The Southern California Earthquake Center, Phase 4 (SCEC4): Tracking Earthquake Cascades

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Project Summary

This proposal requests funding for the Southern California Earthquake Center (SCEC) for the 5-year period from 1 Feb 2012 to 31 Jan 2017 (SCEC4). The Center coordinates basic research in earthