects coupled with basin amplification (Figure 62).

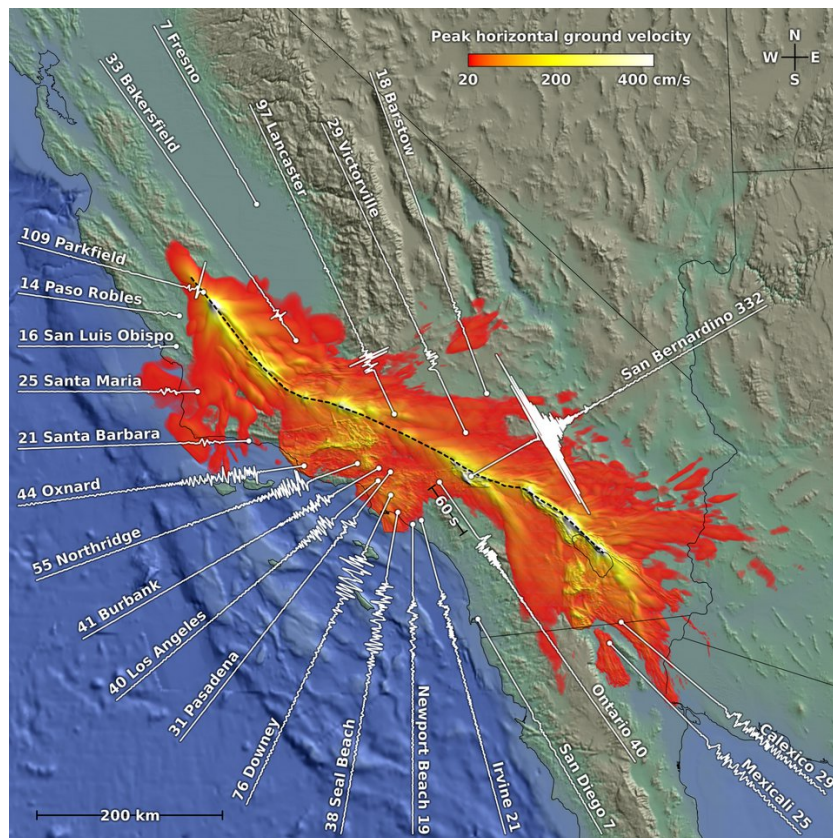


Figure 62. Peak horizontal ground velocity from a simulation for frequencies up to 2.0 Hz for a Mw 8.0 southern San Andreas scenario earthquake. Velocity waveforms (horizontal component in the direction of N46E) are shown at selected locations with their peak velocities (cm/s) listed along the traces.

Earthquake Rupture Characterization

High-Frequency Radiation. Ampuero, Ruiz-Paredes, and Elkoury applied multi-scale signal analysis techniques to identify and quantify signatures of spatial and temporal complexity of rupture propagation in the high-frequency band of strong-motion recordings. The seismic waveform is represented locally as a superposition of a smooth polynomial and a power law

singularity using the Wavelet Transform Modulus Maximum (WTMM). This multi-scale technique has been applied in a variety of fields but has not been applied previously to strong-motion data and earthquake rupture processes.

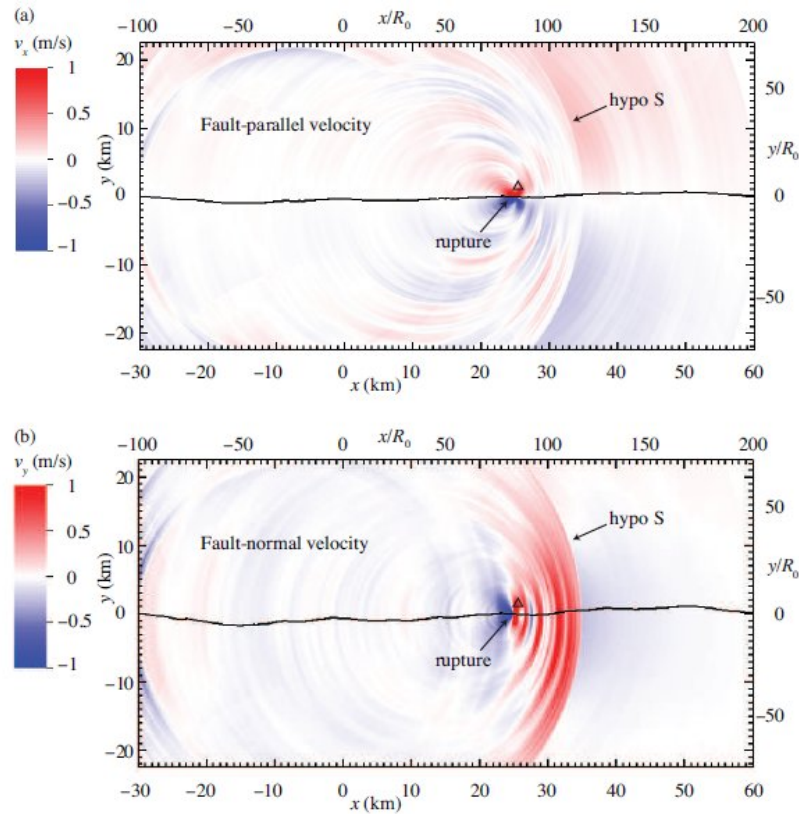


Figure 63. Snapshots of the fault-parallel (top) and fault-normal (bottom) components of the velocity field as the rupture passes the station (triangle) at which waveforms in Figure GMP7 are calculated. The hypocentral shear wave is marked by "hypo S".

Before applying this technique to strong-motion data, they analyzed 2-D in-plane dynamic rupture simulations using a boundary integral equation method with a slip-weakening friction model. They found that the singularity exponent of the radiated strong phases, measured by the WTMM technique on the seismic potency acceleration, matches the singularity exponent of the initial stress. This suggests it may be possible to infer the character and spatial distribution of stress singularities from strong-motion data. Applying the technique to strong-motion data sets from the 1999 Mw 7.6 Chi-Chi, 2004 Mw 6.0 Parkfield, and 2008 Mw 5.4 Chino Hills earthquakes suggests the high-frequency wavefield is controlled by a mono-fractal process rather than a multifractal process with smoothing of the wavefield on the scale of the rupture process zone.

Dunham, Kozdon, and Nordstrom have further developed techniques for simulating high-frequency ground motion generated by irregular rupture propagation on nonplanar faults (Figure 63). In their study (Dunham et al., 2010) the faults are modeled as self-similar fractal surfaces with roughness over three orders of magnitude and at scales larger than the maximum slip in a single event. The simulations include off-fault inelastic deformation (via rate-independent

plasticity or viscoplasticity) to limit large stress concentrations around bends in the fault surface. Recent work shows that fluctuations in rupture speed and slip associated with the fault roughness excite waves with frequencies up to about 10 Hz. Furthermore, this approach produces synthetic waveforms (Figure 64) qualitatively similar to the Lucerne Valley (LUC) strong-motion record from the 1992 Mw 7.3 Landers earthquake, a typical near-source record from a sub-shear strike-slip rupture. The high-frequency ground motion appears to be most correlated with fluctuations in rupture speed associated with bends in the fault.

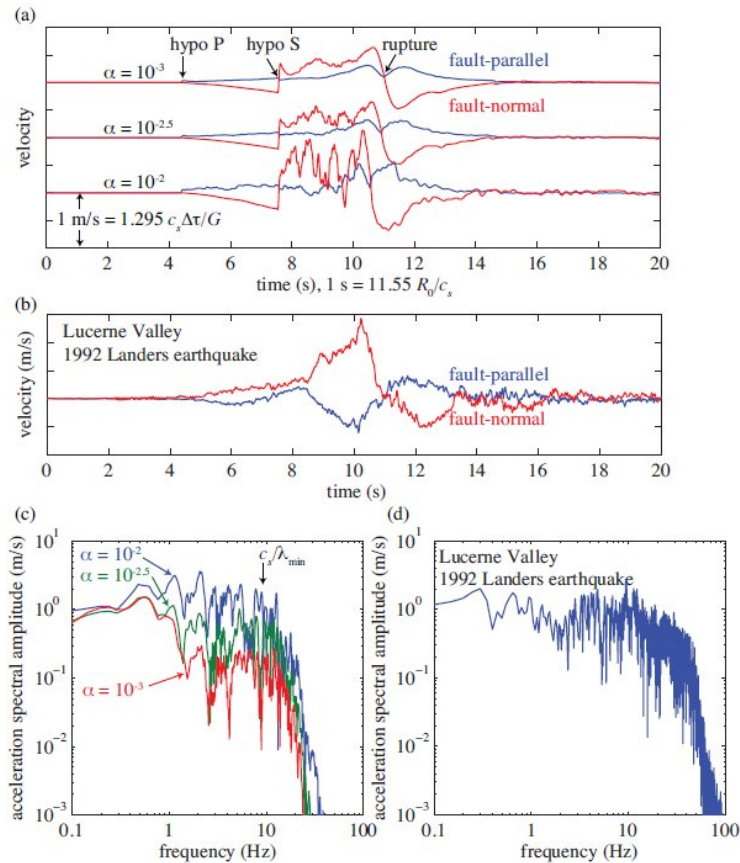


Figure 64. Synthetic velocity waveforms (top) for several values of the amplitude-to-wavelength ratio, α . Hypocentral P- and S-wave arrivals are marked. The Lucerne Valley (LUC) record (middle) from the 1993 Mw 7.3 Landers earthquake. Four amplitude spectra of fault-normal acceleration for the synthetic waveforms (bottom left) and the Lucerne recording (bottom right). The minimum wavelength of fault roughness in the model (λ_{\min}) prevents excitation of waves at frequencies greater than about $\sim c_s/\lambda_{\min}$. A amplitude-to-wavelength ratio of about $10^{-2.5}$ yields waveforms with similar character to the LUC record.

Inelastic Deformation. Two studies have focused on quantifying the effects of off-fault inelastic deformation (plastic yielding) in reducing ground motions with application to dipping faults. Duan and Day (2010) explored the sensitivity of extreme ground-motion estimates at Yucca Mountain to variations in fault geometry, rock strength, fault zone structure, and undrained poroelastic response of the fluid pressure. They found that the peak ground velocity in

the limiting cases of nearly complete stress drop on the Solitario Canyon fault is significantly more sensitive to the geometry of the fault at depth and cohesive strength of the rocks at shallow depth than the fault zone structure and pore pressure response. For example, reducing the dip angle of the Solitario Canyon fault at depth while doubling the cohesive strength at shallow depths results in an increase in the vertical PGV values by more than 25% to values over 5 m/s. Figure 65 summarizes the variation in surface slip and peak ground velocity in the study for different cohesion values.

Ma (2009) examined the potential relationship between off-fault inelastic deformation (plastic strain) and the development of a low-velocity zone surrounding the fault for two generic reverse and normal faults. In both cases including the effects of off-fault inelastic deformation reduced the strong asymmetry in peak ground velocity observed for the elastic case while producing asymmetric flower-like plastic strain structures (Figure 66 and Figure 67). These results aid observational efforts to image shallow low-velocity fault zone structures surrounding dipping faults by providing insight into the physical processes behind the origin of the low-velocity material.

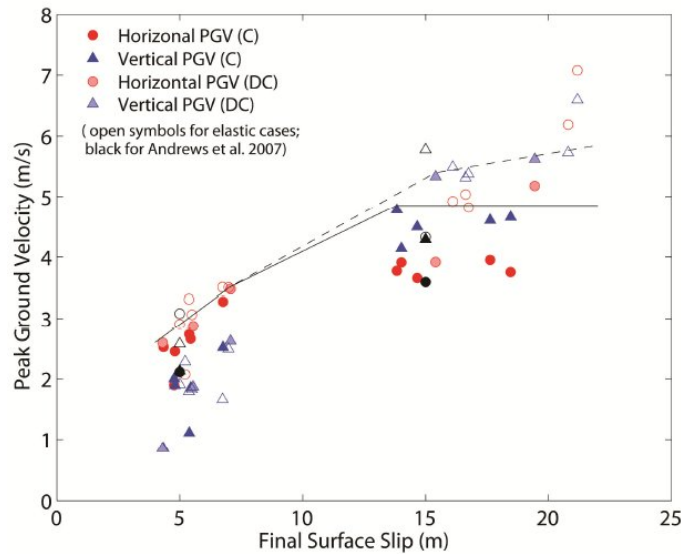


Figure 65. Peak ground velocity (PGV) at the repository site as a function of surface fault slip from 2D dynamic rupture models of scenario earthquakes on the Solitario Canyon fault. Dark shading (C) denotes PGV estimates with Mohr-Coulomb strength parameter values (cohesion and internal friction angle) of Andrews et al. (2007). Light shading (DC) denotes PGV estimates with cohesion values two times larger for the shallow rock units. Open symbols denote PGV estimates with purely elastic response. Including off-fault inelastic deformation reduces the PGV values.

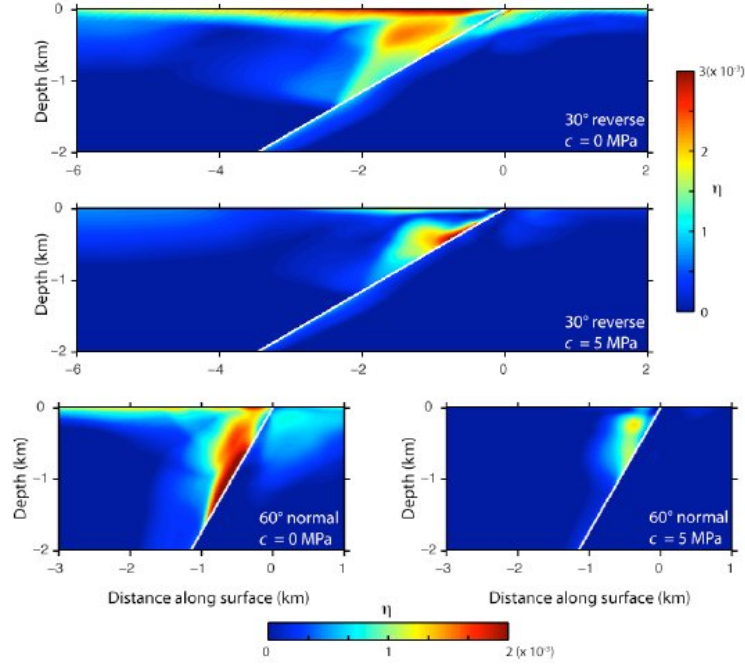


Figure 66. Inelastic strain around the fault tip with strong asymmetric across the fault. As cohesion increases, the inelastic strain near the surface and in the footwall is decreases.

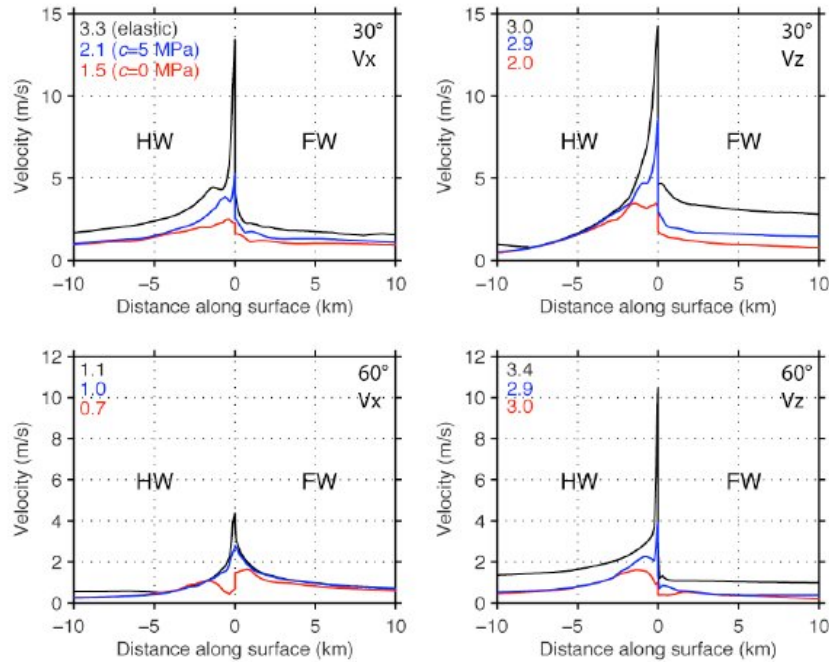


Figure 67. Peak ground velocity (PGV) along the surface for the 30 degree dipping reverse fault (top row) and 60 degree dipping normal fault (bottom row). The ratios of the hanging wall to footwall PGV values are shown in each panel in the upper left corner. The inelastic response reduces the asymmetry and peak motions significantly.

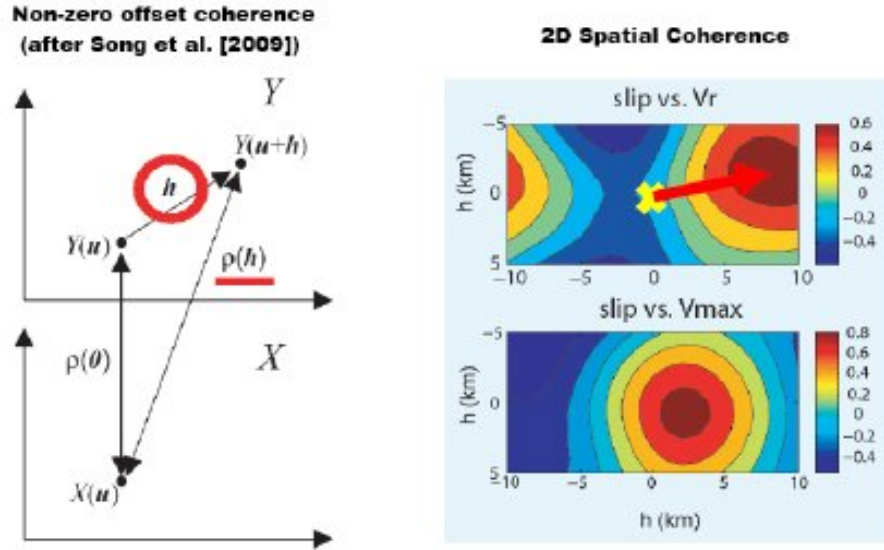


Figure 68. Schematic diagram showing the correlation coefficient as a function of separation vector, h (left) and the 2-D correlograms obtained from a square-shaped asperity rupture model (Song and Somerville, 2010).

Model Parameterization. Efforts to develop methodologies for constructing kinematic rupture models consistent with rupture dynamics continue to advance. Schmedes, Archuleta and Lavallee (Schmedes et al., 2010) analyzed 315 dynamic rupture models to deduce the amplitude distributions and correlations of kinematic rupture parameters. Focusing on subshear rupture they found (1) final slip does not correlate with local rupture speed, (2) final slip correlates with rise time, (3) rupture speed correlates with peak slip rate, (4) rupture speed is controlled by the fracture energy and rate of slip-weakening, and (5) the rupture front becomes more pulse-like away from the hypocenter.

Using a similar approach based on one-point and two-point statistics, Song and Somerville (2010) analyzed kinematic and dynamic rupture models of the 1992 Mw 7.3 Landers earthquake and kinematic rupture models of 1999 Mw 7.6 Izmit earthquake. They demonstrated that the approach quantifies important features of the rupture models. By allowing a spatial offset in the correlation (which was not included in the analysis by Schmedes et al.), they found a correlation between rupture speed and slip; the rupture speed increased after propagation through a region with larger slip (Figure 68). They also found a zero-offset correlation between slip and peak slip rate. Application of this approach to kinematic rupture models highlights the inconsistencies among models for the same event, which are likely due to discretization, regularization, and positivity constraints in the inversion. Song and Somerville are continuing to develop the technique so that it can be used to construct kinematic rupture models consistent with rupture dynamics.

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Seismic Hazard and Risk Analysis

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

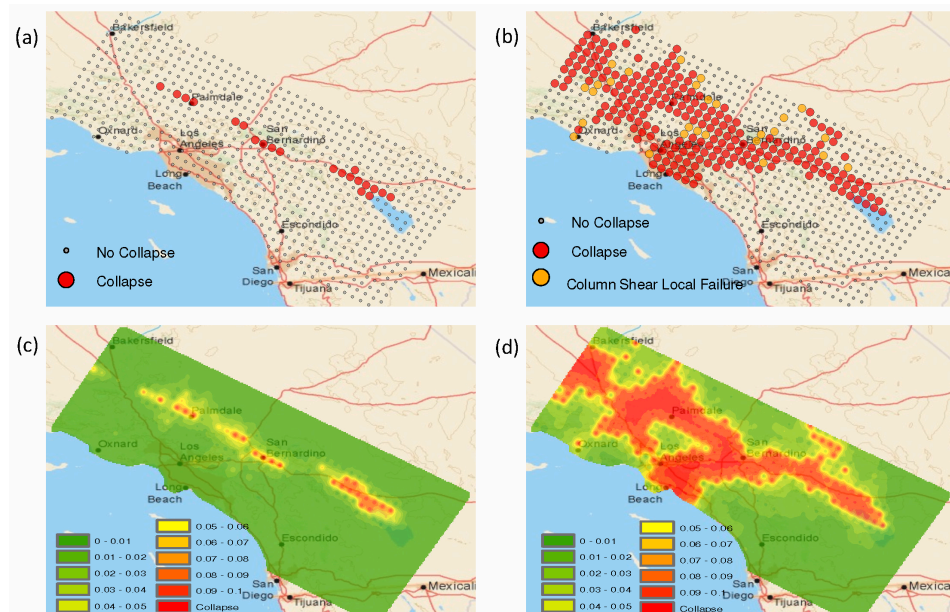


Figure 69. Seismic performance predictions for 4-story modern, (a) and (c), and older, (b) and (d), space frames indicated by collapses and interstory drift ratios.

Seismic Performance of Reinforced Concrete Frame Buildings in Southern California Due to the Magnitude 7.8 Shakeout Scenario Earthquake

(Liel). Because of the prevalence of reinforced concrete frames in Southern California, it is important to understand their response in the event of a large earthquake. This study examines both older, nonductile, RC frames and their modern counterparts to determine the building response due to the ShakeOut scenario earthquake. Results from the seismic analysis indicate that older, nonductile, RC frames are much more susceptible to collapse during large earthquakes than those designed to current code provisions. Although results varied according to height and framing system, on average, the older 6 RC buildings were predicted to collapse at 22% of 735 case study sites, compared to 4% of sites for the modern RC frame buildings. Predicted areas of significant seismic risk for older nonductile RC frame buildings extend along the entire San Andreas Fault line, including San Bernardino and Palm Springs. Based on this analysis, sites analyzed in downtown Los Angeles and Hollywood, where the largest concentration of

nonductile RC buildings exist, are predicted to have a collapse rate of approximately 30-40%. Based on the available inventory data and mapped collapse risk a rough estimate of 50 to 300 collapsed nonductile RC frame buildings could occur during the ShakeOut scenario earthquake. This study is specific to the building type, region and scenario earthquake event, but illustrates a prototype study that can be conducted for different buildings, earthquake scenarios or regions - as a tool for mitigation and emergency response planning to improve the level of seismic readiness in our communities. This type of research is made possible by combining advanced ground motion simulations, such as those that are the focus of SCEC efforts, with robust nonlinear building analysis models, in an effort to better understand how a given earthquake event will affect losses and vulnerability (Figure 69).

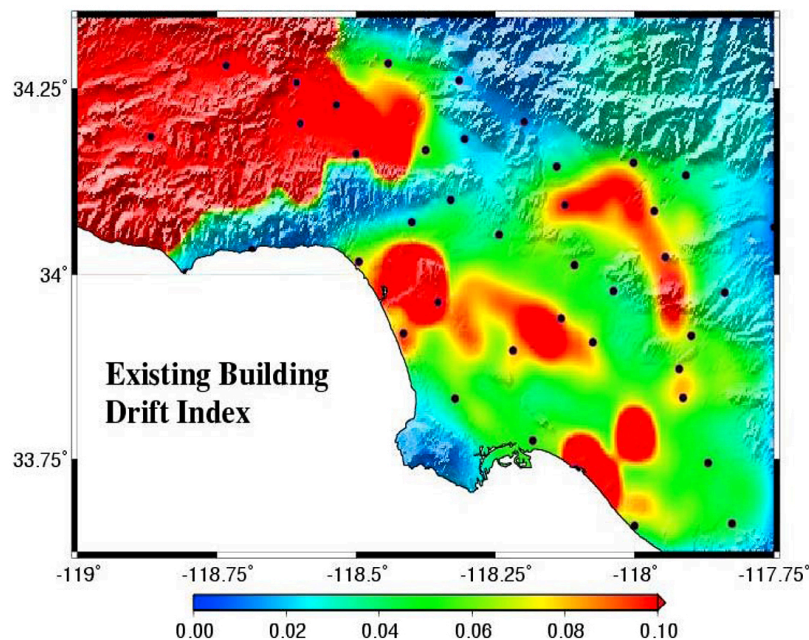


Figure 70. Interstory Drift Ratios (IDR's) in an existing 18-story steel moment frame building subjected to the calculated ground motions from a 1857-like hypothetical magnitude 7.9 earthquake on the San Andreas fault, initiating at Parkfield and rupturing in a southeasterly direction with a peak displacement of 2 m and peak velocity of 2 m.s⁻¹. The color bar refers to the peak IDR at each site.

How Would Tall Steel Moment Frame Buildings Collapse Under Seismic Loading

(Krishnan). This study pursued the question of how tall steel moment frame buildings would collapse under seismic loading. The distribution of moments in a steel moment frame subjected to lateral loads is such that it produces double curvature in all the columns and beams resulting in shear-racking of the frame. Thus, shear deformation and not flexural deformation dominates moment-frame response. Strain doubling occurs due to constructive interference of the reverse phase of the incident wave with the forward phase that is reflected off the free end, similar to the behavior of an ideal beam. Such strain doubling can lead to damage localization, which in turn can result in the formation of a shear-compliant block collapse mechanism, consisting of column yielding at floors corresponding to the top and bottom of the shear-compliant block, with significant yielding of the beams or columns or panel zones at each joint in each of the

intermediate floors. For moderate loading (motions that are not strong enough to cause structural collapse), the Confines of the Most Pronounced Localization of Yielding (CoMPLY) is controlled by the period of the input ground motion relative to the fundamental period of the structure. However, the response to “collapsogenic” input motions shows a “convergence” of the CoMPLY to the same few stories, rendering it invariant with respect to different measures of the ground motion. This implies that there is a characteristic mechanism of collapse for a given building regardless of the frequency-duration characteristics of the incident ground motion (Figure 69). This characteristic collapse mechanism is a function of the structural system alone and can be predicted using its basic properties. The ability to predict these characteristics encourages exploration of possible local retrofitting measures to reduce the collapse potential of these structures. Arnar Bjorn Bjornsson, who is a graduate student at Caltech, has been exploring simple retrofitting measures using steel braces. He has successfully demonstrated the increased collapse resistance of a model of an existing 18-story steel moment frame building using such a retrofit measure (Figure 70).

Trimming the Hazard Logic Tree, Phase 2

(Porter, Scawthorn). This is the second year of an effort to test and depict the sensitivity of societal risk estimates to branches in the UCERF hazard logic tree. The work is not yet complete. In this phase, probabilistic seismic vulnerability functions have been created that relate building repair costs to shaking intensity, by structure type and occupancy classification. Intensity is measured using a vector measure: 5%-damped elastic spectral acceleration response at 0.3-sec and 1.0-sec periods, also conditioned on magnitude, distance, site soil classification, and tectonic regime. Casualty-rate seismic vulnerability functions were previously created for another (USGS) project and both mean and probabilistic seismic vulnerability functions of repair cost were created for SCEC under the SCEC 2008 year. In the current year, a portfolio of assets exposed to seismic risk was also estimated, in work for this 2009 SCEC project and another USGS project. (The USGS work quantified indoor occupants; the SCEC work added square footage and replacement costs, by census tract, occupancy classification, and structure type.) A component of the OpenRisk software, designed for SCEC in previous work and developed in collaboration with USGS programmers, will be used to carry out the loss calculations. The sensitivity analysis, not yet begun, will employ a tornado-diagram-analysis approach developed for decision analysis and applied and extended in the last 10 years by SPA personnel and others for use in earthquake engineering loss estimation. Examples of trends in damage-factor uncertainty versus mean damage factor are shown in (Figure 71).

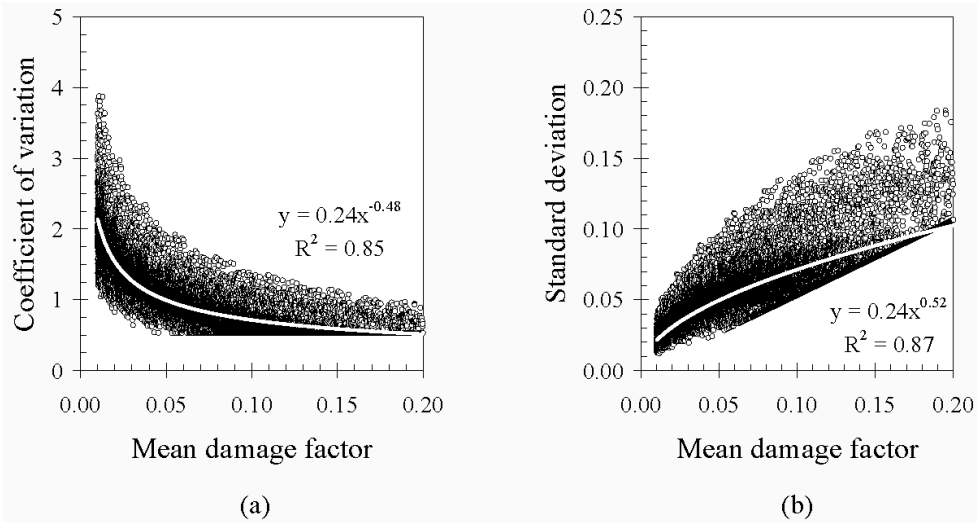


Figure 71. Trends in (a) COV versus MDF and (b) standard deviation versus MDF

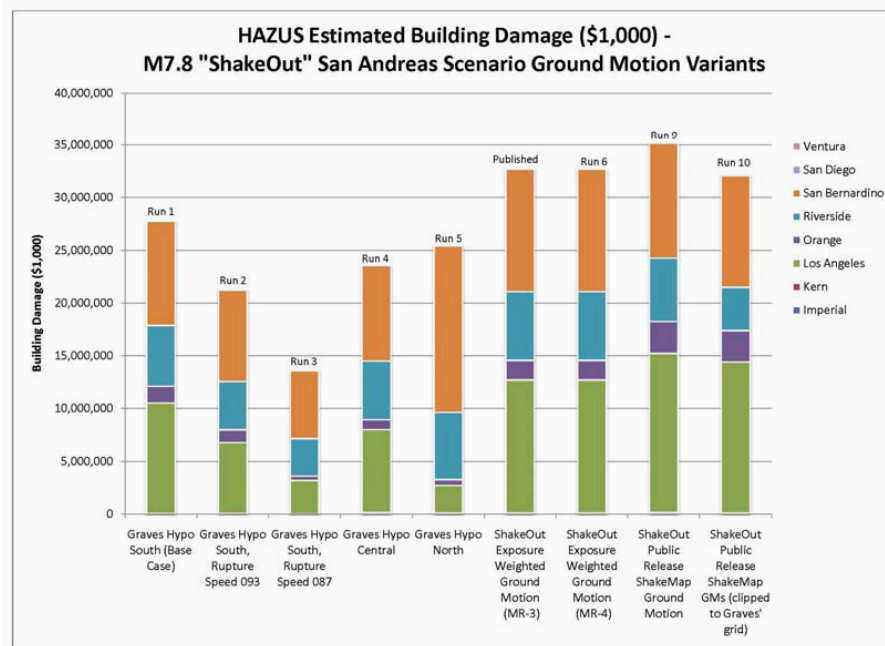


Figure 72. HAZUS® Estimates of Building Damage for the ShakeOut Scenario Ground Motion Variants

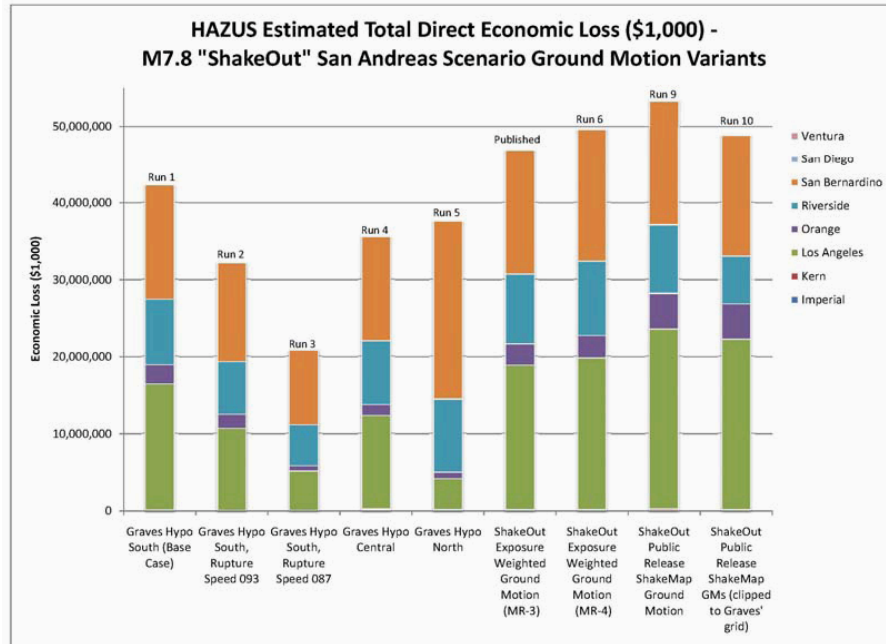


Figure 73. HAZUS® Estimate of Total Direct Economic Loss for the ShakeOut Scenario Ground Motion Variants

Sensitivity Analyses of HAZUS®' Loss Estimates for the ShakeOut Scenario: Assessment of the Impact of Ground Motion Variation on Loss

(Seligson). The “ShakeOut scenario” – a comprehensive impact assessment for a M 7.8 earthquake on the Southern San Andreas Fault – was developed by a regional, multi-disciplinary team of scientists and engineers. The scenario’s regional building damage and loss estimates were developed using FEMA’s nationally applicable loss estimation software HAZUS®MH (HAZards U.S. Multi-Hazard). The objective of the study was to assess the potential variation in loss resulting from different ground motion representations, including both kinematic simulations (Graves et al., 2008) and dynamic simulations (Olsen et al., 2009). Comparisons of estimated building damage and total direct economic loss using the various ground motion data sets analyzed to date are provided in Figure 72 and Figure 73. Within HAZUS®, total direct economic loss includes building and content losses, as well as inventory loss and income losses (which include relocation costs, proprietor’s income losses, wage losses and rental income losses). As shown in Figure 72, there is no discernible difference between the building damage estimated using HAZUS®MH MR-3 (“Published”) and MR-4 (Run 6). However, MR-4 included a methodological change in the estimation of relocation loss. The impact of this change is visible in Figure 73 as a 5.8% increase in overall total direct economic loss for the MR-4 run. The reduction in loss associated with limiting the analysis to the area within the Graves analysis grid is small, but not insignificant for the publicly released ShakeMap ground motion data (Run 10 vs. Run 9); an 8.8% reduction for building damage alone, and 8.5% for total direct economic loss overall. For the exposure weighted ground motions, the difference is insignificant; less than 0.1% for both building damage and total direct economic loss (Run 6 vs. Run 7, not shown on charts). As shown in Figure 72 and Figure 73, the baseline kinematic

simulation data (Run 1) yields results on the order of 13 – 15% smaller than either the grid-limited exposure weighted ground motions (Run 7, not shown, but approximately equal to Run 6) or the grid-limited publicly-released ground motions (Run 10). Changes in rupture speed can be seen to have a significant impact on losses; a 7% reduction in rupture speed (speed 0.93, Run 2) results in a 24% reduction in both building damage and total direct economic loss, while a 13% reduction in rupture speed (speed 0.87, Run 3) results in a 51% reduction in loss. Changes to the hypocenter location have a smaller impact on loss than rupture speed variation. Relative to the southern base case (Run 1), losses resulting from a scenario with a central hypocenter location (Run 4) are 15% smaller, while losses from a northern hypocenter (Run 5) are 10% smaller than the base case (Figure 72 and Figure 73).

Characterization of Earthquake Slip Distribution of the Central San Jacinto Fault

(*Salisbury, Rockwell, Hudnut*). The south-central San Jacinto Fault (SJF) from Hemet southeastward to Clark Valley represents the longest and straightest contiguous segment of the SJF zone. It is exceptionally well localized (Rockwell and Ben-Zion, 2007) and is easily identifiable in the geomorphology. The “Anza Seismicity Gap” falls in the middle of this section of the fault with microseismicity to nearly 20 km depth on the edges of the gap. The Hog Lake trench site, located in the Anza Seismic Gap, records the timing of the past 18 surface ruptures in the past 3800 years with an average return period of about 210 years. Work at Hog Lake dates the most recent event (MRE) at ca. 1790, suggesting this was the November 22, 1800 earthquake. In 2006, Middleton evaluated the southern 55 km of the Clark strand of the SJF for offset features using a combination of aerial photography, field techniques, and B4 LiDAR imagery. Displacement estimates show that the MRE produced an average of 2.7 m of dextral slip, with a maximum of 4 m near Anza to less than a meter near the southeast termination of the fault. For this continuation project, the work begun by Middleton was completed by mapping the detailed tectonic geomorphology along the remaining 25 km section of the Clark Fault (NW of the Anza Seismicity Gap to Hemet) using aerial photography, B4 LiDAR data, and field techniques. Together, these data provide a robust assessment of the slip distribution for the entire Clark fault in the last few events. This project involved mapping of small geomorphic offsets for 75 km of the Clark fault from the southern end of Clark Valley (east of Borrego Springs) northwest to the mouth of Blackburn Canyon near Hemet. To the northwest, the flat valley bottom and young aggradation makes additional measurements with LiDAR impossible. Nevertheless, these data argue that much or all of the Clark fault, and possibly also the Casa Loma fault, tends to fail from end to end in large earthquakes. They also recognize the likely rupture from the 1918 earthquake, which broke a short ~15 km section of the fault in Blackburn Canyon, perhaps due to lower displacement in that area in the ca 1800 event. Figure 74.

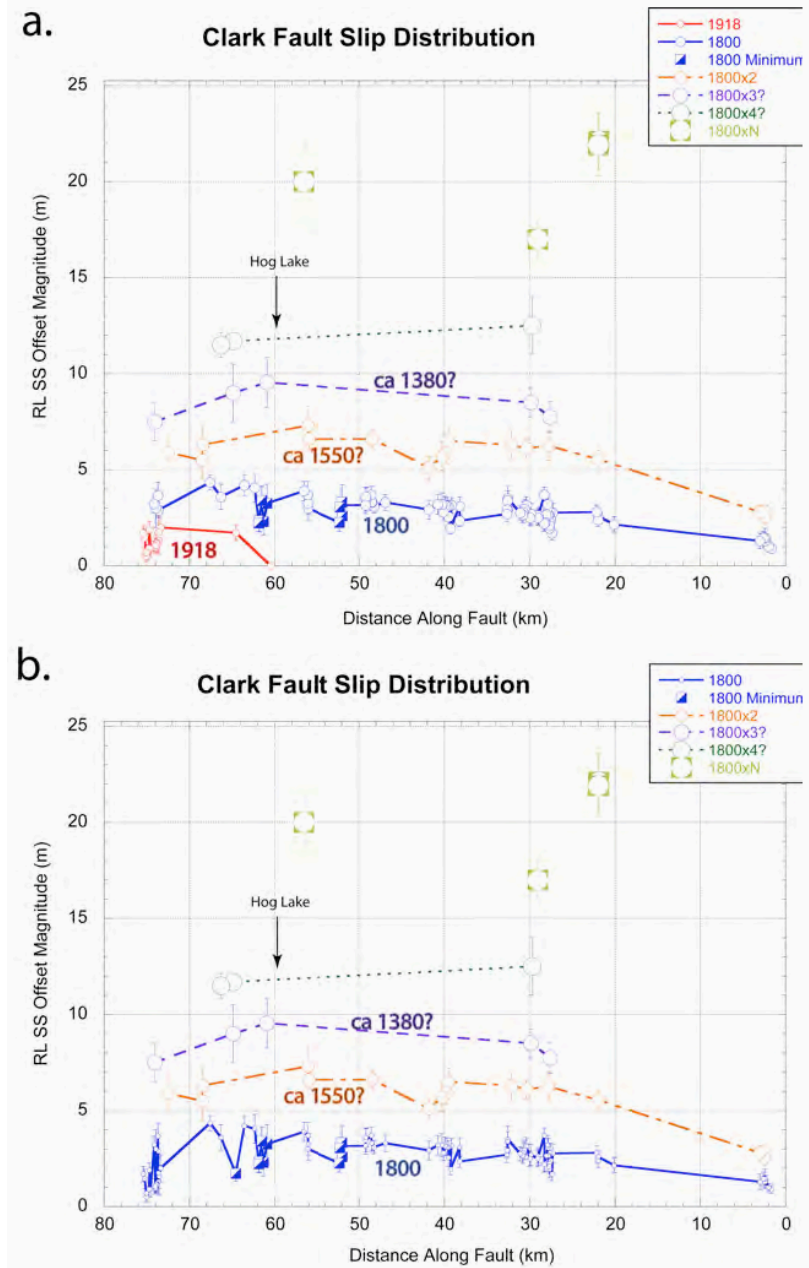


Figure 74. Slip distribution models for geomorphic offsets collected along the Clark strand of the San Jacinto fault from highway S22 northwest to Blackburn Canyon, southeast of Hemet.

Special Projects

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

Southern San Andreas Fault Evaluation

The primary goal of the Southern San Andreas Fault Evaluation (SoSAFE) project is to document the timing of large paleoearthquakes and amount of slip released by the southern San Andreas and San Jacinto Faults over the past 2000 years. Additional goals include examination of longer-term slip rates and modeling studies which directly impact seismic hazard assessments. SoSAFE is funded through SCEC by the U.S.G.S. Multi-hazards Demonstration Project. Research included earthquake trenching studies, radiocarbon dating supported with Geology infrastructure funding, geomorphic studies using LiDAR and other aerial imagery data in tandem with field measurements, and examination of new methods for analyzing and incorporating neotectonic data. A workshop highlighting the 2008-2009 accomplishments was held during the SCEC Annual Meeting in September, 2009 and attracted ~125 attendees. The workshop ended with a discussion aimed at generating new ideas for integrating paleoseismic data along the fault and use of such models in formal earthquake hazard assessments (e.g. UCERF). Research accomplishments of SoSAFE researchers are addressed in the Section 1.3 under Earthquake Geology.

Working Group on California Earthquake Probabilities

Formulated the "UCERF3 Project Plan", available at <http://www.wgcep.org>.

Collaboratory for the Study of Earthquake Predictability

The CSEP collaboration continues to expand, not only including a wider group of national and international scientists, but also covering more and more topics regarding earthquake predictability and its relation to seismic hazard assessment. The CSEP collaboration is now involved in the research into the physical basis for earthquake predictability, implementation of earthquake prediction algorithms as computer software, and the development of new earthquake prediction evaluation techniques.

The physical infrastructure for SCEC's CSEP activities are housed in the W.M. Keck Testing Center at USC. This facility includes computer resources, data storage devices, custom CSEP software designed to automate the running of earthquake prediction algorithms, and seismological application codes. The CSEP systems are designed to be modular, reliable, and low-cost to acquire and operate. A development system is available to CSEP scientists for the development and testing of forecasting algorithms. Access to the operational system, which runs all model codes and tests, is restricted to ensure the integrity of the evaluation process. A certification system is used to test model codes and testing center codes for proper functionality before deployment to the operational system. The SCEC web server hosts the CSEP web pages for all testing centers.

CSEP Software Development

Many improvements have been made to the CSEP software system since it went into operation in September, 2007. The development has been structured such that the software can be installed in a regional testing center with only minimal changes required to adapt to the specific testing region. To broaden the user base, we have also developed the so-called miniCSEP distribution, which allows researchers to use the CSEP outside of the testing center environment; e.g., as research and teaching tools. The CSEP webpages have been redesigned to include content of all testing centers and to be the portal for a wide variety of CSEP-related information.

The W.M. Keck CSEP Testing Center software has been released under the open-source General Public License and is freely available for use by other research groups. The distribution system has been designed such that the CSEP Testing Center software can be easily updated through periodic releases of the latest version to other testing centers around the world.

New Regions Under Test

The SCEC Testing Center has supported the RELM experiment and placed new classes of time-dependent forecasts for California under test. Because large magnitude events are rare in California, we have been cooperation with foreign research groups to expand the testing program to other regions. Testing centers have been established at GNS Science in Wellington, New Zealand; at the Earthquake Research Institute (ERI) of the University of Tokyo, Japan; and at ETH Zürich in Switzerland. Testing programs are now operational in New Zealand (since January, 2008), Japan (since September, 2008), and Italy (since September, 2009), and plans are underway to begin testing in China's South-North Seismic Belt during the next year, which will be managed by a new testing center at the CEA Institute of Geophysics in Beijing.

In 2008, a testing program was initiated in the western Pacific, and during the past year, this program has been extended to global earthquake forecasting. The global program currently tests forecast models registered on a $1^\circ \times 1^\circ$ grid that target shallow earthquakes of magnitude 5.95 and larger. Efforts are underway to refine global testing using higher-resolution grids and a greater range of focal depths.

New Earthquake Forecasting Models and Testing Procedures

The initial CSEP models, which included 5-year forecasts from the RELM Project, were grid-based models; i.e., they were formulated as expected rates of events on a geographical grid. The original RELM model class has been supplemented by new model classes, including time-dependent forecasts updated on 1-day, 3-month, and 1-year intervals. These models are mostly seismicity-based forecasts, although the RELM set includes models that forecast future seismicity from geodetic and geologic data.

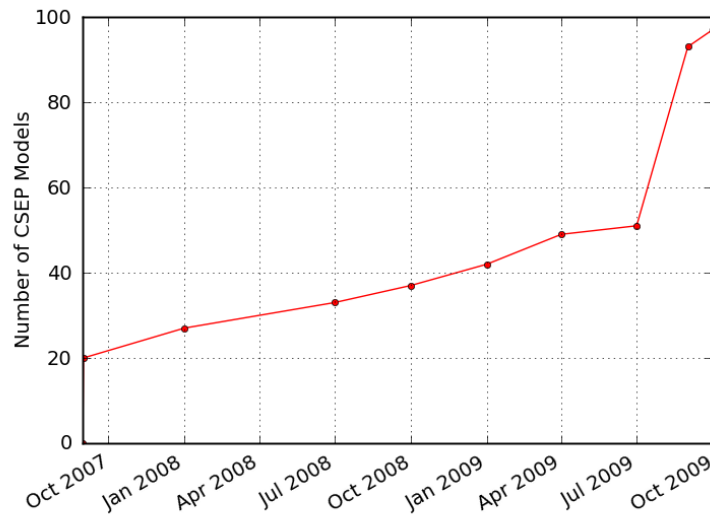


Figure 75. Number of models in all CSEP testing centers over time. The largest additions of models are in October 2007 (RELM models) and September 2009 (5-year models in Italy).

Alarm-based forecasts were introduced as a new class of models during the last year. Alarm-based forecasts do not provide forecast rates per grid cell but monitor input data for particular signals and issue space-time alarms for target events if they detect one or more signals. Several new alarm-based tests (ASS, ROC, Molchan) were developed and implemented to assess this model class. New tests (S- and M-Test) have also been devised for likelihood scoring. These tests allow the likelihood score to be separated into components characterizing earthquake number, spatial distribution, and magnitude distribution. The number of models under CSEP testing worldwide is growing rapidly, as illustrated in Figure 75.

Extreme Ground Motion Project

Extreme ground motions are the very large amplitudes of earthquake ground motion that can arise at very low probabilities of exceedance, as was the case for the Yucca Mountain PSHA when extended out to hazard levels of 10⁻⁸/yr. The Extreme Ground Motion project (ExGM) has been a 5-year, \$5M research program funded by the Department of Energy to investigate the origin, nature, and physical plausibility of extreme ground motions along three different avenues: physical limits to earthquake ground motion, unexceeded ground motions, and “event frequencies,” the frequency of occurrence of very large ground motions or of earthquake source parameters (such as stress drop and faulting displacement) that cause them.

The Cooperative Agreement with DOE ends on September 30, 2010, and ExGM activities in the past year have been concentrated on writing the Final Report, currently in its final stages of preparation. The report’s authors are the members of the Extreme Ground Motion Committee [ExGMCom, T.C. Hanks (chair), N.A. Abrahamson, J.W. Baker, D.M. Boore, M. Board, J.N. Brune, and J.W. Whitney] all of whom have participated extensively in SCEC activities over the past five years.

The agreement with DOE called for an independent review by a team of SCEC scientists, composed of G.C. Beroza (chair), S.M. Day, L. Grant-Ludwig, R.B. Smith, and R.J. Weldon. ExGMCom hosted a field trip for the SCEC Review Team April 7-10, 2010, so that they could observe in the field some of the more relevant and dramatic geologic and geomorphic observations that are part of the Final Report. These include cliffs of densely welded tuffs shattered by the extreme ground motions of underground nuclear explosions on Pahute Mesa, precarious rocks on the west face of Yucca Mountain, and the evidence for the “million-year-old” landscape on and around Yucca Mountain. See photos below. Upon its completion, the SCEC Review Team will provide a written review of the Final Report.

The Final Report will recount the major advances in earthquake science driven by ExGm over the past six years, to all of which SCEC scientists have contributed. They include:

- Delineating the ground motions and faulting displacements that accompany spontaneous, dynamically-propagating, complete stress-drop earthquake models.
- Understanding the causes and effects of non-linear stress-wave propagation in rock and how this leads to physical limits of ground motion.
- Refining the toppling probabilities for and the fragility ages of precariously balanced rocks (PBR), thus allowing better probabilistic portrayals of unexceeded ground motions. These methods are general; the ExGM applications have been to PBRs on the west face of Yucca Mountain.
- Quantifying the spectacular morphological differences of the UNE-shattered cliffs (extreme geomorphology) and the comparatively “clean” west face of Yucca Mountain.
- Determining the surprising antiquity of the Yucca Mountain landscape (the “million-year-old landscape”) through many new surface-exposure ages.
- Developing the Points-in-Hazard-Space methodology, allowing a great variety of geologic, geomorphic, and geophysical hazard data and constraints to be placed in a single graphic.
- Developing arms stress drops from the global mb-M database and determining that the distribution of these stress drops for 441 crustal earthquakes is log-normal to more than 2 sigma at its upper end.
- Compiling a global database of the largest surface-faulting displacements for normal-faulting earthquakes, both historic and late-Pleistocene (paleoseismic) events.
- Documenting the magnitude-independence of apparent stresses in the western United States.



Figure 76. ExGMCom and the SCEC Review Team at the "Grandstand," the viewing area for atmospheric nuclear tests in the 1950s, for the April 2010 field review.



Figure 77. Google Earth image of the crater of the UNE Boxcar (left), the nation's first megaton nuclear device detonated April 26, 1968, and Boxcar Bluff (right), cliffs of densely welded tuffs shattered by Boxcar (Figure 78). The crater is about 400 m in diameter.



Figure 78. Looking up at the shattered cliffs of Boxcar Bluffs, scientist for scale at top.



Figure 79. The "clean" west face of Yucca Mountain. The boulders in the foreground have rolled down from the cliffs of Tiva canyon Tuff on the Yucca Mountain crest (skyline). They have surface-exposure ages in excess of 200 ka.



Figure 80. The precarious rock (stack) Tripod, with Jim Brune, Tom Jordan, and Greg Beroza for scale.

Community Modeling Environment

Overview of SCEC Community Modeling Environment (CME) Collaboration

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

Many SCEC research areas require the use of computer modeling and the CME collaboration helps to develop the scientific computing systems SCEC needs. CME researchers are working to improve a broad range of predictive seismic hazard parameters include scenario ground motion maps (used in emergency management exercises), scenario broadband seismograms (used in seismic engineering of tall buildings), and probabilistic seismic hazard curves (used in insurance loss estimations). The CME integrates new SCEC science results into highly-scalable computational models and runs large-scale physics-based seismic hazard calculations using national open-science supercomputer facilities.

SCEC, as a system science organization with broad research goals, has a wide variety of computational science research needs. The CME provides the computer science capabilities for SCEC to conduct one of the largest and most comprehensive seismic hazard computational research activities. SCEC has developed one of the world's most computationally scalable wave propagation codes (AWP-ODC) and one of the largest and most complex scientific workflow systems (CyberShake1.0) in existence. The CME full 3D Tomography research establishes SCEC as one of the most data intensive computational groups in any NSF research domain. The CME research program has helped to establish a leadership role for SCEC in national scientific computing. CME project members regularly present SCEC research at computer science and HPC conferences such as Supercomputing and TeraGrid. CME research projects typically require both geoscientific and computer science expertise. Each year, the CME works to improve the accuracy, scale, efficiency of our seismic hazard modeling software. Then we apply these new computational capabilities to important SCEC research questions.

Computational tool developments by the CME this year include significant performance improvements in our highest performance earthquake wave propagation codes AWP-ODC and Hercules. The CME has collaborated with the CVM-H development group on the CVM-Toolkit which is a set of software tools for constructing very large meshes using SCEC CVM-H. The CME also performed collaborative development of the second generation SCEC Broadband platform by integrating SCEC scientific codes into a computational system that provides interoperability between codes including rupture generators and non-linear site effect models.

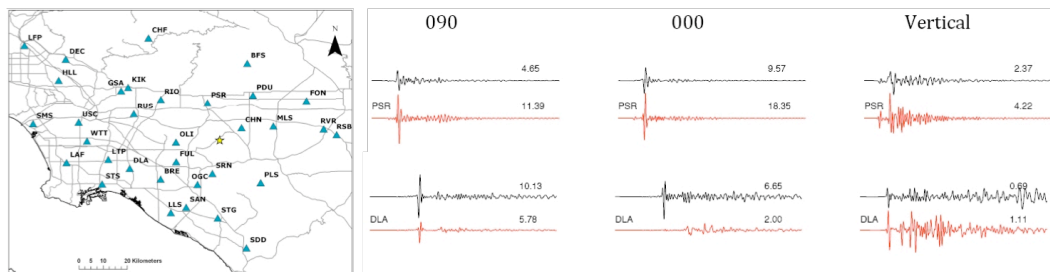


Figure 81. The Chino Hills M5.4 event is used in validation of wave propagation simulations because it is just outside the Los Angeles Basin and is well centered within the CISEN network. Waveform comparisons using Olsen-AWP (0.1 – 2.0Hz with min V_s = 500m/s - Data black, Simulation red) show good fit for some components at stations to the north of the event, and mismatches between direct S-Waves and observed S arrivals at station DLA as the seismic waves cross the Los Angeles Basin structure. As we push to higher frequencies, we must understand the causes of these mismatches from source descriptions, velocity models, minimum V_s parameters and local site effects to continue increases in deterministic simulation frequencies.

Several seismic hazard research studies were run this year using CME computational capabilities. Three CME modeling groups ran 1Hz+ wave propagation validation simulations of the M5.4 Chino Hills earthquake (Figure 81). SDSU and SDSC ran an ensemble of three magnitude 8.0+ spontaneous rupture simulations with a rupture length exceeding 500km and an ensemble of three San Andreas Wall 2 Wall simulations at 1Hz. Geoff Ely at USC ran an Elsinore Fault rupture and wave propagation simulation which is part of what we call the SCEC

Big Ten simulation effort. A collaborative group lead by Y. Cui at SDSC and K. Olsen at SDSU ran the SCEC M8 simulation, a scenario M8 San Andreas event simulation using a dynamic rupture source at frequencies up to 2Hz. The SCEC M8 simulation ran on the largest open-science computer in the world (NCCS Jaguar) and is one of the largest earthquake wave propagation simulations ever performed.

Development of the CVM-Toolkit (CVM-T)

The CME has worked this year to develop new software tools to help SCEC HPC modeling groups build 3D velocity meshes. The SCEC Community Velocity Model Toolkit (CVM-T) enables earthquake modelers to quickly build, visualize, and validate large-scale meshes using SCEC CVM-H or CVM-4. CVM-T is comprised of three main components: (1) the most current version of the CVM-H community velocity model for Southern California, (2) tools for extracting meshes from this model and visualizing them, and (3) an automated test framework for evaluating new releases of CVM's using SCEC's AWP-ODC forward wave propagation software and one, or more, ground motion goodness of fit (GoF) algorithms.

CVM-T is designed to help SCEC modelers build large-scale velocity meshes by extracting material properties from an extended version of Harvard University's Community Velocity Model (CVM-H). The CVM-T software provides a highly-scalable interface to CVM-H 6.2 (and later) voxets. Along with an improved interface to CVM-H material properties, the CVM-T software adds a geotechnical layer (GTL) to CVM-H 6.2+ based on Ely's Vs30-derived GTL. The initial release of CVM-T also extends the coverage region for CVM-H 6.2 with a Hadley-Kanamori 1D background. Our goodness-of-fit measures include map-based measure which shows variations in matches across a simulation region.

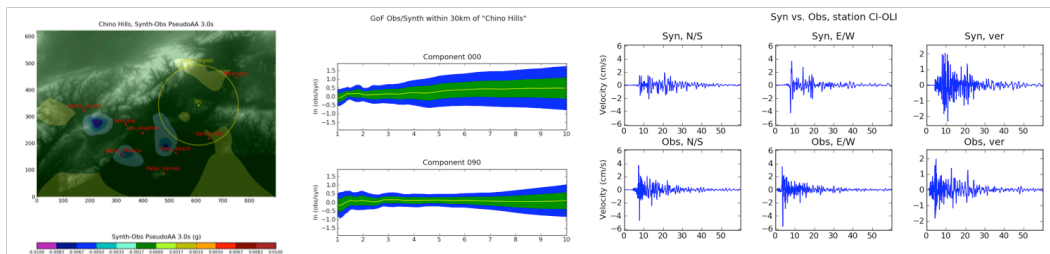


Figure 82. To support modifications and improvements to SCEC Community Velocity Models (CVM's), we have developed an automated CVM evaluation that builds a mesh from the CVM under tests and runs a 1Hz Chino Hills M5.4 event. The automates the running and post processing for this reference event and produces validation information as goodness-of-fit measures. (a) map-based goodness-of-fit, (b) bias comparison for synthetics, and (c) comparison of synthetic and observed seismograms.

The CVM-T system automates the processing needed to configure and run a 1Hz Chino Hills simulation and post-process the results into standard goodness-of-fit reports as shown in Figure 82. The goodness-of-fit algorithms we have developed help identify critical areas in need of improvement in the Community Velocity Model (CVM), and to help SCEC researchers assess the accuracy of different velocity models.

Development of the Second Generation Broadband Platform

The SCEC Broadband platform development involves SCEC researchers, graduate students, and the SCEC/CME software development group. The SCEC Broadband Platform integrates SCEC scientific modeling codes into a system capable of computing broadband seismograms (0-10 Hz) for scenario earthquakes in California. Scientific codes integrated into the SCEC Broadband Platform include pseudo-dynamic rupture generators, low frequency deterministic seismogram synthesis, high frequency stochastic seismogram synthesis, and non-linear site effect modeling codes. The Broadband Platform is designed to be used by both scientific and engineering groups and is designed to be portable and easy-to-use. Users may calculate broadband seismograms for both historical (validation events including Northridge, Loma Prieta, and Landers) earthquakes, as well as user-defined (scenario) earthquake. For each simulation, users may also select among various codebases for rupture generation, 1D low-frequency synthesis, high-frequency synthesis, and incorporation of non-linear site effects, with the option of running a goodness-of-fit comparison against observed or simulated seismograms. The platform produces a variety of ground motion-related data products, including broadband seismograms, rupture visualizations, and goodness-of-fit plots.

Ensemble of Southern San Andreas Wall to Wall Simulations at 1Hz

Large magnitude earthquake (e.g. > M8.0) simulations are computationally demanding because the affected regions are large and the frequencies of interest are high. Much of the seismic hazard in southern California, however, comes from rare, but very large, scenario earthquakes. In a magnitude 8, the San Andreas Fault might rupture for 500km. The area affected by such a wall-to-wall earthquake is large (~800 km by 400 km), and until recent advances in parallel computation, simulations of this scale have been out of reach.

To study these large events, CME researchers have developed the scientific and computational tools needed to simulate a set of Mw 8.0 earthquakes on the southern San Andreas Fault at 1Hz. Based on earlier SCEC research, dynamic rupture-based source descriptions provide source complexity needed for large-scale wave propagation simulations at higher frequencies. CME researchers optimized both the dynamic rupture modeling algorithms and the wave propagation software in our AWP-ODC software. Then, using NICS Kraken, we simulated three Mw8.0 wall-to-wall scenarios in a 32 billion grid point (800 km by 400 km by 100 km with a grid spacing of 100m) subset of the SCEC Community Velocity Model (CVM) V4 with a minimum shear-wave velocity of 500 m/s up to a maximum frequency of 1 Hz. We modeled for 3 wall-to-wall source realizations, namely two uni-lateral (southeast-to-northwest and northwest-to-southeast) ruptures, and a bi-lateral rupture starting in the center of the fault as shown in Figure 83.

The Wall-2-Wall simulations were run using 96,000 processor cores (out of 99,072) on the TeraGrid Kraken Cray XT5 supercomputer. Each run required 2.6 hours wall clock time, obtaining 53 sustained Teraflops. Peak ground motion maps produced by these simulations are shown in Figure 83. All realizations are characterized by strong directivity effects of the rupture, with highly variable pattern of the strong ground motion, and ‘sun-bursts’ radiating from the fault due to the complexity in the temporal evolution of rupture. All source realizations generated large amplitudes in the Los Angeles and Ventura basins, with the most localized ‘pockets’ of amplification in Los Angeles for the uni-lateral rupture.

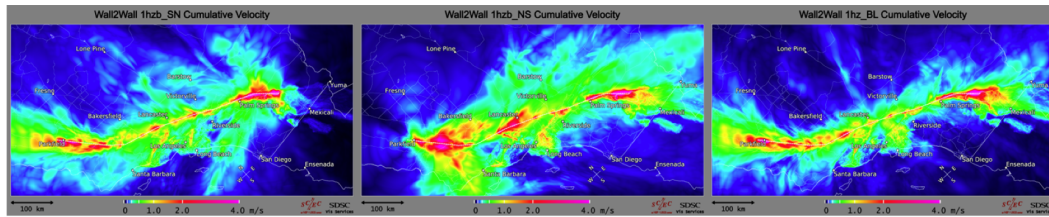


Figure 83. These maps show peak ground velocities for 3 Wall-2-Wall scenario events at 1Hz for M8.0 southern San Andreas ruptures showing the effects of alternative rupture directions. All ruptures are equivalent magnitudes with different rupture directions (left) southeast-northwest; (center) northwest-southeast; and (right) bi-lateral ruptures.

SCEC Big Ten Event Simulations

The SCEC Big Ten project is working to simulate ten of the most probable large ($M > 7$) ruptures in Southern California, with the objective of understanding how source directivity, rupture complexity, and basin effects affect ground motions. The ruptures and moment-magnitudes are selected from events with relatively high probability rates in the Uniform California Earthquake Rupture Forecast, Version 2 (UCERF2) model. The initial Big Ten simulations are being done using a newly developed, second order, mimetic dynamic rupture and wave propagation code. The SORD code supports greater complexity in our fault models but they are less scalable than our finite difference codes at this time and we are working to improve their capabilities. Simulation results from low frequency simulation of M7+ rupture on the Elsinore Fault were performed this year with our recently improved SORD code.

SCEC M8 Simulation

SCEC HPC computational groups at San Diego Supercomputer Center, San Diego State University, Pittsburg Supercomputer Center, and Carnegie Mellon University made outstanding progress this year improving SCEC HPC code performance. The CME research groups have obtained access to large, open-science, computer clusters at TACC, NICS, Argonne, and Oak Ridge. A combination of larger computers and significant software improvements has lead to great improvements in computational capabilities for SCEC wave propagation software, as shown in Figure 84. Wave propagation software performance improvements are critical to SCEC research, because wave propagation codes are used in many of the CME's most common seismic hazard modeling calculations.

CME progress in several areas made it possible for our group to design and run the SCEC M8 simulation, one of the largest wave propagation simulations ever performed. The science and computational performance of the M8 simulation is based on our high frequency validation Chino Hills simulation results, our ensemble Wall-2-Wall San Andreas simulations at 1Hz, our TeraGrid and DOE INCITE allocations of computer time, data storage, and other computer resources, and recent significant performance improvements to our AWP-ODC software.

Our M8 study uses a two-step simulation process in which a dynamic rupture simulation is run to create a physically realistic earthquake slip-time history. This slip-time history is then used as the earthquake source description in the second step, a deterministic earthquake wave propagation simulation. Use of dynamic rupture simulation to generate the M8 source descriptions is one of the reasons that M8 represents a state-of-the-art seismic hazard research

simulation. The M8 dynamic rupture simulation models friction on the fault with a slip-weakening law. The output from this dynamic rupture simulation represents an earthquake slip time history dataset which is a required input for the M8 wave propagation simulation. We transferred this dynamic rupture simulation result from NICS Kraken to NCCS Jaguar, and ran the M8 wave propagation simulation on Jaguar. Figure 85 shows (left) an snapshot of the M8 rupture propagating south on the San Andreas Fault, and (right) an M8 peak ground velocity map with seismograms at specific sites overlaid on the map.

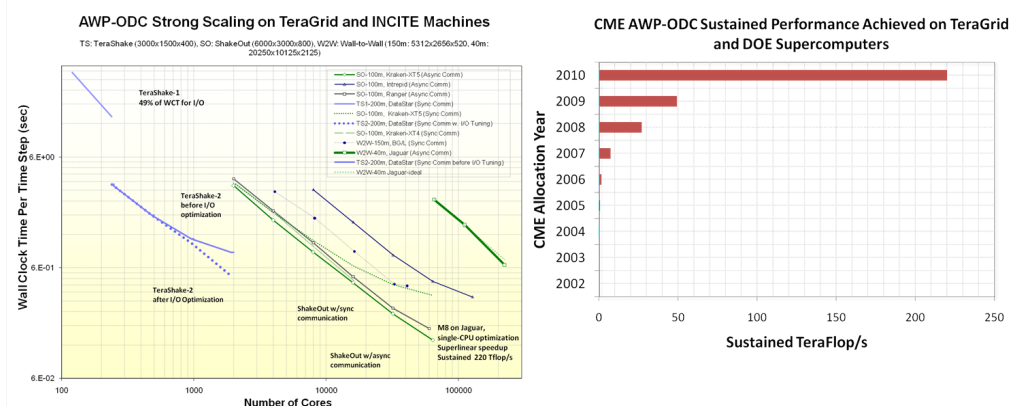


Figure 84. Improvement to SCEC's AWP-ODC software are showing in scaling diagram (a) and sustained performance (b). AWP-ODC, a fourth order, finite difference code, shows excellent scalability on all the largest NSF Track 2 machines, as well as the DOE INCITE computers. On right, the great performance improvements in AWP-ODC between 2009 and 2010 is a result of communications improvements and access to more cores on Jaguar.

The SCEC M8 simulation represents a technological accomplishment that greatly increases the efficiency of SCEC's fundamental seismic hazard calculations. These results will have significant, long-term, impact on SCEC research as we migrate the efficient improvements made to our AWP-ODC code for use in M8 into routine PSHA calculations needed to develop a accurate and precise understanding of seismic hazards.

Upcoming CME Research

The CME helps to implement SCEC's comprehensive, physics-based, system science approach to probabilistic seismic hazard analysis. CME researchers will continue to integrate better physics into seismic hazard calculations by integrating research results from various SCEC research groups together into CME computational tools. Over the next few years, CME researchers will work to improve SCEC ground motion modeling through improved dynamic rupture models, more accurate wave propagation simulations, physics-based probabilistic seismic hazard analysis, and 3D velocity model development. CME researchers expect to contribute to the development by SCEC 4 of time-dependent seismic hazard analysis techniques.

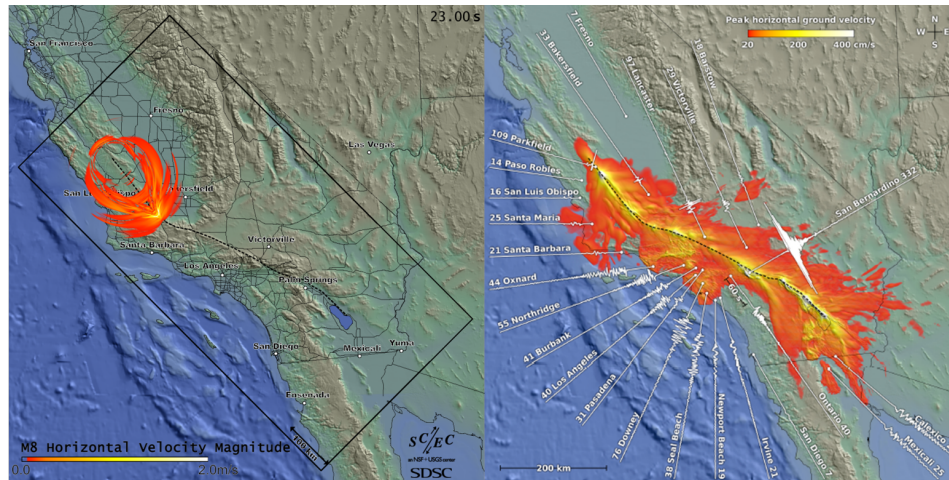


Figure 85. SCEC M8 Simulation Results: (a) View of the M8 simulation showing super-shear rupture with the Mach cone entering the 'Big Bend' section of the San Andreas Fault. Our dynamic rupture-based sources provide evidence of a physical basis for super-shear rupture during large events with slip-weakening friction laws. Further dynamic rupture modeling, investigating alternative friction laws will help identify the causes of super-shear rupture (b) PGVH's derived from M8 superimposed on the regional topography. N46E component seismograms are added at selected locations, with their peak velocities (cm/s) listed along the traces.

Selected CME-Related Publications

- Graves, R. W., B. T. Aagaard, and K. W. Hudnut (2010). The ShakeOut Earthquake source and ground motion simulations, *Earthquake Spectra*, in press.
- Cui, Y., K. B. Olsen, T. H. Jordan, K. Lee, J. Zhou, P. Small, D. Roten, G. Ely, D.K. Panda, A. Chourasia, J. Levesque, S. M. Day, P. Maechling (2010), Scalable Earthquake Simulation on Petascale Supercomputers, *Proceedings of the SC10 International Conference for HPC, Networking and Analysis*. (Accepted as SC10 Gordon Bell Finalist).
- Taborda, R., J. López, H. Karaoglu, J. Urbanic and J. Bielak (2010), Speeding Up Wave Propagation for Large-Scale Earthquake Simulations, *Proceedings of the SC10 International Conference for HPC, Networking and Analysis*. (Submitted for publication).
- Callaghan, Scott, Ewa Deelman, Dan Gunter, Gideon Juve, Philip Maechling, Christopher Brooks, Karan Vahi, Kevin Milner, Robert Graves, Edward Field, David Okaya, Thomas Jordan (2010), Scaling up workflow-based applications, *J. Computer System Science*, special issue on scientific workflows, in press.
- Graves, R., T. Jordan; S. Callaghan; E. Deelman; E. Field; G. Juve; C. Kesselman; P. Maechling; G. Mehta; K. Milner; D. Okaya; P. Small; and K. Vahi (2010). *CyberShake: A Physics-Based Seismic Hazard Model for Southern California*, *Pure Applied Geophys.*, accepted for publication
- Moczo, P., J Kristek, P Franek, E Chalub, PY Bard, S Tsune, F Hollender, T Iwata, A Iwaki, E Priolo, P Klin, S Aoi, C Mariotti, J Bielak, R Taborda, H Karaoglu, V Etienne, J Virieux (2010), Numerical Modeling of Earthquake Ground Motion in the Mygdonian Basin, Greece: Verification of the 3D Numerical Methods, *Proc. of the Annual Meeting of the Seis. Soc. of America*.

- Olsen, K.B., and J.E. Mayhew (2010). Goodness-of-fit Criteria for Broadband Synthetic Seismograms with Application to the 2008 Mw5.4 Chino Hills, CA, Earthquake, *Seism. Res. Lett.*, accepted for publication.
- Cruz-Atienza, V.M. and K.B. Olsen (2010). Supershear Mach-Waves Expose the Fault Breakdown Slip, *Tectonophysics*, in revision for the special volume on 'Supershear Earthquakes'.
- Juve, G., Ewa Deelman, Karan Vahi, Gaurang Mehta, Bruce Berriman, Benjamin P. Berman, Phil Maechling (2010), Data Sharing Options for Scientific Workflows on Amazon EC2, 22nd IEEE/ACM Conference on Supercomputing (SC10), New Orleans, Louisiana, November 2010
- Juve, G., Ewa Deelman, Karan Vahi, Garuang Mehta, Bruce Berriman, Benjamin P. Berman and Phil Maechling (2009), Scientific Workflow Applications on Amazon EC2, Workshop on Cloud-based Services and Applications in conjunction with 5th IEEE International Conference on e-Science (e-Science 2009), Oxford UK, December 2009.
- Lee, K., Cui, Y., Maechling, P., Olsen, K. and Jordan, T., Communication Optimizations of SCEC AWP-Olsen Application for Petascale Computing (accept, Supercomputing 09, Portland, 2009; Lee, K., Cui, Y., Kaiser, T., Maechling, P., Olsen, K. and Jordan, T., IO Optimizations of SCEC AWP-Olsen Application for Petascale Earthquake Computing (both FINALISTS of Best Posters), SC09, Portland, 2009.
- Rojas, O., E. Dunham, S.M. Day, L.A. Dalguer, and J.E. Castillo (2009). Finite difference modeling of rupture propagation with strong velocity-weakening friction, *Geophys J. Int.*, in review.
- Bielak, J., R.W. Graves, K.B. Olsen, R. Taborda, L. Ramírez-Guzmán, S.M. Day, G.P. Ely, D. Roten, T.H. Jordan, P.J. Maechling, J. Urbanic, Y. Cui, G. Juve, "The ShakeOut earthquake scenario: Verification of three simulation sets," *Geophysical Journal International* doi: 10.1111/j.1365-246X.2009.04417x, 2009.
- Maechling, P., E. Deelman, Y. Cui (2009), Implementing Software Acceptance Tests as Scientific Workflows, *Proceedings of the IEEE International Parallel & Distributed Processing Symposium 2009*, Las Vegas Nevada, July, 2009 (published)
- Doser, D.I., K.B. Olsen, F.F. Pollitz, R.S. Stein, and S. Toda (2009). The 1911 M~6.6 Calaveras earthquake: Source parameters and the role of static, viscoelastic and dynamic Coulomb stress changes imparted by the 1906 San Francisco earthquake, *Bull. Seis. Soc. Am.* 99, 1746-1759.
- Cui, Y., Chourasia, A., Moore, R., Olsen, K., Maechling, P., Jordan, T., The TeraShake Computational Platform, *Advances in Geocomputing, Lecture Notes in Earth Sciences* 119, DOI 10.1007/978-3-540-85879-9_7, pp229-278, editor H. Xing, Springer-Verlag Berlin Heidelberg, 2009.

IV. SCEC Communication, Education, and Outreach

Mark Benthien / Bob de Groot

CEO Director for SCEC / CEO Education Programs Manager

Introduction

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

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

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

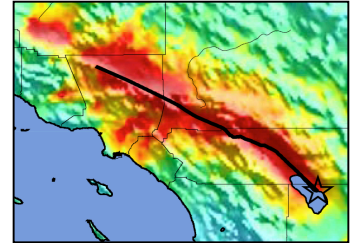
Partnerships are key to achieving SCEC's mission, research objectives, and outreach goals. These partners include other science organizations (e.g. IRIS, EarthScope, and UNAVCO), engineering organizations (e.g. PEER and EERI), education organizations (e.g. Los Angeles County Unified School District,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

Immediately following the 2009 SCEC Annual Meeting, a major review meeting was held of the SCEC CEO program. An extensive evaluation document was prepared in summer 2009 by evaluation consultants, which an external review panel used as the basis of its analysis. The review panel's report was quite thorough and provided several excellent recommendations. Overall, they concluded that "It is the strong consensus of the review committee that the SCEC CEO program has been an overwhelming success both in terms of breadth and impact." The SCEC Advisory Council commented that "the review strongly indicates that SCEC has demonstrated success in meeting the Broader Impacts criterion of NSF reviews, has become a leading force in education and outreach efforts related to earthquake science in Southern California, and has set a standard for others to emulate in all of California or elsewhere." The review was very important to the SCEC4 proposal process and was supported with funding from the NSF.

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

Public Outreach Activities

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



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

Expanding statewide has been much more complicated than simply deleting the word “Southern” from all materials and webpages. The 2008 ShakeOut was based on a single earthquake scenario, which does not apply to the entire state. Thus, 11 “ShakeOut Information Areas” were created, based on earthquake hazards, geography, media markets, and other factors, to provide local hazard information for participants throughout California. The redesigned *ShakeOut.org* website contains a description of each area’s earthquake hazard and ShakeOut registration statistics down to the county level.

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

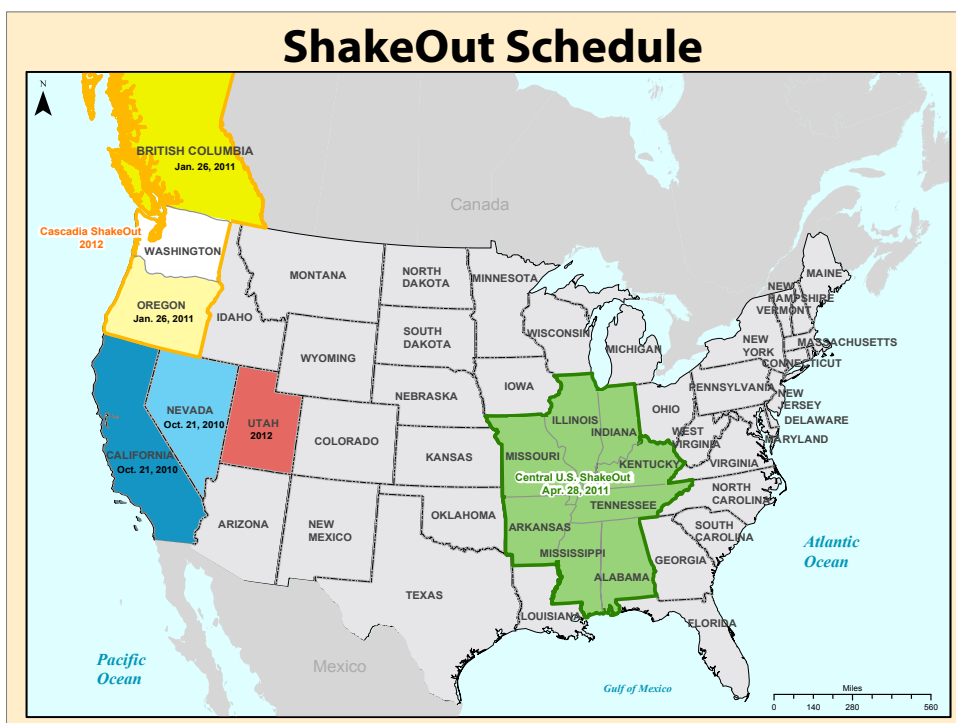
6.9 million people participated in the 2009 ShakeOut. Many of the 2008 participants registered again, along with new participants from all 58 of California’s the states 58 counties. 5 million of the participants were staff and students from K-12 schools, but the rest were people and organizations that typically do not have earthquake drills.

In 2010 the California ShakeOut grew even larger with more than 7.9 million participants, and was joined by the first Nevada ShakeOut (116,000 participants) and first Guam ShakeOut (38,000 participants). All are planned to be annual events together on the third Thursday of October. Media coverage was extensive throughout California, nationwide, and even internationally, with 28 drills identified for the media to attend (listed at www.shakeout.org/venues). A list of over 300 print and online stories is at www.shakeout.org/news. For the first time ShakeOut was in the New York Times, with a front-page photo. A story on



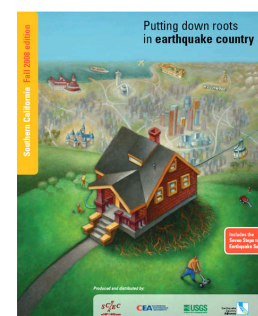
CBS Sunday Morning featured the ShakeOut, SCEC's latest high-performance computing earthquake simulation, and interviews with SCEC scientists (<http://www.cbsnews.com/stories/2010/10/24/sunday/main6987014.shtml>). More than 500 TV and radio news stories across the state and country aired in the days surrounding the drill.

In 2009 SCEC also created and hosted the website for “New Zealand Great West Coast Shakeout.” Over 27 percent of the region’s 30,000 residents participated. The British Columbia ShakeOut on January 26, 2011 will be the next non-California drill, along with a local drill in Oregon (Washington may join in 2012 as part of a Cascadia ShakeOut). In April, 2011, the Great Central US ShakeOut will be held as part of the lead up to the New Madrid Bicentennial. And in 2012 Utah and possibly New Zealand (nationwide) will launch ShakeOut drills. ShakeOut has really changed the way people and organizations are approaching the problems of earthquake preparedness. SCEC is hosting the website for each of these drills, to maintain consistency in the brand and work towards unified earthquake messaging worldwide.



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

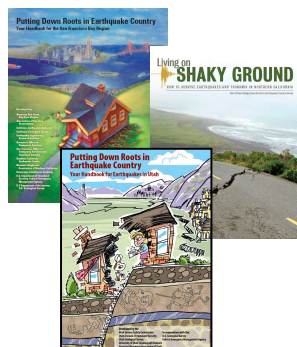
The creation of the Earthquake Country Alliance in 2003 was concurrent with the desire to update *Putting Down Roots* in advance of the 10th anniversary of the Northridge earthquake. The process brought the ECA together to develop consensus messaging and notably introduced the “Seven Steps to Earthquake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



overview of the Uniform California Earthquake Rupture Forecast study led by SCEC. A new version is being worked on currently, to be printed in Fall, 2010, and will include new tsunami science and preparedness content.

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

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



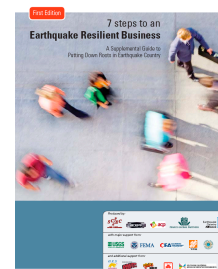
The new version of *Putting Down Roots* was designed to allow other regions to adopt and adapt its structure to create additional versions. The first is a Greater San Francisco Bay Area version produced by a partnership led by the USGS with SCEC, local and state emergency managers, the Red Cross and many other organizations. Over 2.3 million copies have been printed, many distributed in newspapers, with funding from the California Earthquake Authority, USGS, FEMA, Red

Cross, OES, CGS, and several others). In addition, a new booklet, *Protecting Your Family From Earthquakes— The Seven Steps to Earthquake Safety*, was produced in 2006 as part of the *Putting Down Roots* series, in two versions - English and Spanish in one booklet, and English, Chinese, Korean, and Vietnamese in another booklet. All Bay Area booklets can also be accessed from www.earthquakecountry.info/roots. All printings of the Bay Area version to date have been coordinated through SCEC.

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

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

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



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

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

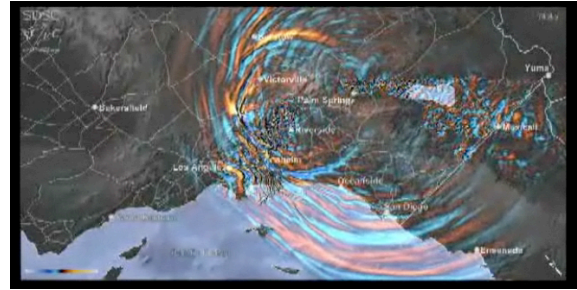
The Earthquake Country Alliance is now the primary SCEC mechanism for maintaining partnerships and developing new products and services for the general public. Following the success of developing and implementing the 2008 Great Southern California, the ECA has now been expanded into a statewide organization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

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

Media Relations. SCEC engages local, regional and national media organizations (print, radio and television) to jointly educate and inform the public about earthquake-related issues. The goal has been to communicate clear, consistent messages to the public—both to educate and inform, and to minimize misunderstandings or the perpetuation of myths. 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.

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

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



Education Program

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

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

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

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

SCEC Experiential Learning and Career Advancement programs. Since 1994, SCEC has provided 404 internships to undergraduate and graduate students, with 330 internships since 2002 (charts included here are for 2002-2009 only). SCEC offers two summer internship programs (SCEC/SURE and SCEC/USEIT) and a year-round program for both undergraduate and graduate students (ACCESS). These programs are the principal framework for undergraduate student participation in SCEC, and have common goals of increasing diversity

and retention. In addition to their research projects, participants come together several times during their internship for orientations, field trips, and to present posters at the SCEC Annual meeting. Students apply for both programs at www.scec.org/internships.

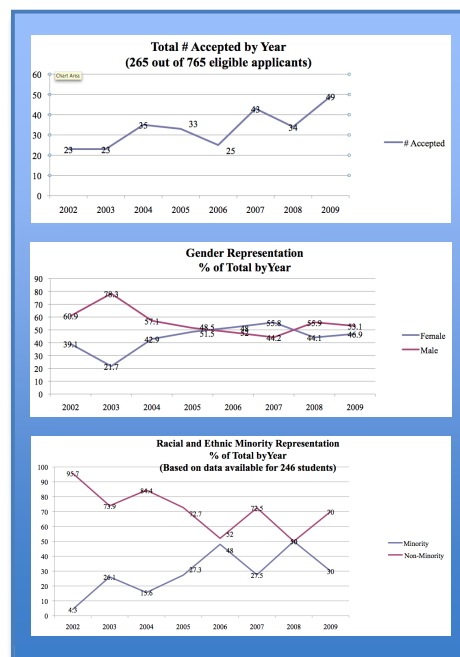
The SCEC *Summer Undergraduate Research Experience* (SCEC/SURE) has supported **189** students to work one-on-one as student interns with SCEC scientists since 1994 (118 since 2002). SCEC/SURE has supported students working on numerous projects in earthquake science, including the history of earthquakes on faults, risk mitigation, seismic velocity modeling, science education, and earthquake engineering.

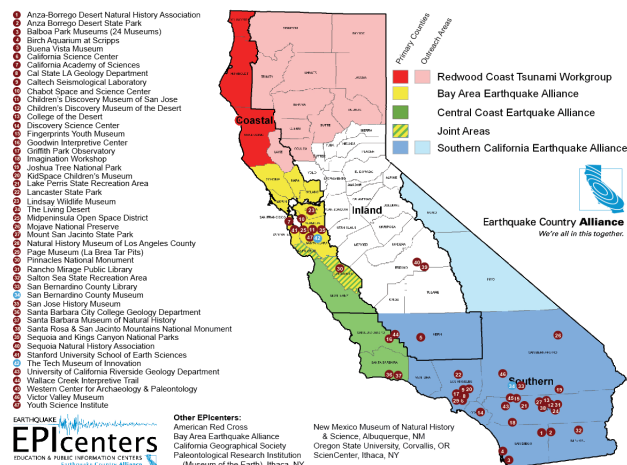
The SCEC *Undergraduate Studies in Earthquake Information Technology* (SCEC/USEIT) program, unites undergraduates from across the country in an NSF REU Site at USC. SCEC/USEIT interns interact in a team-oriented research environment with some of the nation's most distinguished geoscience and computer science researchers. Since 2002, **148** students have participated.

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

Our USEIT and CME experience has identified a “weak link” in cyberinfrastructure (CI)-related career pathways: the transition from discipline-oriented undergraduate degree programs to problem-oriented graduate studies in earthquake system science. We address this educational linkage problem through a CI-TEAM implementation project entitled the *Advancement of Cyberinfrastructure Careers through Earthquake System Science* (ACCESS). The objective of the ACCESS project is to provide a diverse group of students with research experiences in earthquake system science that will advance their careers and encourage their creative participation in cyberinfrastructure development. Its overarching goal is to prepare a diverse, CI-savvy workforce for solving the fundamental problems of system science. Undergraduate (ACCESS-U) internships support CI-related research in the SCEC Collaboratory by undergraduate students working toward senior theses or other research enhancements of the bachelor's degree. Graduate (ACCESS-G) internships support up to one year of CI-related research in the SCEC Collaboratory by graduate students working toward a master's thesis. The SCEC ACCESS program ends in 2010 with **31** internships having been awarded.

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





EPIcenters share a commitment to demonstrating and encouraging earthquake preparedness. They help coordinate Earthquake Country Alliance activities in their county or region (including the ShakeOut), lead presentations or organize events in their communities, or in other ways demonstrate leadership in earthquake education and risk reduction. EPIcenters are found in a variety of public meeting places such as museums, science centers, libraries, and universities. Just as the ShakeOut became a statewide effort in 2009 so did the EPIcenter Network. Currently over 50 free-choice learning institutions statewide

participate in the ShakeOut and other activities throughout the year. The statewide Network is coordinated by SCEC Education Program Manager Robert de Groot with Kathleen Springer (San Bernardino County Museum) and Candace Brooks (The Tech Museum) coordinating Network activities in Southern and Northern California respectively.

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

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

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

As a result of the successful collaboration on *Living on the Edge*, SCEC was asked to participate in the development of SBCM's *Hall of Geological Wonders*. To be completed in 2011, the Hall is a major expansion of this important cultural attraction in the Inland Empire. One of the main objectives of the Hall is to teach about the region from a geologic perspective. The museum is devoting a large space to the story of Southern California's landscape, its evolution and dynamic nature. SCEC has played an ongoing advisory role, provided resources for the development of the earthquake sections of the exhibit, and will have an ongoing role in the implementation of educational programming.

The most recent debut of a SCEC earthquake display is the *Earthquake Information Center* at California State University, Los Angeles (CSULA). This exhibit, created in partnership with the

geology department at CSULA, features two computer screens showing recent worldwide and local earthquakes. Located in the lobby of the Physical Science Building this exhibit also displays the seven steps to earthquake safety and components of a basic earthquake disaster supply kit. Many hundreds of students pass by the exhibit every day on their way to science classes. Development of other EPIcenter exhibits and resource areas are occurring at the Rancho Mirage Public Library, The California Science Center, Los Angeles, and the Natural History Museum of Los Angeles County.

K-12 Education Partnerships and Activities

Partnerships with Science Education Advocacy Groups and Organizations with Similar Missions. SCEC is an active participant in the broader earth science education community including participation in organizations such as the National Association of Geoscience Teachers, the Coalition for Earth System Education, and local and national science educator organizations (e.g. NSTA). Improvement in the teaching and learning about earthquakes hinges on improvement in earth science education in general. Hence, SCEC contributes to the community through participation on outreach committees wherever possible, co-hosting meetings or workshops, and building long-term partnerships. An example of a current project is a partnership with EarthScope to host a San Andreas Fault workshop for park and museum interpreters that was held in Spring 2009. In 2010 SCEC is collaborating with IRIS and EarthScope in developing the content for the San Andreas fault Active Earth Kiosk. The Active Earth Kiosk is an interactive website where visitors learn about earth hazards in a particular region. EarthScope is creating an Active Earth Kiosk for each of the regions covered by its Interpretive Workshops. Also in 2010 Arizona State University, the OpenTopography Facility, and SCEC developed three earth science education products to inform students and other audiences about LiDAR and its application to active tectonics research. First, a 10-minute introductory video titled *LiDAR: Illuminating Earthquakes* was produced and is freely available online. The second product is an update and enhancement of the Wallace Creek Interpretive Trail website. LiDAR topography data products have been added along with the development of a virtual tour of the offset channels at Wallace Creek using the B4 LiDAR data within the Google Earth environment. Finally, the virtual tour to Wallace Creek is designed as a lab activity for introductory undergraduate geology courses to increase understanding of earthquake hazards through exploration of the dramatic offset created by the San Andreas Fault (SAF) at Wallace Creek and Global Positioning System-derived displacements spanning the SAF at Wallace Creek. This activity is currently being tested in courses at Arizona State University. The goal of the assessment is to measure student understanding of plate tectonics and earthquakes after completing the activity. Including high-resolution topography LiDAR data into the earth science education curriculum promotes understanding of plate tectonics, faults, and other topics related to earthquake hazards.

Teacher Workshops. SCEC offers teachers 2-3 professional development workshops each year with one always held at the SCEC Annual Meeting. The workshops provide connections between developers of earthquake education resources and those who use these resources in the classroom. The workshops include content and pedagogical instruction, ties to national and state science education standards, and materials teachers can take back to their classrooms. Workshops are offered concurrent with SCEC meetings, at National Science Teachers Association annual meetings, and at the University of Southern California. In 2003 SCEC began a partnership with the Scripps Institution of Oceanography Visualization Center to develop teacher workshops. Facilities at the Visualization Center include a wall-sized curved panorama screen (over 10m wide). The most recent teacher workshop held in partnership with Mt. San Antonio College was held in April 2010 at the GSA Cordilleran Section meeting.



Since 2009, SCEC has been collaborating with the Cal State San Bernardino/EarthScope RET program led by Sally McGill. During the course of the summer 7-10 high school teachers and their students conduct campaign GPS research along the San Andreas and San Jacinto faults. SCEC facilitates the education portion of the project through the implementation of the professional development model called Lesson Study. This allows for interaction with the teachers for an entire year following their research. For the second year all of the members of the RET cohort participate in the SCEC Annual Meeting by doing presentation of their research, participating in meeting activities such as talks and works culminating in presenting their research at one of the evening poster sessions.

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

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

Development of Educational Products

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

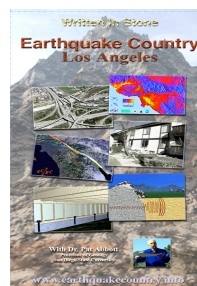


Plate Tectonics Kit. This new teaching tool was created to make plate tectonics activities more accessible for science educators and their students. SCEC developed a user-friendly version of the *This Dynamic Earth* map, which is used by many educators in a jigsaw-puzzle activity to learn about plate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

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



V. State of SCEC, 2010

Welcome to the 2010 Annual Meeting

This will be SCEC's 20th Annual Meeting—twenty years already!—and our fourth community-wide gathering under the five-year SCEC3 program. The agenda for this big anniversary features some very interesting talks by keynote speakers, discussion sessions on major themes, many outstanding poster presentations, and a variety of IT demonstrations, education & outreach activities, and social gatherings. Seven workshops and several project coordination sessions are scheduled before and after the main meeting.

The week's activities will bring together a substantial collaboration in geoscience: 545 people have pre-registered (Figure 1), and 310 poster abstracts have been submitted—the most ever for a SCEC annual meeting. Among this year's pre-registrants are 160 first-time attendees, so we will welcome many new faces!

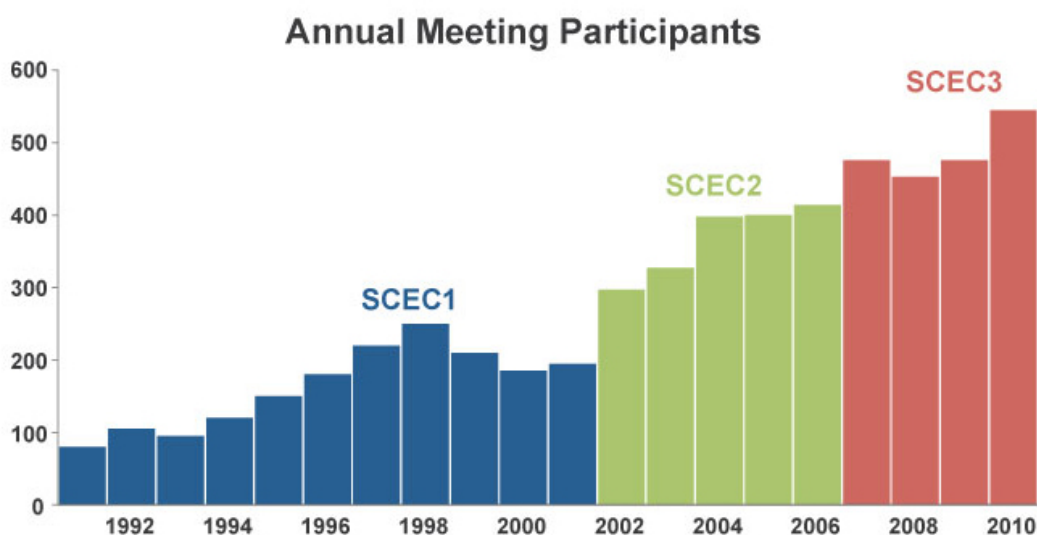


Figure 1. Registrants at SCEC Annual Meetings, 1991-2010. Number for 2010 (545) is pre-registrants.

Goals of the Meeting

Our annual meetings are designed to achieve three goals: to share research results and plans in the sessions, at the meals, and around the pool; to mark our progress toward the priority objectives of the SCEC3 science plan given in Table 1; and to incorporate your ideas for new research into the annual and long-range planning processes. A draft of the 2011 Science Plan, prepared by Deputy Director Greg Beroza and the Planning Committee, is included in this meeting volume.

Greg and the PC have put together an impressive report (also included in the meeting volume) on the research projects supported by SCEC during the past year. This annual report demonstrates substantial progress towards the SCEC3 objectives. Greg will highlight the research results in his plenary address on Monday morning. The poster presentations at the Annual Meeting will provide a forum for more detailed discussions and interchange of ideas.

Table 1. Priority Science Objectives for SCEC3

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1. Improve the unified structural representation and employ it to develop system-level models for earth-quake forecasting and ground motion prediction
 2. Develop an extended earthquake rupture forecast to drive physics-based SHA
 3. Define slip rate and earthquake history of southern San Andreas fault system for last 2000 years
 4. Investigate implications of geodetic/geologic rate discrepancies
 5. Develop a system-level deformation and stress-evolution model
 6. Map seismicity and source parameters in relation to known faults
 7. Develop a geodetic network processing system that will detect anomalous strain transients
 8. Test of scientific prediction hypotheses against reference models to understand the physical basis of earthquake predictability
 9. Determine the origin and evolution of on- and off-fault damage as a function of depth
 10. Test hypotheses for dynamic fault weakening
 11. Assess predictability of rupture extent and direction on major faults
 12. Describe heterogeneities in the stress, strain, geometry, and material properties of fault zones and understand their origin and interactions by modeling ruptures and rupture sequences
 13. Predict broadband ground motions for a comprehensive set of large scenario earthquakes
 14. Develop kinematic rupture representations consistent with dynamic rupture models
 15. Investigate bounds on the upper limit of ground motion
 16. Develop high-frequency simulation methods and investigate the upper frequency limit of deterministic ground motion predictions
 17. Validate earthquake simulations and verify simulation methodologies
 18. Collaborate with earthquake engineers to develop rupture-to-rafters simulation capability for physics-based risk analysis
 19. Prepare for post-earthquake response.
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SCEC4 Proposal

A special goal of this year's meeting is to look beyond the annual cycle toward SCEC4, the next five-year phase of the Center (2012-2017). The SCEC4 proposal was submitted in early March to our sponsoring agencies, the National Science Foundation (NSF) and the U.S. Geological Survey (USGS). Both agencies convened a panel for a joint site review, held at USC on June 21-24. We are expecting to receive news about the status of the proposal from our agency representatives in the first session of the meeting on Monday morning.

The SCEC4 scientific program is framed in terms of a very challenging, long-term research goal: *to understand how seismic hazards change across all time scales of interest, from millennia to seconds*. This problem is well suited to SCEC's integrated approach to earthquake system science. Earthquakes emerge from complex, multiscale interactions within active fault systems that are opaque, and are thus difficult to observe. They cascade as chaotic chain reactions through the natural and built environments, and are thus difficult to predict. We propose a 5-year research program that will focus on time-dependent seismic hazard analysis—the geoscience required to “track earthquake cascades” (Figure 2).

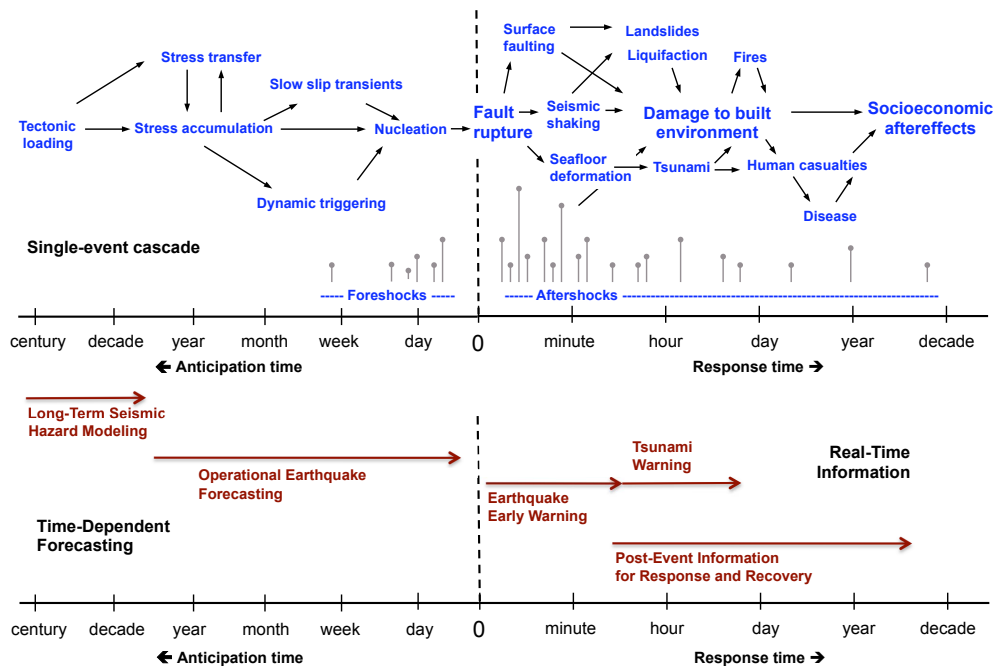


Figure 2. Earthquake processes (in blue) cascade through the natural and built environments, depicted here for a single damaging event on a nonlinear timeline. Advancing the science behind long-term hazard modeling, operational forecasting, earthquake early warning, and delivery of post-event information (in red) will help reduce seismic risk and improve community resilience.

The SCEC4 science plan was developed by the Center’s Board of Directors and Planning Committee with broad input from the SCEC community. A committee chaired by Nadia Lapusta assessed the basic research that will be needed to move towards the Center’s scientific goals, identifying six fundamental problems in earthquake physics:

- Stress transfer from plate motion to crustal faults: long-term fault slip rates
- Stress-mediated fault interactions and earthquake clustering: evaluation of mechanisms
- Evolution of fault resistance during seismic slip: scale-appropriate laws for rupture modeling
- Structure and evolution of fault zones and systems: relation to earthquake physics
- Causes and effects of transient deformations: slow slip events and tectonic tremor
- Seismic wave generation and scattering: prediction of strong ground motions

These problems are clearly interrelated and require an interdisciplinary, multi-institutional approach. Each was described in the proposal by a short problem statement, a set of SCEC4 objectives, and a listing of priorities and requirements.

We reformulated our working group structure in accordance with the overall SCEC4 research plan, which is organized around a set of four system-level challenges. (1) discover the physics of fault failure; (2) improve earthquake forecasts by understanding fault-system evolution and the

physical basis for earthquake predictability; (3) predict ground motions and their effects on the built environment by simulating earthquakes with realistic source characteristics and three-dimensional representations of geologic structures; and (4) improve the technologies that can reduce long-term earthquake risk, provide short-term earthquake forecasts and earthquake early warning, and enhance emergency response.

We developed a coherent set of interdisciplinary research initiatives that will focus on special fault study areas, the development of a community geodetic model for Southern California (which will combine GPS and InSAR data), and a community stress model. The latter will provide a new platform for the integration of various constraints on earthquake-producing stresses. Improvements will be made to SCEC's unified structural representation and its statewide extensions. The SCEC4 program, which lies squarely within Pascal's Quadrant, has been designed to help:

- transform long-term seismic hazard analysis, the most important geotechnology for characterizing seismic hazards and reducing earthquake risk, into a physics-based science
- develop operational earthquake forecasting into a capability that can provide authoritative information about the time dependence of seismic hazards to aid communities in preparing for potentially destructive earthquakes
- enable earthquake early warning—advanced notification that an earthquake is underway and predictions of when strong shaking will arrive at more distant sites
- improve the delivery of post-event information about strong ground motions and secondary hazards

The Center will create, prototype, and refine these capabilities in partnership with the USGS and other responsible government agencies. SCEC4 contributions will include research within the Collaboratory for the Study of Earthquake Predictability (CSEP), a cyberinfrastructure for the prospective (and retrospective) testing of forecasting models against authoritative data.

The SCEC4 organizational structure will comprise disciplinary working groups, interdisciplinary focus groups, special projects, and technical activity groups. The Southern San Andreas Fault Evaluation (SoSAFE) project, which has been funded by the USGS Multi-Hazards Demonstration Project for the last four years, will be transformed into a standing interdisciplinary focus group to coordinate research on the San Andreas and the San Jacinto master faults. Research in seismic hazard and risk analysis will be bolstered through an Implementation Interface that will include educational as well as research partnerships with practicing engineers, geotechnical consultants, building officials, emergency managers, financial institutions, and insurers. A set of special projects funded separately by the NSF, USGS, and other agencies will leverage core research support.

The theme of the CEO program during SCEC4 will be *creating an earthquake and tsunami resilient California*. SCEC and its partners in the statewide Earthquake Country Alliance will prepare individuals and organizations for making decisions (split-second and long-term) in response to changing seismic hazards and introduce them to the new technologies of operational earthquake forecasting and earthquake early warning. A public education and preparedness thrust area will educate people of all ages—in California, across the country, and internationally—about earthquakes, and motivate them to become prepared. A K-14 earthquake education initiative will seek to improve earth science education and school earthquake safety, and SCEC's

experiential learning and career advancement program will provide students and early-career scientists with research opportunities and networking to encourage and sustain careers in science and engineering.

The SCEC leadership is committed to the growth of a diverse scientific community, and the SCEC4 diversity plan provides a strategy and review process to pursue this goal. It recognizes that the most effective long-term strategy is to promote diversity among students and early-career scientists; i.e., to address the “pipeline problem.”

The SCEC4 management plan contains specific “smart & green” objectives that will contribute to a sustainable future for the Center. The Center will continue to work towards an effective post-earthquake scientific response, in coordination with the USGS, California Geological Survey, and other organizations.

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 57 participating institutions (Table 2). SCEC currently involves more than 800 scientists and other experts in active SCEC projects. A key measure of the size of the SCEC community—registrants at our Annual Meetings—is shown for the entire history of the Center in Figure 1. With the current number topping last year’s by 17%, it is clear that participation in SCEC is continuing to grow.

The current core institutions have all committed resources to SCEC4. Two new institutions have requested to join the core, the California Geological Survey (CGS) and California State University Center for Collaborative Earthquake Science (CSUCCES), and a third, UC Davis, is exploring the possibility. CSUCCES, a 6-campus consortium of CalState (the nation’s largest university system), will be included as a “distributed” core institution in SCEC4. This 6-campus consortium of CalState—the nation’s largest university system—will be included as a “distributed” core institution in SCEC4. The CSUCCES initiative, led by Prof. David Bowman of CalState Fullerton, will benefit an outstanding group of faculty and students who have contributed substantially to the SCEC research program.

Board of Directors. Under the SCEC3 by-laws, each core institution appoints one member to the Board of Directors, and two at-large members are elected by the Board from the participating institutions. The Board is chaired by the Center Director, who also serves as the USC representative; the Vice-Chair is Lisa Grant Ludwig. The complete Board of Directors is listed on page ii of the meeting volume.

Advisory Council. The Center’s external Advisory Council (AC), chaired by Dr. Mary Lou Zoback, is charged with developing an overview of SCEC operations and advising the Director and the Board. Since the inception of SCEC in 1991, the AC has played a major role in maintaining the vitality of the organization and helping its leadership chart new directions. A verbatim copy of the AC’s 2009 report follows this report in the meeting volume.

Dr. Zoback has announced her intention to step down as AC chair after completing this year’s report. She has been an outstanding leader, and we will use the opportunity at the meeting to thank her for her efforts on behalf of the SCEC community. Other members cycling off the Council will be Patti Guatteri, Kate Miller, John Rudnicki, and Lloyd Cluff. We are fortunate that such excellent scientists have been willing to lend us their advice.

I am very happy to report that Jeff Freymueller has agreed to take over as AC chair. Jeff is very experienced in the ways of SCEC, having served on the SCIGN advisory committee from 1998 to 2002 and the AC since the beginning of SCEC2 in 2002. Please join me in welcoming him to this important leadership role.

We can also look forward to welcoming five new members to the AC: Roger Bilham (U. Colorado), Farzad Naiem (John A. Martin & Associates), Meghan Miller (UNAVCO), John Vidale (U. Washington), and Andrew Whittaker (U. Buffalo). Two additional members, Donna Eberhart-Phillips (U.C. Davis) and Bob Lillie (Oregon State U.), will begin their terms in 2011. All of them will bring exceptional qualities and experience to the AC.

Table 2. SCEC Institutions (March 1, 2010)

Core Institutions (16)	Participation Institutions (57)
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) New SCEC4 Core Institutions: California Geological Survey CalState Consortium	Appalachian State University; Arizona State University; Berkeley Geochron Center; Boston University; Brown University; Cal-Poly, Pomona; Cal-State, Chico; Cal-State, Long Beach; Cal-State, Fullerton; Cal-State, Northridge; Cal-State, San Bernardino; California Geological Survey; Carnegie Mellon University; Case Western Reserve University; CICESE (Mexico); Cornell University; Disaster Prevention Research Institute, Kyoto University (Japan); ETH (Switzerland); Georgia Tech; Institute of Earth Sciences of Academia Sinica (Taiwan); Earthquake Research Institute, University of Tokyo (Japan); Indiana University; Institute of Geological and Nuclear Sciences (New Zealand); Jet Propulsion Laboratory; Los Alamos National Laboratory; Lawrence Livermore National Laboratory; National Taiwan University (Taiwan); National Central University (Taiwan); Ohio State University; Oregon State University; Pennsylvania State University; Princeton University; Purdue University; SUNY at Stony Brook; Texas A&M University; University of Arizona; UC, Berkeley; UC, Davis; UC, Irvine; University of British Columbia (Canada); University of Cincinnati; University of Colorado; University of Illinois; University of Massachusetts; University of Miami; University of Missouri-Columbia; University of New Hampshire; University of Oklahoma; University of Oregon; University of Texas-El Paso; University of Utah; University of Western Ontario (Canada); University of Wisconsin; University of Wyoming; URS Corporation; Utah State University; Woods Hole Oceanographic Institution

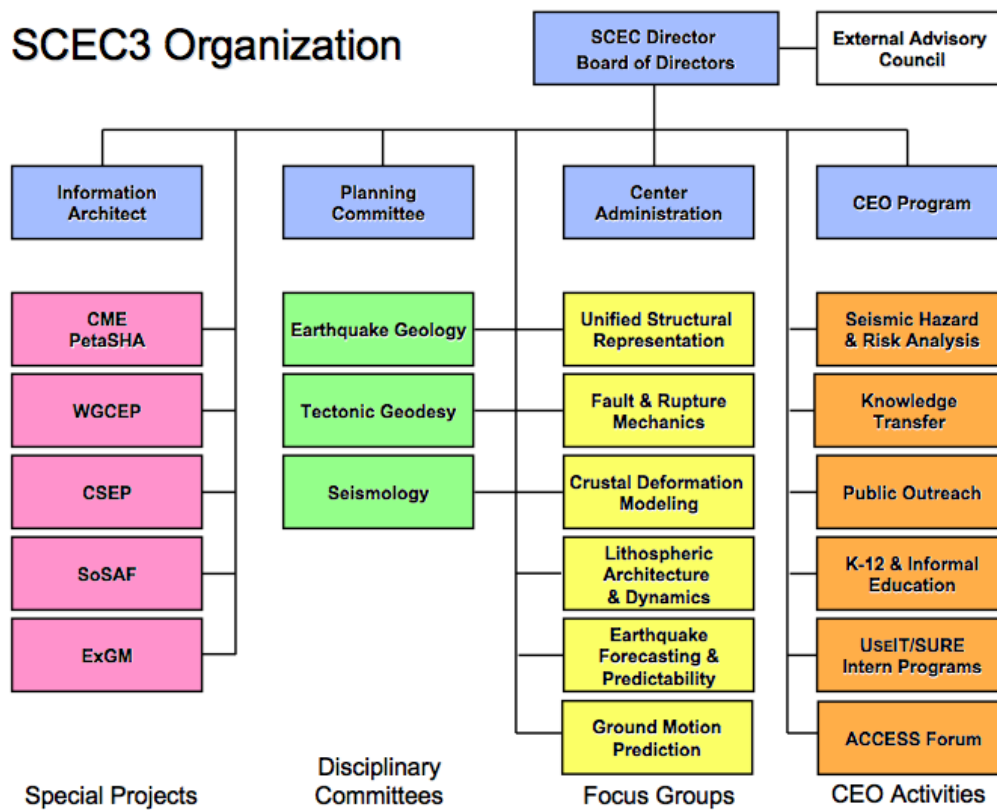


Figure 3. The SCEC3 organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects (pink), CEO activities (orange), management offices (blue), and the external advisory council (white).

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, Tectonic Geodesy, and Earthquake Geology (green boxes of Figure 3). They are responsible for disciplinary activities relevant to the SCEC Science Plan, and they make recommendations to the Planning Committee regarding the support of disciplinary research and infrastructure.

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

A sixth interdisciplinary focus group on Seismic Hazard & Risk Analysis (SHRA) manages the “implementation interface” as part of SCEC Communication, Education & Outreach (CEO) program (orange box). In particular, SHRA coordinates research partnerships with earthquake

engineering organizations in end-to-end simulation and other aspects of risk analysis and mitigation.

SCEC sponsors Technical Activity Groups (TAGs), which self-organize to develop and test critical methodologies for solving specific problems. TAGs have formed to verify the complex computer calculations needed for wave propagation and dynamic rupture problems, to assess the accuracy and resolving power of source inversions, and to develop geodetic transient detectors and earthquake simulators. TAGs share a *modus operandi*: the posing of well-defined “standard problems”, solution of these problems by different researchers using alternative algorithms or codes, a common cyberspace for comparing solutions, and meetings to discuss discrepancies and potential improvements.

Table 3. SCEC3 Working Group Leadership

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

* *Planning Committee members*

Planning Committee. The SCEC Planning Committee (PC) is chaired by the SCEC Deputy Director, Greg Beroza, and comprises the leaders of the SCEC science working groups—

disciplinary committees, focus groups, and special project groups—who together with their co-leaders guide SCEC’s research program (Table 3).

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

Center Budget and Project Funding

In 2010, SCEC received \$3.0M from NSF and \$1.1M from the USGS under its five-year cooperative agreements with these two agencies. Supplementing the \$4.1M in base funding was \$240K from the USGS Multi-Hazards Demonstration Project for SoSAFE and \$80K from Pacific Gas & Electric Company for the rupture dynamics project. Other funds available for core projects included \$20K from the Keck CSEP grant, \$200K from the geodesy royalty funds, \$58K from the UCERF3 project, and \$80K rolled over from the 2009-2010 Director’s. Therefore, SCEC core funding for 2010 totaled \$4,778K.

The base budget approved by the Board of Directors for this year allocated \$3,514K for science activities managed by the SCEC Planning Committee; \$463K (including \$25K for intern programs) for communication, education, and outreach activities, managed by the CEO Associate Director, Mark Benthien; \$170K for information technology, managed by Associate Director for Information Technology, Phil Maechling; \$301K for administration and \$200K for meetings, managed by the Associate Director for Administration, John McRaney; and \$130K for the Director’s reserve account.

Structuring of the SCEC program for 2010 began with the working-group discussions at our last Annual Meeting in September, 2009. An RFP was issued in October, 2009, and 171 proposals (including collaborative proposals) requesting a total of \$5,276K were submitted in November, 2009. 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 11-12, 2010, 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:

1. Scientific merit of the proposed research
2. Competence and performance of the investigators, especially in regard to past SCEC-sponsored research
3. Priority of the proposed project for short-term SCEC objectives as stated in the RFP
4. Promise of the proposed project for contributing to long-term SCEC goals as reflected in the SCEC3 science plan
5. Commitment of the P.I. and institution to the SCEC mission
6. Value of the proposed research relative to its cost
7. Ability to leverage the cost of the proposed research through other funding sources
8. Involvement of students and junior investigators

9. Involvement of women and underrepresented groups
10. Innovative or "risky" ideas that have a reasonable chance of leading to new insights or advances in earthquake physics and/or seismic hazard analysis.
11. 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 January 31-February 1, 2010. The Board voted unanimously to accept the PC's recommendations. After minor adjustments and a review of the proposed program by the NSF and USGS, I as Center Director approved the final program in March, 2010.

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.

Immediately following the 2009 SCEC Annual Meeting, a major review meeting was held of the SCEC CEO program. An extensive evaluation document was prepared in summer 2009 by evaluation consultants, which an external review panel used as the basis of its analysis. The review panel's report was quite thorough and provided several excellent recommendations. Overall, their analysis was that the SCEC CEO program is excellent and should be an example to all similar programs. The review was very important to the SCEC4 proposal process and was supported with funding from the NSF.

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

A major focus of the ECA and the SCEC/CEO programs during the past year has been the expansion of the Great California ShakeOut, which was held in mid-October, 2009, with over 6.9 million participants statewide. ShakeOut is now an annual event and recruitment for the 2010 drill is on track to exceed the participation in 2009. The ShakeOut is also expanding to other regions. New Zealand's Great West Coast ShakeOut was the first test of the concept in another area, held the day after the 2009 SCEC Annual Meeting. The British Columbia ShakeOut on January 26, 2011, will be the next non-California drill, along with a local drill in Oregon (Washington may join in 2012 as part of a Cascadia ShakeOut). In April, 2011, the Great Central US ShakeOut will be held as part of the lead up to the New Madrid Bicentennial. And in 2012, Utah and possibly New Zealand (nationwide) will launch ShakeOut drills. ShakeOut has really changed the way people and organizations are approaching the problems of earthquake preparedness. The SCEC staff, led by Mark Benthien, really put a huge effort into supporting

ShakeOut, and the Annual Meeting will be an appropriate time to thank them for contributing to its success.

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

SCEC CEO staff continues to work with museums and other informal education venues to develop content and programs for earthquake education and to distribute SCEC resources, such as the extensive set of publications that has grown out of *Putting Down Roots in Earthquake Country*. In 2008, SCEC organized a group of museums and other locations interested in earthquake education into a network of *Earthquake Education and Public Information Centers* (Earthquake EPIcenters), which has since been expanded to over 50 venues distributed throughout California. The EPIcenters are essential partners in the ShakeOut, as many hold public events on drill day, and help promote participation.

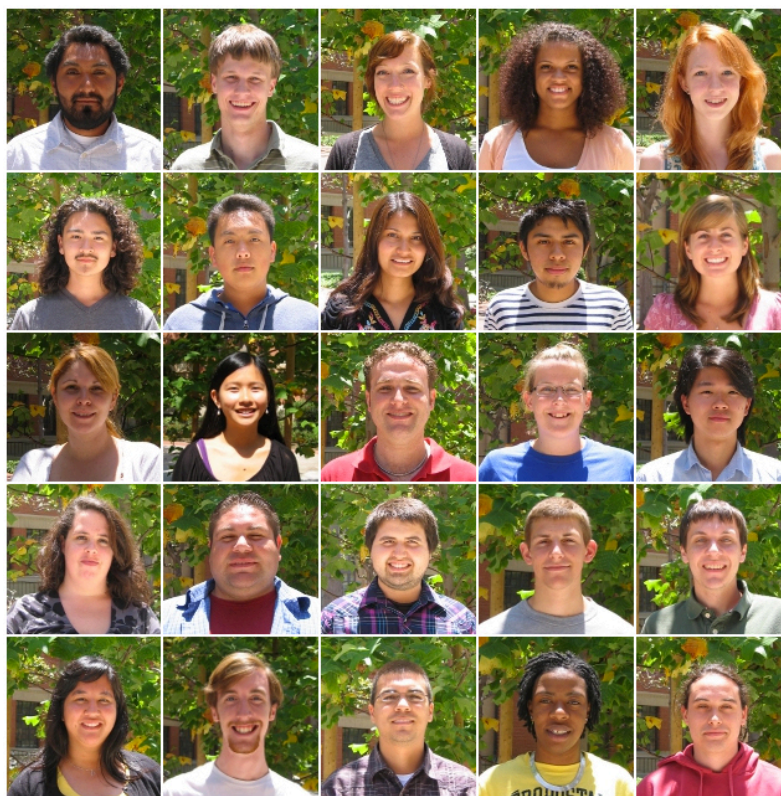


Figure 4. This “Brady Bunch” picture shows the students from around the country who participated in the 2010 UseIT summer program at USC. At the center is Michael Ihrig, an ACCESS-U intern and alumnus of UseIT, who helped to supervise the UseIT activities. Many will be attending the Annual Meeting to present posters, demos, and animations.

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). SCEC Education Programs Manager Bob de Groot leads these efforts. In 2010 SCEC is collaborating with IRIS and EarthScope in developing the content for the San Andreas fault Active Earth Kiosk, building on a workshop SCEC co-organized in 2009. Also in 2010, Arizona State University, the OpenTopography Facility, and SCEC developed three earth science education products to inform students and other audiences about LiDAR and its application to active tectonics research.

Bob de Groot is also skillfully leading SCEC's Office for Experiential Learning and Career Development. His office manages three SCEC intern programs: Summer Undergraduate Research Experiences (SURE, 189 interns since 1994), Undergraduate Studies in Earthquake Information Technology (USEIT, 148 interns since 2002), and Advancement of Cyberinfrastructure Careers through Earthquake System Science (ACCESS, 31 since 2007). The ELCA office promotes diversity in the scientific workforce and the professional development of early-career scientists (Figure 4). As someone very involved in these intern programs, I really enjoy seeing the students grapple with the tough but engaging problems of cutting-edge earthquake science. For example, the "grand challenge" for this year's USEIT program was to *develop a Seismic Crisis Visualization System based on SCEC-VDO that can display information needed for operational earthquake forecasting*. Many of the summer interns will be presenting their work at this meeting, and I hope you'll have the opportunity to check out their posters and demos.

A Word of Thanks

As SCEC Director, I want to express my deep appreciation to all of you for your attendance at the Annual Meeting and your sustained commitment to the collaboration. Greg Beroza and the PC for have developed a brilliant program, so the entire meeting should be a pleasant experience for us all. I'd especially like to thank Tran Huynh, the SCEC Special Projects and Events Coordinator, and her associates for their hard work and exceptional skill in organizing this meeting and arranging its many moving parts. Please do not hesitate to contact me, Greg, Tran, or other members of the SCEC team if you have questions or comments about our meeting activities and future plans. Now please enjoy Palm Springs and its surrounding tectonic environment!

VI. 2010 Advisory Council Report

Report of the Advisory Council Southern California Earthquake Center September 2010 Annual Meeting

Advisory Council Membership*:

Mary Lou Zoback, Chair, Risk Management Solutions RMS

Gail Atkinson, University of Western Ontario

Roger Bilham, University of Colorado

John Filson, USGS (Emeritus)

Jeffrey T. Freymueller, University of Alaska

Jim Goltz, CA Emergency Management Agency

Anne Meltzer, Lehigh University

Dennis Mileti, University of Colorado, Boulder (Emeritus)

Steve Mahin, Pacific Earthquake Engineering Research Center (PEER)

Farzad Naeim, John A. Martin & Associates

John Vidale, University of Washington

Andrew Whitaker, University of Buffalo

** Members highlighted in bold attended the 2010 Annual Meeting and contributed to this report. Gail Atkinson was unable to attend but did contribute to the report.*

Introduction

The Advisory Council of the Southern California Earthquake Center (SCEC) met during the 2010 SCEC Annual Meeting, held in Palm Springs, California, 12-15 September 2010. The principal meeting of the Advisory Council (AC) was during the afternoon and early evening of 14 September; an earlier session was held prior to the start of the Annual Meeting on 12 September to outline areas of focus. The incoming Council chair, Jeff Freymueller, summarized the principal Council findings and recommendations in an oral report delivered during the closing session of the Annual Meeting on the morning of 15 September.

Prior to the Annual Meeting on 10 September the SCEC Director circulated to the Advisory Council a confidential 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:

- Evaluation of the Communication, Education, and Outreach (CEO) Program
- Input on Collaboratory for the Study of Earthquake Predictability (CSEP) and operational earthquake forecasting
- Advice on initiatives in earthquake simulation and ground motion prediction and interface with the earthquake engineering community
- Documenting SCEC earthquake system science accomplishments in an integrated report
- Advisory Council structure/representation
- Input and reaction to the SCEC4 proposal
- Advice on leadership development and succession planning within SCEC
- SCEC's role in international collaborations

After some general introductory remarks, we provide input on these issues raised by the Director. We also comment on some topics raised by the AC--some are new and some are recurring:

- Increasing the visibility of workshops within SCEC and awareness of their outcomes
- Input on the effectiveness of annual meeting sessions for science planning
- Reflections on the size of the annual meeting

Finally, we note that in this year's AC report we include some recommendations for the USGS in areas where their programmatic interests strongly overlap with those of SCEC.

Some General Impressions

Congratulations are in order on multiple fronts. Foremost, at the 2010 meeting we celebrated SCEC's 20th anniversary and were thrilled to learn that both the USGS and NSF have agreed to fund SCEC4. We applaud the herculean scientific planning and proposal writing effort produced an on time submittal despite the occurrence of the M7 Haiti earthquake in January and the M9.2 Chile earthquake just days before the deadline. By all accounts the June site visit to SCEC by both USGS and NSR review panels was extremely well organized and succeeded in portraying the many facets of SCEC and hence was critical in assuring the continued funding.

We also applaud the SCEC CEO's initiative in building a statewide coalition of regional earthquake alliances that helped plan and promote an all-California ShakeOut drill in October 2010 which engaged more than 7.9 million state residents. In addition, the Earthquake Country Alliance, under Mark Benthien's able leadership, is actively exporting the ShakeOut exercise to both other regions of the U. S. and to at least one international site, New Zealand. We view the ShakeOut exercise as a unique scientific leadership and effective outreach outcome that was only possible as a result of the shared vision, the stature, strong participatory spirit, and integrative organization of SCEC as a dedicated science center.

We also want to strongly commend the outstanding, on-going commitment to involving undergrads in SCEC research through intern programs under the leadership of Bob de Groot. The enthusiasm, breadth and diversity of the outstanding undergrads getting an opportunity to participate directly in earth science research are inspiring. The entire SCEC community benefits from energy and stimulation these students bring to the Annual Meeting through their participation and presentation posters on their work.

All these CEO efforts were all highlighted in a very positive review of the effectiveness of the CEO program conducted by an independent review panel in the fall of 2009. The review panel's report was included in the SCEC4 proposal.

Since members of the Advisory Council are not 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 2010 meeting and associated workshops proved again to be impressive demonstrations of the energy and enthusiasm of the SCEC community. The 160 registrants who were attending their first SCEC Annual Meeting (nearly 30% of the 545 total registrants), including many students and interns, provided heartening evidence of the center's growing participation and its compelling mission.

The Advisory Council also lauds the entire SCEC membership for its persistently selfless community spirit which enables considerable progress in developing communal, system-level models and representations that are advancing the goals of both fundamental and applied earthquake system science. In particular, we would like to recognize Deputy Director Greg

Beroza's superb leadership of the science collaboration process. Beroza's kickoff keynote on SCEC scientific accomplishment did a superb job of highlighting breakthrough science and the progress made towards SCEC3 goals.

Finally, the Advisory Council would like to particularly acknowledge Tom Jordan's exemplary leadership of SCEC over the past 10 years. Tom arrived in 2000 and brought an infusion of energy and creative ideas to SCEC as it went into its SCEC2 planning process. Under his direction the SCEC2 proposal was funded and numerous new research directions were launched. Tom's vision and ability to cultivate and seize funding opportunities outside of the core support has brought new perspectives, expertise and tools to address earthquake system science. Under Tom's initiative and leadership, SCEC now leads the earthquake science community in active engagement of the high performance computing community. The California Earthquake Authority was so impressed with the joint SCEC-USGS-CGS' UCERF2 uniform statewide assessment of earthquake likelihood analysis that they have funded a UCERF3 proposal to address a number of key issues and uncertainties leading to an improved assessment.

As Tom is always the first to admit, the outstanding staff support provided by John McRaney, SCEC's Associate Director of Administration and Tran Huynh, Special Project Manager, are vital to the success of SCEC. John and Tran keep SCEC running smoothly and money flowing to researchers in a timely fashion, and they make sure workshops are easy to organize and run flawlessly. We especially thank them for providing all manner of cheerful and indefatigable assistance while managing all the details involved in carrying out another highly successful Annual Meeting.

Evaluation of the Communication, Education and Outreach (CEO) Program

The Advisory Committee makes a number of recommendations regarding the CEO program:

1. Carry out a “forward-looking” Phase II CEO Review
2. Develop SCEC4 CEO Program targets and create metrics to track program progress toward targets
3. Expand oversight of and input to the SCEC CEO program
4. Deepen the CEO’s relationship with FEMA.
5. Institute risk communication training for SCEC members likely to speak with the media
6. Bring the latest social science research on risk communication to operational earthquake forecasting and the Collaboratory for the Science of Earthquake Prediction (CSEP) activities

Each of the six recommendations is discussed in more detail below.

Carry out a “forward-looking” Phase II CEO Review

The Advisory Council continues to call for a “forward-looking “ Phase II review of the SCEC CEO Program (as opposed to the retrospective review carried out in the Fall of 2009). We recommend the review panel be comprised of a broad range of disciplinary experts, e.g. marketing and/or advertising, psychology, risk communication, and more. The purpose of the review would be to detect and explore potential new ideas for the SCEC4 CEO workplan, activities and directions. This review might best occur if it were phased as follows: (1) add a new disciplinary member to the Advisory Council as described in a later section, (2) involve new and existing Advisory Council members in planning the review, and (3) conduct the review in a meeting format and compile its results. The critical time issue is that the Phase II review happens in time to have the maximum impact on all of SCEC4 CEO activities.

Develop SCEC4 CEO program targets and create metrics to track program progress toward targets

The Advisory Committee recommends that the CEO program develop a comprehensive list of SCEC4 targets—those that are “social process orientated” as well as those with more readily quantified targets. The targets should first be generated and then metrics should be developed to measure progress toward them. This could be done by SCEC CEO staff with input from external outreach experts (including social scientists, practitioners, and education experts). It would ideally be informed by the forward-looking review recommended above.

Examples of such targets include:

- Prepare and Distribute a “Baseline Public Preparedness Summary”. The State of California funded a recently completed scientifically-based study to measure the state of adoption by households of 40+ SCEC CEO-recommended preparedness and mitigation actions for earthquakes. Data was gathered on three California populations: (1) high risk southern California counties, (2) high risk northern California counties, and (3) the rest of the state. This study was intended to provide a baseline against which the impact of the 2008 Shake Out and others could be assessed. SCEC CEO should synthesize, distribute, and use this baseline against which to evaluate past, present and future Shake Out and other public information dissemination activities. The distribution of these baseline data could be used to motivate others to provide or procure funds to replicate the study to determine the impacts of subsequent efforts to motivate household preparedness and mitigation action-taking.
- Prepare, Distribute and Use a “Motivating Public Preparedness Metric”. A definitive study of what factors motivate public preparedness and mitigation has recently been funded by the Department of Homeland Security. It produced clear, certain, and replicated scientific conclusions for all hazards on the entire population of the U.S., high risk cities, and the nation’s major racial and ethnic minority groups. This study’s findings about “what works” and “what does not work” to motivate public preparedness and mitigation should be clearly synthesized into a metric. This metric(s) should be disseminated, and used to inform choices about future SCEC outreach activities.

Many other SCEC CEO public information and education targets should be catalogued and metrics developed to track progress toward them. Among these is clarification regarding the program’s mission in southern California versus in other regions.

Expand oversight of and input to the SCEC CEO Program

The Advisory Council recommends that SCEC incorporate a broader range of disciplines to better evaluate SCEC CEO activities and potentially to provide input more frequently. Specific recommendations are:

- Expand Disciplinary Membership by adding an additional Advisory Council member, to represent other CEO-relevant disciplines beyond those of the disciplines of sociology and emergency management currently on the AC. SCEC might also consider an advisory committee specifically for CEO activities, involving, but not exclusive to, AC members. Suggested additional disciplines include:
 - advertising and/or marketing

- the psychology of risk communication
- public science education
- Expand CEO Oversight Structure whereby an increased number and more diverse set of outreach and education experts can offer advice and oversight to the SCEC CEO Program more than once a year as is now the case. This could possibly be done through a dedicated subcommittee reporting to the AC.

Deepen the CEO Program's Relationship with FEMA

The Advisory Council notes that SCEC's CEO Program is likely the most successful CEO Program in the nation, and perhaps the world. We are proud of the progress that its Director has made in the last year to increase funding for CEO activities from groups such as FEMA. But we recommend that a more aggressive set of activities be put in place to cultivate SCEC CEO relationships with FEMA. There are a number of possible projects that might be appropriate to pursue with FEMA. However, the following ShakeOut related projects are "prime candidates" and should be pursued first.

- Leverage the SCEC ShakeOut with FEMA as a Best Practice. The ShakeOut model is now being emulated by other places, states, nations, and other hazards (the Great Hurricane Blowout is being run for hurricane awareness, see <http://www.greathurricaneblowout.org>). A long-standing practice in FEMA is to identify "a national best practice" and then export it. This is already underway at FEMA but could be upgraded. First, SCEC CEO should seek FEMA funding for an individual to distinguish and write-up the ShakeOut's design parameters and implementation procedures to enhance its export by FEMA to other entities (e.g., produce a briefing book to spread the ShakeOut approach as a FEMA "best practice"). This project should be pursued with the endorsement and cooperation of the USGS and Cal-EMA.
- Rigorously evaluate the effectiveness of the ShakeOut program. SCEC CEO should s FEMA to evaluate the effectiveness of the ShakeOut program to determine what about it works best and what does not. This would be easy to accomplish because of the baseline data described above. Such an evaluation would enable the Shake Out to adjust its approach, if needed, and fine-tune details about its export to other places so that its effectiveness is maximized.

Institute risk communication training for SCEC members likely to speak with the media

The Advisory Council continues to recommend that risk communication training be sought and delivered to SCEC members likely to talk about earthquakes or earthquake hazard in southern California on the radio, in front of a television camera, or on other public media. It would be appropriate to involve new Advisory Council or subcommittee member(s) in the discipline of risk communication to help organize this training. Different levels and types of training are likely appropriate for different types and levels of SCEC participants.

Bring latest social science research on risk communication to operational earthquake forecasting and the Collaboratory for the Science of Earthquake Prediction (CSEP) activities

Two areas of knowledge in the social sciences can inform CSEP and operational earthquake forecasting activities. The Advisory Council recommends an active two-part role for CEO in helping craft operational earthquake forecasting communication for both SCEC and the USGS:

- Transfer of existing knowledge and stimulating new research. There is a rich research literature in the social and behavioral sciences regarding risk communication (including changed probabilities and public warning statements) conducted primarily in this nation, but also internationally. The topics covered include:
 - public warning information system design to assure that rarely used systems are highly reliable
 - public messaging and the importance of the words that are made public to maximize societal benefits and minimize societal disruptions
 - the best methods to accomplish public education activities to upgrade what the public know about such topics

The CEO should explore formats to isolate applicable knowledge from this research and to clarify new formal social science research needed to support the emergence of operational earthquake forecasting (OEF) practices. Possible formats include:

- request that either NEHRP or the USGS fund an NRC/NAS Committee to review the relevant literature and make recommendations on needed research (e.g., a study similar to the NRC effort evaluating the National Tsunami Warning Program, report released September 27, 2010).
- Alternatively, a group of social science experts on these topics could be assembled for a workshop.

The range of research topics that might emerge are likely to be varied including message testing in psychological laboratories, the role of social media in influencing what people hear, think, and do, and many more.

- Take advantage of cutting edge research in peripheral fields. Public risk communication is in a state of rapid change related to the advent of Web 2.0 and rapidly expanding use of social media (e.g., people are warning themselves and their friends). The role of social media in the domain of risk communication is one of the hottest research topics in risk communication today, well-funded by the Department of Homeland Security. SCEC and the USGS would do well to reach out to researchers in this field to be informed by new discoveries applicable to CSEP/OEF. A key research center is the START Center of Research Excellence at the University of Maryland at College Park. There is no reason to duplicate this research, but there is strong reason to know what their research is revealing.

Input on the Collaboratory for the Study of Earthquake Predictability (CSEP) and Operational Earthquake Forecasting

We applaud SCEC for its continued progress in developing CSEP and in promoting test centers in other countries--special congratulations are due for establishing a CSEP test center in China. CSEP uniquely fulfills the role of open, scientifically rigorous and consistent evaluation of earthquake prediction methodologies.

Despite its successes, the enterprise is currently at risk, as the Keck seed funding expired in 2010 and funding is scarce in the USGS, the natural home for the operational side of this effort.

The Advisory Council recommends the following actions to the SCEC leadership:

1. The AC strongly endorses the continuation of the CSEP, as this program is a well-conceived, well-executed, and critical step toward quantifying the temporal variations in earthquake hazard. It is particularly critical as prediction methodologies are far from mature, and new evidence such as deformation and paleoseismology are continually expanding the measurements being monitored, and early warning systems and aftershock probabilities estimates are coming to fruition.
2. CSEP should continue to avoid monitoring responsibilities and focus only on evaluation of forecasts.
3. CSEP should evolve from its current development phase to one of sustained operations as a matter of economy. This may involve reducing or curtailing of investment of resources in international collaborations. Nevertheless, CSEP is to be strongly commended for having helped to launch a suite of international efforts with similar goals.

4. As the goals of CSEP are directly aligned with NEHRP statutory evaluation of hazard and public safety responsibilities, we strongly urge USGS take a leadership role within NEHRP in securing funding to sustain CSEP operations.
5. CSEP should be the scientific element of an end-to-end operational earthquake forecasting system that is informed by risk communication science (see specific recommendations in the CEO section). CSEP should work with USGS and state agencies to implement an OEF plan.

Advice on initiatives in earthquake simulation and ground motion prediction and building collaboration with the earthquake engineering community

The Advisory Council commends SCEC for its continued progress in broadband and large-scale ground motion simulations. Significant progress has been made in confirmation of these simulations through comparison with recorded data and through assessments of the consistency and accuracy of results from various investigators.

The scientific foundations and methods used in this work are solid and the potential applications, as a supplement to recorded data, are significant. With regard to the science, the Advisory Council notes that studies of recent earthquakes in Haiti, Chile, and northwestern Mexico (Sierra El Mayor) discovered unexpected complexities of the earthquake source. Such complexities may be necessary to take into account in ground motion simulations and the study of the variability in these simulations.

The utilization of ground motion simulations within engineering practice remains a challenge. Despite the wide range of scenarios for which simulations can be computed, far exceeding the number of events with recorded data, their acceptance by the engineering community has remained muted. Without general acceptance by the engineering profession, the ground motion simulation projects of SCEC will remain an exercise of great interest to some but will not realize their full potential. The reservations of the engineering profession regarding simulated ground motions may have several causes, including:

- The difficulty in assuring practitioners of the consistency of the simulations with existing recordings of strong motions.
- The difficulty in capturing the sensitivity of simulations to the range of unpredictable parameters, i.e., quantifying the uncertainty in a useful way.
- Lack of knowledge of the scientific underpinnings of the simulation methods.
- Lack of awareness of recent advances in simulation studies.

- Lack of general availability of “user-friendly” access and well-documented sets of simulations that are readily useable by the research engineering community in comparative studies of the applicability of such simulations relative to “real” recordings.

The needed level of engineering acceptance would be accelerated by proactive outreach, indeed a campaign, by SCEC to engage the engineering community to address these issues.

The Advisory Council recommends the following actions to the SCEC leadership:

1. Create a technical activity group (TAG) specifically charged to engage the engineering community. This group should be comprised of ground motion model developers and earthquake engineers. The TAG should convene, early on, a topical workshop on engineering needs, the status of ground motion simulation, and means to establish a sustained and energetic dialog between the scientific and engineering interest in this topic. One promising mechanism for this dialog of might be for SCEC to participate in the Ground Motion Selection and Modification group at PEER.
2. Investigate methods of delivering and promoting simulations to the engineering community by making them more comprehensive and accessible. As an example, a recent PEER initiative provides a web tool by which engineers can search and/or scale a database of time histories to match given target scenarios and conditions. Perhaps a similar database could be compiled (and accessed through the same or similar tool) for simulated time histories; this would make it apparent how these simulations “fleshed out” the recorded time histories, and also enable comparisons. It would also provide a good vehicle for collaboration with PEER.
3. Motivate and facilitate active participation of members of the engineering community in the Advisory Council. A meeting of the Advisory Council at a different time from the Annual Meeting to discuss means of building rapport with the engineering community may be necessary.
4. Actively seek to involve young engineering students in SCEC’s student intern programs to build more integration into the next generation of engineers.

Documenting SCEC earthquake system science and outreach accomplishments in an integrated report

The Advisory Council was asked to consider how the SCEC story might be told, and how its findings might be integrated in an appropriate publication.

The two decades of SCECs unique existence have resulted in a sequence of findings that many perceive justifies an equally unique report. This report will be eagerly awaited by not only by the SCEC community and by funding bodies, but also by the international science community. The success or otherwise of SCEC's systems approach to science and embedded

outreach justifies a full account - what worked, what didn't, and where would earthquake science be without SCEC.

The committee discussed conventional journal reporting versus a monograph, or possibly a book. The anticipated scope was considered inappropriate and too wide ranging for most journals, with the possible exception of Reviews of Geophysics, but a length limitation in that journal would restrict a full treatment of the motivation behind, and the successes ensuing from SCEC's unusual interdisciplinary collaboration and its system-level approach to earthquake science.

The Advisory Committee recommends:

1. SCEC consider a full length monograph, *e.g.* AGU's Geodynamic series, or a dedicated book as the best setting for telling the integrated story of SCEC - from conception, to evolution, to results. Such a comprehensive report would be a formidable undertaking for SCEC leadership, but it should be possible to lessen the burden through shared authorship and dedicated editing.

Advisory Council

In past years, the Advisory Council has done essentially all its business at the SCEC Annual Meeting. As SCEC has grown, this model has been increasingly strained. Given the time constraints at the meeting, it is difficult for the AC to do more than discuss items brought to it by the SCEC leadership, plus a few of the most pressing issues that may be raised or observed at the meeting. Probably we could do a bit more if we received some materials farther in advance of the meeting, but this would only reduce rather than eliminate the time crunch. It may be time to augment the AC meeting at the Annual Meeting with a shorter, focused meeting at USC during a less hectic period. Ideally, this would also mean a lighter workload for the AC at the Annual Meeting.

There has been a pattern of irregular AC attendance in certain disciplines (for example, engineering). Holding a ~1-day meeting at USC in addition to the Annual Meeting might help reduce this problem, especially if the time of the meeting was flexible. Other suggestions outlined earlier in this report may also help as well. The suggested Technical Activity Group on ground motion simulations and their use may also provide an additional hook to draw further participation from the engineering community. Providing progress reports and soliciting specific advice from the AC on this endeavor may be an effective way to increase participation (if not, you may need to choose different people from the engineering community).

As mentioned before, the SCEC AC could use additional expertise on CEO matters. Adding several CEO-focused members would result in a lack of balance in the AC, but adding one more would be a positive step. Through the forward-looking CEO evaluation that we have recommended, SCEC has an opportunity to engage experts in a broader range of disciplines and these people could be asked to provide advice on an ongoing basis to SCEC (directly or through the AC) on specific CEO-related topics.

Input and reaction to the SCEC4 Proposal

We thank SCEC for the copy of the SCEC4 proposal, and we congratulate SCEC on another success! Time has not yet allowed us to make serious comments about the final submitted proposal, which we received in the packet for the Annual Meeting. In any case, it may be more important for SCEC to get our input to the proposal once the peer and panel reviews have been received. We recommend that SCEC ask for further input in the spring once these reviews have been received.

Most likely, SCEC will have to make some difficult choices in its prioritization of activities under SCEC4, given that the funding level will be lower than requested. In 2008 the Advisory Council was told that the SCEC Planning Committee would be tracking progress toward the achievement of the 19 SCEC3 research objectives. We have yet to receive the results of this tracking or a report on the status of progress on the various SCEC3 goals. We suggest again that such a report be generated, not as a bean-counting exercise but as a helpful self-assessment of SCEC3 successes (and remaining challenges) that will aid in the prioritization of SCEC4 research priorities. To some extent this self-assessment was done in the SCEC4 planning process. We recommend:

1. An annual report tracking progress toward the achievement of the SCEC4 research objectives, even if only for internal use.

Advice on Leadership Development and Succession Planning within SCEC

The AC was delighted that Tom Jordan committed to continue to lead SCEC through the SCEC4 proposal process. However, with Tom Jordan's stated desire to step down from the directorship, the challenges of attracting a new director remain. The AC strongly recommends that a plan be defined as soon as possible for recruiting a new director with a specific time table. The plan should also include strategies for cultivating a pool of potential candidates such as engaging them in SCEC by inviting potential candidates to serve on the Advisory Council, or by inviting them to attend SCEC meetings and workshops. It will also be important to consider alternate leadership structures for the future as an element of this succession planning. For example, the leadership should consider the possibility that there could be separate directors of special projects that are not funded through the core science budget. This kind of thinking might be important both to the future growth of SCEC and to attracting a new director with management strengths different from the current director.

Defining SCEC's role in international collaborations

The Advisory Council was asked to consider when it might be appropriate for SCEC to expand its research activities beyond the confines of California.

The AC recommends that SCEC should clearly focus its international efforts on partnerships that support its core science mission. Although it is tempting to export SCEC findings to address similar tectonic settings elsewhere in the world, SCEC's motivation in such involvement should lie in identifying opportunities that are perceived to complement or advance ongoing SCEC research tasks. Examples include:

- Fault networks in Southern California that extend beyond the US national border. One cannot conceive of studying the fault systems of southern California in isolation. Ties and collaborative projects with Mexican scientists should be pursued with vigor especially in the aftermath of the El Mayor-Cucapah earthquake. Methods to exchange seismic and fault slip data transparently and in a timely fashion are recognized as especially important.
- Partnerships with other organizations working on operational earthquake forecasting are clearly beneficial to SCEC. In this case the societal complexities of “uncertain information” communication have common ground in numerous countries.
- One can envisage that future opportunities may arise to study scientific problems that SCEC cannot solve locally – in these instances international partnerships would be of benefit. An example might be the availability of deep boreholes elsewhere in the world that might illuminate the physics of hypocentral processes, or the physics of fault slip.
- SCEC provides an unusual but exemplary template for innovative coordinated science that might benefit other regions. SCEC may thus have an international role in showcasing its methodology to a worldwide scientific community.
- SCEC may have an important advisory role in guiding international efforts at the design stage (e.g., acquisition of new forms of remotely sensed data suited to the study of earthquake processes).

Increasing the visibility of workshops within SCEC and awareness of their outcomes

SCEC fills a tremendous need of the community by facilitating easy-to-convene topical workshops in a short time frame. The Advisory Council has noted that while many SCEC members are aware of recent workshops in a related area, in general they are not very aware of the workshop outcomes if they did not personally attend. These workshops are a tremendous resource for the entire community, and the benefit will be enhanced if the outcomes are better publicized.

Expanding on the AC focus on this issue for the past two years, we recommend:

1. Continue SCEC-wide promotion of workshop opportunities (this part of the process seems to be working well)
2. Provide brief oral summaries of outcomes of the pre-annual meeting workshops as part of each Annual Meeting program
3. Provide a tab on the SCEC website to provide easy access to information upcoming as well as past workshops.



4. Require all SCEC workshop conveners to submit a brief summary of workshop outcomes for posting online within 45 days of the workshop. An email notification to the SCEC community to alert them to the posting with a link to the summary would enhance the impact of the workshop discussions on the broader SCEC community.

Input on the effectiveness of science planning at annual meeting sessions

The SCEC annual meeting exists as a forum for presenting cutting edge scientific results and for planning future year's activities. The advisory committee was asked to comment on the success of the meeting format for addressing those two goals.

During the 2010 meeting a number of the plenary sessions were organized to focus on emerging new results and potential future science directions. The keynote presentations in these discussion sessions were uniformly interesting and informative. There was, however, more variability in the 1.5 hour science planning discussion sessions that followed.

The discussions that were most successful were those that placed the scientific presentation and issues raised in it directly in the context of a SCEC planning process. The most effective of these discussions were those that followed a template of prearranged questions designed to seed and stimulate audience participation. Plenary sessions that were aimed at general science topics rather than focused SCEC collaboration goals, though interesting, were perceived to be less successful.

Size of the annual meeting

The SCEC meeting is very popular, and continues to grow in size each year. On the positive side, this reflects the steady growth in interest in SCEC and SCEC activities. On the negative

side, the meeting is already much larger than a “small meeting”, and if the meeting grows too much larger it may be difficult to manage. Yet any attempt to limit the size of the meeting would require difficult and awkward choices.

When thinking about the size and scope of the annual meeting the most critical question to keep in mind is whether this meeting continues to meet the focused needs of the SCEC collaboration. In our assessment, it still does even at the present size, although science planning sessions are difficult with such a large group. That was not a serious problem this year, but because the next meeting or two will focus on SCEC4 plans and priorities it will be important to ensure that there is still an effective forum for participating SCEC scientists to provide input and feedback on the collaboration science plans and priorities. Otherwise, the general participants could begin to feel that these are set behind closed doors rather than in an open process.

Final Comments

It is the current sense of the Advisory Council that the researchers and, particularly, the senior leadership of SCEC are doing an outstanding job. The many individuals now leading committees and focus groups constitute a broadly diverse, extremely able, and committed group. The Advisory Council applauds SCEC's continued role in catalyzing and supporting special projects such as UCERF3, high performance computing, and CSEP. Developing new 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 SCEC funders as well as the seismological community, including individuals and groups both inside and outside SCEC membership, on how best to provide that assistance.

The Advisory Council welcomes new members Roger Bilham, University of Colorado; Meghan Miller, UNAVCO; Farzad Naeim, John A. Martin & Associates; John Vidale, University of Washington; Andrew Whitaker, University of Buffalo. We regretfully say goodbye to Patti Guatteri, Swiss Re; John Rudnicki, Northwestern University; and Lloyd Cluff, Pacific Gas and Electric. Patti and John in particular have been very active members of AC for a number of years and we will miss their input and perspective. We all look forward to working with SCEC leadership in helping successfully launching SCEC4 and in helping ensure that the products and accomplishments of the center are well-documented and widely disseminated.

Finally, on a personal note, as of this meeting Mary Lou Zoback is stepping down from the AC and as the chair. This transition is bittersweet; I am balancing the value of rotational leadership with the opportunity to be part of the exciting scientific dialog that is the SCEC collaboration. It has been an honor and a privilege to serve SCEC in this capacity. I depart the AC knowing I leave it in the very able hands of Jeff Freymueller.

VII. Financial Report

Table VII.1 gives the breakdown of the SCEC 2010 budget by major categories. The list of individual projects supported by SCEC in 2010 was sent to the NSF and USGS program officers in the spring of 2010.

Table VII.1 2010 Budget Breakdown by Major Categories

Total Funding (NSF and USGS):	\$4,100,000
Management	301,000
CEO Program	437,500
Annual, AC, Board, and PC Meetings	200,000
Information Technology	170,000
Director's Reserve Fund	130,000
SCEC Summer Intern Program	25,000
Budgets for Disciplinary and Focus Group Activities: (including workshops)	\$ 2,836,500
SoSAFE Supplement (from USGS)	240,000
Geodesy Royalties	100,000
UCERF3	58,000
Pacific Gas and Electric	80,000

VIII. Report on Subawards and Monitoring

The process to determine funding for 2010 began with discussions at the SCEC annual meeting in Palm Springs in September, 2009. An RFP was issued in October, 2009 and 173 proposals (including collaborations) were submitted in November, 2009. Proposals were then sorted and sent out for review in late November, 2009. 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 Beroza) met on January 13-14, 2010 and spent 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 2010 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 1-2, 2010. 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 core funding for 2010 was \$4,100M. The board approved \$301K for administration; \$437.5K for the communications, education, and outreach program; \$200K for workshops and meetings; and \$170K for the information technology program. We also received \$25K from NSF for the summer undergraduate intern program and \$240K from the USGS for the SoSAFE project. \$100K was made available from the geodesy royalty fund and \$58K from CEA/UCERF3 funds. In addition, Pacific Gas and Electric donated \$80,000 to center funding.

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 2010 are shown in the table below for both the USGS and NSF components of SCEC funding.

Table VIII.1 SCEC Subcontracts for 2009

USGS Funds

Appalachian State University	\$40,000
Cal State, Long Beach	\$17,166
Cal State, Northridge	\$31,000
Cal State, San Bernardino	\$17,000
California Institute of Technology	\$214,000
San Diego State University	\$85,000
SPA Risk	\$30,000
Stony Brook University	\$23,000
University of British Columbia	\$18,000
University of California, Davis	\$98,000
University of California, Irvine	\$88,928
University of Colorado	\$20,000
University of Nevada, Reno	\$88,000
University of Oregon	\$23,000
Utah State University	\$14,700
Total USGS	\$807,795

NSF Funds

Arizona	\$38,000
Arizona State	\$19,000
Berkeley Geochron Center	\$5,000
Brown	\$78,500
California Institute of Technology	\$25,000
California State University-Chico	\$7,000
Columbia	\$120,000
Cornell	\$10,000
Earthquake Consultants International	\$13,000
Georgia Tech	\$71,934
Harvard	\$209,000
Illinois	\$20,000
Indiana University	\$19,000
Massachusetts	\$20,000
MIT	\$43,000
New Hampshire	\$19,000
Princeton	\$57,000
San Diego State University	\$63,028
Stanford	\$209,688
Texas A&M	\$81,000
UCB	\$17,000
UCI	\$30,000
UCLA	\$168,998
UCR	\$203,800
UCSB	\$170,000
UCSC	\$82,000

UCSD	\$168,700
URS	\$39,000
UNR	\$28,300
Utah State	\$35,000
UTEP	\$10,000
WHOI	\$20,000
Wyoming	\$18,000
Total NSF	\$2,118,950

Report on 2010 SCEC Cost Sharing

The University of Southern California contributes substantial cost sharing for the administration of SCEC. In 2010, USC provided \$366,916 for SCEC administration and staff costs, waived \$713,000 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 2010

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

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

2. USC waives overhead on subcontracts. There are 46 subcontracts in 2010.

\$1,150,000	Amount Subject to Overhead
0.62	USC Overhead Rate
\$713,000	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
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\$1,343,277 2010 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	6	14	20	6	12
Black	0	0	1	0	4
Hispanic	1	2	0	0	0
White	31	102	113	21	42
Native American	1	2	0	0	4
No Information	67	69	101	153	25
Ethnicity					
Latino	6	5	5	14	21
Not Latino	45	120	116	48	46
No info/Withheld	55	62	114	118	20
Gender					
Female	34	39	49	67	41
Male	72	148	186	110	46
Withheld/No Info	0	0	0	3	0
Citizenship					
US	52	106	100	54	65
US Resident	2	16	15	5	8
Other	5	15	45	17	1
No Info/Withheld	47	50	75	104	13
Disability Status					
None	23	89	100	11	48
Hearing	0	1	1	0	0
Visual	2	0	2	0	0
Mobility	0	0	1	1	0
Other	0	1	0	0	0
No Info/Withheld	83	96	132	168	39

X. Report on International Contacts and Visits

- 1. SCEC Advisory Council.** We have one international member of our Advisory Council, Gail Atkinson of the University of Western Ontario.
- 2. ACES (APEC Cooperative for Earthquake Simulation).** SCEC and JPL are the U.S. organizations participating in ACES. Information on ACES can be found at <http://www.quakes.uq.edu.au/ACES/>. Andrea Donnellan of SCEC/JPL is the U.S. delegate to the ACES International Science Board and John McRaney of SCEC is the secretary general. The ACES group held a workshop in Japan in October, 2010. There will be a meeting of ACES representatives in Maui in May, 2011 to plan the next workshop to be held in Maui in 2012.
- 3. ETH/Zurich.** Stefan Wiemar, Jeremy Zechar and Martin Mai (also at KAUST) of ETH are participants in the SCEC/CSEP projects.
- 4. IGNS/New Zealand.** Mark Stirling and David Rhoades of the Institute for Geological and Nuclear Sciences of New Zealand are involved in the RELM/CSEP program.
- 5. University of Western Ontario/Canada.** Kristy Tiampo of the University of Western Ontario in London, Ontario is funded through the SCEC core program.
- 6. University of British Columbia/Canada.** Elizabeth Klein of UBC is funded through the SCEC core program.
- 7. SCEC Annual Meeting.** The SCEC annual meeting continues to attract international participants each year. There were participants in the 2010 annual meeting from Australia, China, Japan, India, Mexico, Canada, France, Switzerland, Germany, Russia, Italy, Taiwan, Turkey, and New Zealand.
- 8. International Participating Institutions.** ETH/Zurich, CICESE/Mexico, University of Western Ontario, University of British Columbia, and Institute for Geological and Nuclear Sciences/New Zealand; and 4 institutions from Taiwan (Academia Sinica; National Central University; National Chung Cheng University; National Taiwan University) are participating institutions in SCEC.
- 9. International Travel by PI and SCEC Scientists.** The PI and other SCEC scientists participated in many international meetings and workshops during the report year. They include: 1) UJNR Workshop in Japan in October, 2010, 2) the ACES workshop in Japan in October, 2010, 3) CSEP workshops in Japan and China in March and November, 2010, 4) the Hokudan Symposium in Japan in January, 2010 on the 15th anniversary of the Kobe Earthquake, 5) Global Earthquake Model (GEM) meetings in Zurich and Singapore, 6) meetings at ERI in Tokyo in March, 2010; 7) meetings at INGV/Rome on the l'Aquila earthquake in June and July, 2010, and 8) the AGU meeting of the Americas in Brazil in August, 2010.

XI. Publications

Note: Publication numbers listed here are continued from the SCEC list that was initiated in 1991. This list includes on research publications that had updates between October, 2009 and October, 2010.

- 1315 Rojas, O., E.M. Dunham, S.M. Day, L.A. Dalguer, and J.E. Castillo, Finite difference modeling of rupture propagation with strong velocity-weakening friction, *Geophysical Journal International*, 179, 1831-1858, 2009.
- 1316 Dalguer, L. A., and S. M. Day, Asymmetric rupture of large aspect-ratio faults at bimaterial interface in 3D, *Geophysical Research Letters*, 36, 2009.
- 1317 Pitarka, A., L.A. Dalguer, S.M. Day, P. Somerville, and K. Dan, Numerical study of ground motion differences between buried and surface-rupturing earthquakes, *Bulletin of the Seismological Society of America*, 99, 1521-1537, 2008.
- 1319 Daub, E. G., and J. M. Carlson, Stick-slip instabilities and shear strain localization in amorphous materials, *Physical Review E*, 80, 066113, 2009.
- 1320 Ganev, P.N., Dolan, J.F., Blisniuk, K., Oskin, M. and Owen, L.A., Paleoseismologic evidence for multiple Holocene earthquakes on the Calico fault: Implications for earthquake clustering in the Eastern California Shear Zone, *GSA Lithosphere*, J. Pelletier, in review, 2010.
- 1321 Li, Y.-G., P. E. Malin, and E. M. Cochran, High-Resolution Imaging of the San Andreas Fault Damage Zone from SAFOD Main-Hole and Surface Seismic Records, *PAGEOPH*, Brian Mitchell, Birkhäuser Basel Publication , Special Volume, submitted, 2009.
- 1322 Schmedes, J., R. J. Archuleta, and D. Lavallée, Correlation of Earthquake Source Parameters Inferred from Dynamic Rupture Simulations, *Journal Geophysical Research - Solid Earth*, accepted, 2009.
- 1323 Ma, Shuo, and D. J. Andrews, Inelastic Off-fault Response and Three-Dimensional Dynamics of Earthquake Rupture on a Strike-Slip Fault, *Journal of Geophysical Research, Solid Earth*, accepted, 2009.
- 1324 Kaneko, Y., and N. Lapusta, Supershear transition due to a free surface in 3-D simulations of spontaneous dynamic rupture on vertical strike-slip faults, *Tectonophysics*, published, 2010.
- 1325 Duan, B., and S. M. Day, Sensitivity Study of Physical Limits on Ground Motion at Yucca Mountain, *Bulletin of the Seismological Society of America*, in review, 2010.
- 1326 Gentili, S., M. Sganzi, L. Peruzza, and D. Schorlemmer, Probabilistic Completeness Assessment of the Past 30 Years of Seismic Monitoring in Northeastern Italy, *Bulletin of the Seismological Society of America*, submitted, 2010.
- 1327 Sleep, N. H., Nonlinear Behavior of Strong Surface Waves Trapped in Sedimentary Basins, *Bulletin of the Seismological Society of America*, 100, 2, 826-832, 2010.
- 1328 Hermundstad, A. M., E. G. Daub, and J. M. Carlson, Energetics of strain localization in a model of seismic slip, *Journal of Geophysical Research - Solid Earth*, Tom Parsons, in revision, 2009.
- 1331 Tanimoto, T., Equivalent forces for colliding ocean waves, *Geophysical Journal International*, Blackwell, accepted, 2010.

- 1332 Ohtani, R., J. J. McGuire, and P. Segall, The Network Strain Filter - A New Tool for Monitoring and Detecting Transient Deformation Signals in GPS Arrays, *Journal of Geophysical Research*, in revision, 2010.
- 1333 Wang, Q., D.D. Jackson, and J. Zhuang, Are spontaneous earthquakes stationary in California? , *Journal of Geophysical Research*, published, 2009.
- 1334 Wang, Q., F. Schoenberg, and D.D. Jackson, Standard errors of parameter estimates in the ETAS model, *Bulletin of the Seismological Society of America*, published, 2010.
- 1335 Barbot, S. and Y. Fialko, Fourier-Domain Green Function for an Elastic Semi-Infinite Solid under Gravity, with Applications to Earthquake and Volcano Deformation, *Geophysical Journal International*, in review, 2010.
- 1336 Barbot, S. and Y. Fialko, A Unified Continuum Representation of Postseismic Relaxation Mechanisms: Semi-Analytic Models of Afterslip, Poroelastic Rebound and Viscoelastic Flow, *Geophysical Journal International*, in review, 2010.
- 1337 Lozos, J.C., D.D. Oglesby, B. Duan, and S.G. Wesnousky, The Effects of Fault Bends on Rupture Propagation: A Geometrical Parameter Study, *Bulletin of the Seismological Society of America*, submitted, 2010.
- 1338 Kate Huihusan Chen, Roland Bürgmann, and Robert M. Nadeau, Triggering Effect of M 4-5 Earthquakes on the Earthquake Cycle of Repeating Events at Parkfield, California , *Bulletin of the Seismological Society of America*, Stefan Wiemer, 100, accepted, 2010.
- 1339 Sleep, N. H., Sudden and gradual compaction of shallow brittle porous rocks, *Journal of Geophysical Research - Solid Earth*, accepted, 2010.
- 1340 Zechar, J. D., M. C. Gerstenberger, D. A. Rhoades, Likelihood-based Tests for Evaluating Space-Rate-Magnitude Earthquake Forecasts, *Bulletin of the Seismological Society of America*, accepted, 2010.
- 1341 Wisely, B.A., and Schmidt, D., Deciphering vertical deformation and poroelastic parameters in a tectonically active fault-bound aquifer using InSAR and well level data, San Bernardino basin, California, *Geophysical Journal International*, in revision, 2009.
- 1342 Nunley, M., D. Oglesby, and D. Bowman, Dynamic Slip Partitioning in a Branched Oblique Fault System, *Geophysical Research Letters*, in preparation, 2010.
- 1343 Assimaki, D., W. Li, and M. Fragiadakis, Site Effects in Structural Performance Estimation, *Earthquake Spectra*, EERI, in review, 2010.
- 1344 Assimaki, D., W. Li, and M. Fragiadakis, Site Effects in Ground Motion Models for Structural Performance Estimation, *Computational Methods in Earthquake Engineering*, Papadrakakis et al, Springer, submitted, 2010.
- 1345 Porter, R., Zandt, G., McQuarrie, N., Pervasive lower crustal seismic anisotropy in southern California: Evidence for underplated schists, *Journal of Geophysical Research*, submitted, 2009.
- 1346 Platt, J.P. and T.W. Becker, Where is the real transform boundary in California?, *Geochemistry, Geophysics, Geosystems*, in review, 2010.
- 1347 Brothers, D. S., N. W. Driscoll, G. M. Kent, A. J. Harding, J. M. Babcock and R. L. Baskin, Tectonic evolution of the Salton Sea inferred from seismic reflection data, *Nature Geosciences*, 2009.
- 1348 Brothers, D. S., N. W. Driscoll, G. M. Kent, A. J. Harding, J. M. Babcock, and R. L. Baskin, Late-Holocene earthquake and sedimentary histories beneath the Salton Sea, California: relationship between lake flooding and fault rupture, *Bulletin of the Seismological Society of America*, in review, 2010.

- 1349 Fang, Z., J. H. Deterich, and G. Xu, Effect of Initial Conditions and Loading Path on Earthquake Nucleation, *Journal of Geophysical Research*, accepted, 2009.
- 1350 Pei, D., J. N. Louie, and S. K. Pullammanappallil, Application of simulated annealing inversion on high-frequency fundamental-mode Rayleigh wave dispersion curves, *Geophysics*, 72, R77-R85, 2007.
- 1351 Leon, L. A., Dolan, J. F., Shaw, J. H., and Pratt, T. L., Evidence for Large Holocene Earthquakes on the Compton Thrust Fault, Los Angeles, California, *Journal of Geophysical Research*, 2009.
- 1352 Lavallée, D., H. Miyake and K. Koketsu, Stochastic Model of a Subduction-Zone Earthquake: Sources and Ground Motions for the 2003 Tokachi-oki, Japan, *Earthquake, Bulletin of the Seismological Society of America*, submitted, 2009.
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XII. SCEC 2011 Collaboration Plan and Research Goals

I. Introduction

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

II. Guidelines for Proposal Submission

- A. *Due Date.*** Friday, November 5, 2010, 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 "2011 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 X). 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, 2011.

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.

2010 Annual Report: Scientists funded by SCEC in 2010 must submit a report of their progress by 5:00 pm PST February 28, 2011. 2011 proposals approved by the PC will not be funded until all progress reports are submitted. Reports should be up to five pages of text and figures. Reports should include bibliographic references to any SCEC publication during the past year (including papers submitted and in review), including their SCEC contribution number. Publications are assigned numbers when they are submitted to the SCEC publication database at <http://www.scec.org/signin>.

Special Note on Workshop Reports. Reports on results and recommendations of workshops funded by SCEC in 2011 are to be submitted no later than 30 days following the completion of the workshop. The reports will be posted on the SCEC web site as soon as possible after review by SCEC directors.

Labeling the Submitted PDF Proposal. PI's must follow the proposal naming convention. Investigators must label their proposals with their last name followed by 2011, e.g., Beroza2011.pdf. If there is more than one proposal, then the file would be labeled as: Beroza2011_1.pdf (for the 1st proposal) and Beroza2011_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 the annual meeting, workshops and working group meetings), and contribute data, analysis results, and/or models to the appropriate SCEC data center (e.g., Southern California Earthquake Data Center—SCEDC), database, or community model (e.g., Community Velocity Model—CVM). Publications resulting entirely or partially from SCEC funding must include a publication number available at <http://www.scec.org/signin>. By submitting a proposal, investigators are agreeing to these conditions.

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

- U.S. Academic institutions
- U.S. Private corporations
- International Institutions (funding will mainly be for travel)
- For the Special Project on Next Generation Attenuation, Hybrid Phase, scientists from the USGS may apply for funding.

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

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

Special note 1. The cooperative agreements from the National Science Foundation and the United States Geological Survey that fund the SCEC3 core research program will end on January 31, 2012. No-cost extensions are NOT allowed on cooperative agreements. Therefore any funds awarded under this science plan MUST be spent by January 31, 2012.

Special Note 2. CSEP global travel grants from 2006 to 2010 were funded with a grant from the W. M. Keck Foundation. The Keck grant will end in early 2011 and future funding for CSEP global travel has not yet been obtained at the time of the release of this document.

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 the Appendix.

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 VIII.

C. *Interdisciplinary Focus Areas.* Interdisciplinary research is organized within seven 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 IX.

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

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 XI. 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 X) or in an educational or outreach mode (see Section XI).
- C. **Workshops.** SCEC participants who wish to host a workshop between February 2011 and January 2012 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 XI. 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, 2010, 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 2011 SCEC proposals, and then respond to the recruitment emails.

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

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

V. Evaluation Process and Criteria

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

2. Leveraging additional resources
 - From other agencies
 - From your institution
 - By expanding collaborations
3. 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.
4. Educational opportunities
 - Graduate student research assistantships
 - Undergraduate summer and year-round internships (funded by the project)
 - K-12 educator and student activities
 - Presentations to schools near research locations
 - Participation in data collection
- C. All research proposals will be evaluated by the appropriate disciplinary committees and focus groups, the Science Planning Committee, and the Center Director. CEO proposals will be evaluated by the CEO Planning Committee and the Center Director.
- D. The Science Planning Committee is chaired by the Deputy Director and comprises the chairs of the disciplinary committees, focus groups, and special projects. It is responsible for recommending a balanced science budget to the Center Director.
- E. The CEO Planning Committee is chaired by the Associate Director for CEO and comprises experts involved in SCEC and USGS implementation, education, and outreach. It is responsible for recommending a balanced CEO budget to the Center Director.
- F. Recommendations of the planning committees will be combined into an annual spending plan and forwarded to the SCEC Board of Directors for approval.
- G. Final selection of research projects will be made by the Center Director, in consultation with the Board of Directors.
- H. The review process should be completed and applicants notified by the end of February, 2011.

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. Ken Hudnut, 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://earthquake.usgs.gov/research/external/>, describes program priorities, projects currently funded, results from past work, and instructions for submitting proposals. The EHRP external funding cycle is several months offset from SCEC's, with the RFP due out in February and proposals due in May. Interested PI's are encouraged to contact the USGS regional or topical coordinators for Southern California, Earthquake Physics and Effects, and/or National (PSHA) research, as listed under the "Contact Us" tab.

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

VII. SCEC3 Science Priorities

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

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

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

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

A2. Investigate implications of geodetic/geologic rate discrepancies

- A3. Develop a system-level deformation and stress-evolution model
- A4. Statistical analysis and mapping of seismicity and source parameters with an emphasis on their relation to known faults
- A5. Develop a geodetic network processing system that will detect anomalous strain transients
- A6. Test scientific prediction hypotheses against reference models to understand the physical basis of earthquake predictability
- A7. Determine the origin, evolution and implications of on- and off-fault damage
- A8. Test hypotheses for dynamic fault weakening
- A9. Assess predictability of rupture extent and direction on major faults
- A10. Develop statistical descriptions of heterogeneities (e.g., in stress, strain, geometry and material properties), and understand their origin and implications for seismic hazard by observing and modeling single earthquake ruptures and multiple earthquake cycles.
- A11. Constrain absolute stress and understand the nature of interaction between the faulted upper crust, the ductile crust and mantle, and how geologic history helps to resolve the current physical properties of the system.

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

- B1. Develop kinematic and dynamic rupture representations consistent with seismic, geodetic, and geologic observations.
- B2. Investigate bounds on the upper limit of ground motion.
- B3. Develop high-frequency simulation methods and investigate the upper frequency limit of deterministic ground-motion predictions.
- B4. Validate ground-motion simulations and verify simulation methodologies.
- B5. Improve our understanding of site effects and develop methodologies to include these effects in broadband ground-motion simulations.
- B6. Collaborate with earthquake engineers

C. Improve and develop community products (data and 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 to improve 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, to develop plans for use of

simulations in post-earthquake response for evaluation of short-term earthquake behavior and seismic hazards, and to improve the SCEC post-earthquake response plan.

VIII. 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:

A. Seismology

Objectives. The objectives of the Seismology group are to gather data on the range of seismic phenomena observed in southern California and to integrate these data into physics-based models of fault slip. Of particular interest are proposals that foster innovations in network deployments, data collection, real-time research tools, and data processing. Proposals that provide community products that support one or more of the numbered goals in A, B, C or D or those that include collaboration with network operators in Southern California are especially encouraged. Proposers should consider the SCEC resources available including the Southern California Earthquake Data Center (SCEDC) that provides extensive data on Southern California earthquakes as well as crustal and fault structure, the network of SCEC funded borehole instruments that record high quality reference ground motions, and the pool of portable instruments that is operated in support of targeted deployments or aftershock response.

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

- Enhancement and continued operation of the SCEDC and other existing SCEC facilities particularly the near-real-time availability of earthquake data from SCEDC and automated access.
- Real-time processing of network data such as improving the estimation of source parameters in relation to known and unknown faults (A3, A4, A10), especially evaluation of the short term evolution of earthquake sequences and real-time stress perturbations on nearby major fault segments (D).
- Enhance or add new capabilities to existing earthquake early warning (EEW) systems or provide new EEW algorithms. Develop real-time finite source models constrained by incoming seismic and GPS data to estimate evolution of the slip function and potentially damaging ground shaking (D).
- Advance innovative and practical strategies for densification of seismic instrumentation, including borehole instrumentation, in Southern California and develop innovative algorithms to utilize data from these networks. Develop metadata, archival and distribution models for these semi-mobile networks.
- Develop innovative new methods to search for unusual signals using combined seismic, GPS, and borehole strainmeter data (A5, A6); collaborations with EarthScope or other network operators are encouraged.

- Investigate near-fault crustal properties, evaluate fault structural complexity, and develop constraints on crustal structure and state of stress, and (A7, A10, C).
- Collaborations, for instance with the ANSS and NEES projects, that would augment existing and planned network stations with downhole and surface instrumentation to assess site response, nonlinear effects, and the ground coupling of built structures (B4, B6).
- Preliminary design and data collection to seed future passive and active experiments such as dense array measurements of basin structure and large earthquake properties, OBS deployments, and deep basement borehole studies.

Priorities for Seismology in 2011.

1. ***Earthquake early warning research.*** In the next few years, earthquake early warning (EEW) systems will be installed in California. The seismology group seeks proposals that will provide new algorithms, enhance or add new capabilities to existing EEW algorithms. The development of Bayesian probabilities that would take advantage of the extensive knowledge developed by SCEC about fault structures and spatial and temporal seismicity patterns are needed to make EEW algorithms more robust. Similarly, high-sample rate GPS 1 second solutions are being made available real-time for EEW development. Using these new data to develop new EEW algorithms for finite sources is a new area of research for SCEC scientists.
2. ***Community seismic networks.*** Several community seismic networks using low cost sensors are being developed in California. We seek proposals that would address development of seismological algorithms to utilize data from these networks in innovative ways. We also seek proposals that would develop metadata and archiving models for these new semi-mobile networks, as well as archive and serve these data to the SCEC user community.
3. ***The 2010 M7.2 El Mayor-Cucapah Earthquake Sequence.*** The El Mayor sequence ruptured for a distance of more than 120 km, and large data sets were recorded by the SCSN, RESNOM, portable temporary networks, and GPS networks. Proposals that seek to analyze these data and other relevant data sets in the context of SCEC research priorities are welcome.

B. Tectonic Geodesy

Objectives. The broad objective of SCEC's Tectonic Geodesy disciplinary activities is to foster the availability of the variety of geodetic data collected in Southern California and the innovative and integrated use of these observations, in conjunction with other relevant data (e.g., seismic or geologic information), to address the spectrum of deformation processes affecting this region. Topics of interest include, but are not limited to, rapid earthquake response, transient deformation, anthropogenic or non-tectonic 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.

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

- Support efforts to implement continuously operating transient strain detectors by the end of SCEC4 (A5):
 - Adapt methods for detecting, assessing and interpreting transient deformation signals so that they can be run with minimal user intervention as part of an ongoing detection effort that ingests data at frequent (daily to weekly) time intervals.
 - Refine capabilities of detection algorithms and assess their sensitivity thresholds through continued participation in the Transient Detection Blind Test Exercise.
 - Identify means for incorporating other data types into monitoring systems in addition to or instead of GPS.
- Investigate processes underlying detected signals and/or their seismic hazard implications. (A1, A2, A3)
- Extend methods for estimating crustal motion and refine such estimates for southern California (A1, A2, A3, B1, C, D). In all cases, work should include assessment of the sources of uncertainty in the analysis and results. Proposals for the development of new data products or collection of new data must explicitly motivate the need for such efforts and state how the resulting data or products will be used. Resulting velocity fields should be provided for inclusion in a consensus velocity field that is under development for the western U.S. In compliance with SCEC's data policy, data collected with SCEC funding must be made publicly available upon collection by archiving at the appropriate data center (e.g., UNAVCO).
 - Improve vertical velocity estimates and their uncertainties, for example by refining or extending data processing and analysis strategies or approaches for the combined use of multiple data types.
 - Develop methods for combining data types (e.g., GPS, InSAR, strainmeter, and/or other data) that have differing spatial and temporal apertures, sampling frequencies, and sensitivities, and assess the utility of such combinations for interpreting tectonic or nontectonic signals.
 - Develop tools for using high-rate and real-time GPS positions and demonstrate application of these data to address topics such as rapid earthquake response, postseismic analysis, or the combined use of GPS and seismic data.
 - Further development of approaches for incorporating geodetic slip and strain rate estimates into the UCERF3 assessment is encouraged and is specifically targeted under the Crustal Deformation Modeling section of this RFP.
- *The 2010 M7.2 El Mayor-Cucapah Earthquake Sequence.* (B1, C, D) Tectonic Geodesy priorities for response to this event include:
 - Acquisition of data that constrains the coseismic and postseismic deformation field.

- Integration of geodetic observations with constraints from field geology, seismology, etc, with particular focus on the potential for a large aseismic signal associated with this earthquake.
- Evaluation of the impact that geodetic observations have on estimates of loading of regional faults by this earthquake.

C. 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, including data gathering in response to major earthquakes. 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).
- Documentation and analysis of surface ruptures and distributed deformation resulting from the 4 April 2010 El Mayor-Cucapah earthquake.
- 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, including possible sources of great earthquakes off of the San Andreas Fault (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 (meoskin@ucdavis.edu).

IX. Interdisciplinary Focus Areas

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

A. 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 (CVM)***. Improve the current SCEC CVM-H model, with emphasis on more accurate representations of Vp, Vs, density structure, and basin shapes, and derive models for attenuation. Generate improved mantle Vp and Vs models, as well as more accurate descriptions of near-surface property structure that can be incorporated into a revised geotechnical layer. Develop (preferably standardized/automated) procedures to evaluate the existing and future iterations of the CVMs with data (e.g., waveforms, gravity) to distinguish alternative representations and quantify model uncertainties; apply these methods for well-recorded small earthquakes in southern California (including aftershocks of the 4 April Mw 7.2 El Mayor Cucapah earthquake) to delineate areas where CVM updates are needed. 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. An example of such IT mechanism is a web-based system that allows plot and download of profiles and cross sections of the CVMs and related data (i.e., Vs30) at desired locations. Another example is a fast and user-friendly method to extract a sub-volume of the CVM and formatting the results for use by the ground-motion modelers. 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.

B. 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.

For the final year of the SCEC3 research program we solicit proposals that will finalize ongoing research or make significant progress on the following goals:

- 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 poro-mechanical 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, inter-seismic 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).

C. Crustal Deformation Modeling (CDM)

We seek proposals aimed at resolving the kinematics and dynamics of southern California lithosphere over time scales ranging from hours to thousands of years. Our long-term goal is to contribute to the SCEC objective of developing a physics-based probabilistic seismic hazard analysis for southern California by developing and applying system-wide deformation models of processes at time-scales of the earthquake cycle. Our immediate goals include assessing the level of detail necessary in deformation models to achieve the broader SCEC objectives. Collaborations with geologists and researchers in other SCEC groups are strongly encouraged, as is research that ties in with UCERF3.

System-Wide Deformation Models

- Develop kinematic and mechanical models of inter-seismic deformation or the earthquake cycle to estimate slip rates on primary southern CA faults, fault geometries at depth, and spatial distribution slip or moment deficits on faults. Compare with or refine

SCEC CFM and assess discrepancies of the kinematic models with geodetic, geologic, and seismic data (A1, A3).

- Develop a system-wide model of southern California faults, incorporating the SCEC CFM, properties derived from the SCEC CVM, and realistic inferred rheologies, to model inter-seismic deformation, including transfer of stress across the fault system (A3).
- Develop simpler models to compare with the system-wide deformation model above for benchmarking purposes and to assess the degree of detail needed to adequately represent inter-seismic deformation and stress transfer. Various modeling approaches are requested and might include boundary element methods, 2D simplifications, and analytical or semi-analytical methodology (A10, A3).
- Use system-wide models to estimate southern California fault slip rates, locking depths, and stressing rates for use in UCERF3.
- Address the following problems of interest to WGCEP in development of UCERF3: 1. Quantify the amount of on-fault and off-fault deformation, 2. Constrain slip rates on faults lacking geologic slip rate data, 3. Provide estimates of slip rates on closely spaced faults, 4. Constrain slip rate variations along strike, 5. Constrain distribution of aseismic and seismic slip on faults, and 6. Estimate long-term after-effects of large earthquakes.
- Assess whether stress transfer implicitly assumed in earthquake simulator models is similar to stress transfer estimated from either category of deformation model mentioned above (A11).

More Focused Deformation Models

- Determine the extent to which rheological heterogeneity (including damage) influences deformation and stress transfer at various spatial and temporal scales. What level of detail will be required for the system-wide model (A7, A10, A11, A3)?
- Evaluate spin-up effects for viscoelastic models and methods to accelerate this process. How much does deep viscoelastic relaxation influence interseismic deformation and stress transfer? Can it be neglected or “worked around” in a southern-California-wide stress transfer model (A11, A3)?
- Evaluate whether nonlinear rheologies be represented with heterogeneous distributions of linearly viscoelastic material (A11, A3).
- Investigate causes of discrepancies between geologic and geodetic slip rate estimates (for example, different assumptions about fault geometry, or viscoelastic relaxation) (A2).
- Investigate possible causes and effects of transient slip and earthquake clustering (A1, A11).
- Estimate impact of post-seismic deformation from recent large earthquakes on the southern California GPS velocity field and strain rates.

D. 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 understand better 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.

E. Earthquake Forecasting and Predictability (EFP)

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

For research strategies that plan to utilize CSEP, see the description of CSEP under Special Projects to learn of its capabilities. Successful investigators proposing to utilize CSEP would be funded via core SCEC funds to adapt their prediction methodologies to the CSEP framework, to transfer codes to the externally accessible CSEP computers, and to be sure they function there as intended (A6). Subsequently, the codes would be moved to the identical externally inaccessible

CSEP computers by CSEP staff who will conduct tests against a variety of data as outlined in the CSEP description. In general, methodologies will be considered successful only if they do better than null hypotheses that include both time-independent and time-dependent probabilities. Proposals aimed toward developing useful measurement/testing methodology that could be incorporated in the CSEP evaluations are welcomed, including those that address how to deal with observational errors in data sets.

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

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

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

F. Ground-Motion Prediction (GMP)

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

Research topics within the Ground-Motion Prediction program include:

- Developing and/or refining physics-based simulation methodologies, with particular emphasis on high frequency (1-10 Hz) approaches (B3)
- Incorporation of non-linear models of soil response (B2, B4, B5);

- Development of more realistic implementations of dynamic or kinematic representations of fault rupture. In collaboration with FARM, this research could also include the examination of current source-inversion strategies and development of robust methods that allow imaging of kinematic and/or dynamic rupture parameters reliably and stably, along with a rigorous uncertainty assessment. (B1, B2).
- Verification (comparison against theoretical predictions) and validation (comparison against observations) of the simulation methodologies with the objective of being to develop robust and transparent simulation capabilities that incorporate consistent and accurate representations of the earthquake source and three-dimensional velocity structure (B4, C).

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

G. Seismic Hazard and Risk Analysis (SHRA)

The purpose of the SHRA Focus Group is to apply SCEC knowledge to the development of information and techniques for quantifying earthquake hazard and risk, and in the process to provide feedback on SCEC research. Projects in this focus group will in some cases be linked to the Ground Motion Prediction Focus Group, to SCEC special projects such as the Extreme Ground Motion Project, and to Pacific Earthquake Engineering Research Center (PEER) special projects such as the Tall Buildings Initiative (TBI) and Reference Buildings and Bridges Project. Projects that involve interactions between SCEC scientists and members of the community involved in earthquake engineering research and practice are especially encouraged. Examples of work relevant to the SHRA Focus Group follow. Also described below is a new Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV) that will be a focus in 2011.

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 median and variability of ground motions for a given earthquake scenario, in coordination with the Extreme Ground Motion Project.

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. Please see the section below that describes the new Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV).
- 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 Structural Response Analysis

- *Tall Buildings and Other Long-Period Structures.* 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 and other long-period structures (e.g., bridges, waterfront structures). Such projects could potentially build on work done in the PEER TBI Project.
- *End-to-End Simulation.* Interactively identify the sensitivity of structural response to ground motion parameters and structural parameters through end-to-end simulation. Buildings of particular interest include non-ductile concrete frame buildings.
- *Reference Buildings and Bridges.* Participate with PEER investigators in the analysis of reference buildings and bridges using simulated broadband ground motion time histories. The ground motions of large, rare earthquakes, which are poorly represented in the NGA strong motion data base, are of special interest. Coordination with PEER can be done through Yousef Bozorgnia, yousef@berkeley.edu.
- *Earthquake Scenarios.* Perform detailed assessments of the results of scenarios such as the ShakeOut exercise, and the scenarios for which ground motions were generated for the Tall Buildings Initiative (including events on the Puente Hills, Southern San Andreas, Northern San Andreas and Hayward faults) as they relate to the relationship between ground motion characteristics and structural response and damage.

Ground Deformation

- Investigate the relationship between input ground motion characteristics and local soil nonlinear response, liquefaction, lateral spreading, local soil failure, and landslides – i.e., geotechnical hazards. Investigate hazards due to surface faulting and to surface deformation caused by subsurface faulting and folding.

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.

Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV)

As initiated at the 2010 SCEC Annual Meeting in September, in 2011 a TAG focusing on validation of ground motion simulations will be established to develop and implement testing/rating methodologies via collaboration between ground motion modelers and engineering users. A planning workshop for this TAG will be held in early December (2010). Proposals for work that would contribute to the TAG are encouraged. A few general ideas for projects are:

- Research on important ground motion or structural (e.g., building) response parameters and statistics that should be used in comparing simulated versus recorded seismograms.
- Comparisons of simulated ground motions with empirical ground motion prediction equations, in terms of both median predictions and the variability about them. Note that simulations for the CyberShake Project (<http://epicenter.usc.edu/cmeportal/CyberShake.html>) aim to accurately represent both the median and variability of ground motions.
- Compilation of representative nonlinear structural models of different types for which the responses to simulated versus recorded seismograms can be compared.
- Comprehensive analysis and documentation of the sensitivity of simulated ground motions to model input parameters and their interactions and uncertainties.
- Development of testing and/or rating metrics for simulated ground motions, perhaps considering testing concepts from the Collaboratory for the Study of Earthquake Predictability (<http://www.cseptest.org>).
- Implementation of testing/rating methodologies into the SCEC Broadband Strong Motion Simulation Platform (<http://scec.usc.edu/research/cme/groups/broadband>).

Note that such proposals will be reviewed with all other SCEC proposals in January of 2011, with due consideration of outcomes from the December planning workshop.

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.

X. Special Projects and Initiatives

A. Southern San Andreas Fault Evaluation (SoSAFE)

The SCEC Southern San Andreas Fault Evaluation (SoSAFE) Project will continue to increase our knowledge of slip rates, paleo-event chronology, and slip distributions of past earthquakes, for the past two thousand years on the southern San Andreas fault system. From Parkfield to

Bombay Beach, and including the San Jacinto fault, the objective is to obtain new data to clarify and refine relative hazard assessments for each potential source of a future 'Big One.'

Past SoSAFE workshops have led to a focused research plan that responds to the needs and opportunities identified across existing research projects. We strongly welcome proposals that will:

- Help to improve correlation of ruptures over the past 2000 years. This includes short-term (3-5 earthquake) and slip-per-event data from paleoseismic sites, but can include longer-term rates (60,000 years) in some cases.
- Obtain the best possible measurements of geomorphic slip distributions from past earthquake using field and LiDAR approaches.
- Lengthen existing paleoearthquake chronologies or start new sites in key locations along the fault system.
- Use novel methods for estimating slip rates from geodetic data.
- Investigate methodologies for integrating paleoseismic and geologic data into rupture histories. For example, studies may improve or inform interactions between SoSAFE results and scenario rupture modeling or rupture forecasts.

It is expected that much support will go towards improved dating (e.g., radiocarbon and OSL) of earthquakes so that event correlations and coefficient of variation in recurrence intervals may be further refined. Requests for geochronology support (e.g., to date 12 radiocarbon samples) are encouraged and shall be coordinated with Earthquake Geology; a portion of SoSAFE funds will be contributed towards joint support for dating. We also welcome proposals that seek to add other data (such as climate variations) to earthquake chronologies, which may be used to improve age control or site-to-site correlation of events.

Research will address significant portions of the fault system, and all investigators will agree to collaboratively review one another's progress. Research by single or multi-investigator teams will be supported to rapidly advance SCEC research towards meeting priority scientific objectives related to the mission of the SoSAFE special project. SoSAFE objectives also foster common longer-term research interests and engage in facilitating future collaborations in the broader context of a decade-long series of interdisciplinary, integrated and complementary studies on the southern San Andreas Fault system. The fifth year of SoSAFE may again be funded at \$240K by USGS, depending on 1) the report on progress in the previous years, 2) effective leveraging of USGS funds with funds from other sources, 3) level of available funding from USGS for the year, and 4) competing demands for the USGS Multi-Hazards Demonstration Project funding.

B. Working Group on California Earthquake Probabilities (WGCEP)

Following the 2008 release of the Uniform California Earthquake Rupture Forecast version 2 (UCERF2), the WGCEP is now working on adding some major enhancements, in UCERF3. Our primary goals are to relax segmentation, add multi-fault ruptures, and include spatial-temporal clustering (earthquake triggering). As the latter will require robust interoperability with real-time seismicity information, UCERF3 will bring us into the realm of operational earthquake forecasting. This model is being developed jointly by SCEC, the USGS, and CGS, in close

coordination with the USGS National Seismic Hazard Mapping Program. The following are examples of SCEC activities that could make direct contributions to WGCEP goals:

- Reevaluate fault models in terms of the overall fault inventory, and specify more precisely fault endpoints in relationship to neighboring faults, and examine the likelihood of possible multi-fault ruptures.
- Reevaluate fault slip rates, especially using more sophisticated modeling approaches (e.g., that include GPS data, generate kinematically consistent results, and perhaps provide off-fault deformation rates as well).
- Help determine the average along-strike slip distribution of large earthquakes, especially where multiple faults are involved (e.g., is there reduced slip at fault connections?)
- Help determine the average down-dip slip distribution of large earthquakes (the ultimate source of existing discrepancies in magnitude-area relationships).
- Contribute to the compilation and interpretation of mean recurrence-interval constraints from paleoseismic data.
- Develop earthquake rate models that relax segmentation and include multi-fault ruptures.
- Develop ways to constrain the spatial distribution of maximum magnitude for background seismicity (for earthquakes occurring off of the explicitly modeled faults).
- Answer the question of whether every small volume of space exhibits a Gutenberg Richter distribution of nucleations?
- Develop methods for quantifying elastic-rebound based probabilities in un-segmented fault models.
- Help quantify the amount of slip in the previous event (including variations along strike) on any major faults in California.
- Develop models for fault-to-fault rupture probabilities, especially give uncertainties in fault endpoints.
- Determine the proper explanation for the apparent post-1906 seismicity-rate reduction (which appears to be a statewide phenomenon)?
- Develop applicable methods for adding spatial and temporal clustering to the model.
- Develop easily computable hazard or loss metrics that can be used to evaluate and perhaps trim logic-tree branch weights.
- Develop techniques for down-sampling event sets to enable more efficient hazard and loss calculations.

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

C. 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. In 2011, projects to enhance the simulation capabilities at high frequencies by developing new modules for the Broadband Platform will receive priority for support. The main SCEC focus groups that are related to this project are Ground Motion Prediction and Seismic Hazard and Risk Analysis.

D. 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 (woodframe 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.

E. 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:

1. 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 inter-comparisons to evaluate prediction skills;
2. Constructing community-endorsed standards for testing and evaluating probability-based and alarm-based predictions;
3. Developing hardware facilities and software support to allow individual researchers and groups to participate in prediction experiments;
4. 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;

5. Intensifying the collaboration between the US and Japan through international projects, and initiating joint efforts with China;
6. 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
7. Conducting workshops to facilitate international collaborations.

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.

Special Note. CSEP global travel grants from 2006 to 2010 were funded with a grant from the W. M. Keck Foundation. The Keck grant will end in early 2011 and future funding for CSEP global travel has not yet been obtained at the time of the release of this document.

F. 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.

G. 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.

XI. SCEC Communication, Education, and Outreach

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

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

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

CEO Focus Area Objectives

1. ***SCEC Community Development and Resources*** (activities and resources for SCEC scientists and students)
 - SC1 Increase diversity of SCEC leadership, scientists, and students
 - SC2 Facilitate communication within the SCEC Community
 - SC3 Increase utilization of products from individual research projects
2. ***Education*** (programs and resources for students, educators, and learners of all ages)
 - E1 Develop innovative earth-science education resources
 - E2 Interest, involve and retain students in earthquake science
 - E3 Offer effective professional development for K-12 educators
3. ***Public Outreach*** (activities and products for media reporters and writers, civic groups and the general public)
 - P1 Provide useful general earthquake information
 - P2 Develop information for the Spanish-speaking community
 - P3 Facilitate effective media relations
 - P4 Promote SCEC activities

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

I1 Communicate SCEC results to the broader scientific community

I2 Develop useful products and activities for practicing professionals

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

I4 Promote effective mitigation techniques and seismic policies

APPENDIX: SCEC3 Long-Term Research Goals

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

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.

A. Earthquake Source Physics

Problem Statement. Earthquakes obey the laws of physics, but we don't yet know how. In particular, we understand only poorly the highly nonlinear physics of earthquake nucleation, propagation, and arrest, because we lack knowledge about how energy and matter interact in the extreme conditions of fault failure. A complete description would require the evolution of stress, displacement, and material properties throughout the seismic cycle across all relevant scales, from microns and milliseconds to hundreds of kilometers and many years. A more focused aspect of this problem is the physical basis for connecting the behavior of large ruptures at spatial resolutions of hundreds of meters and fracture energies of megajoules per square meter with laboratory observations of friction at centimeter scales and fracture energies of kilojoules 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 fault constitutive models for the numerical simulation of earthquake rupture, test them against seismological data, and extend the simulation methods to include fault complexities such as bends, step-overs, fault branches, and small-scale roughness.
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.

B. 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 S_0 as well as its history?

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

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

C. 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.

D. Ground Motion Prediction

Problem Statement. Given the gross parameters of an earthquake source, such as its magnitude, location, mechanism, rupture direction, and finite extent along a fault, we seek to predict the ground motions at all regional sites and for all frequencies of interest. The use of 3D velocity models in low-frequency (< 0.5 Hz) ground motion prediction was pioneered in SCEC1 (§II.A), and this type of simulation, based on direct numerical solution of the wave equation, has been taken to new levels in SCEC2 (§II.B.6). The unsolved basic research problems fall into four classes: (a) the ground motion inverse problem at frequencies up to 1 Hz; (b) the stochastic

extension of ground motion simulation to high frequencies (1-10 Hz); (c) simulation of ground motions using realistic sources; and (d) nonlinear wave effects, including nonlinear site response. In addition, there remain scientific and computational challenges in the practical prediction of ground motions near the source and within complex structures such as sedimentary basins, as well as in the characterization of the prediction uncertainties.

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

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.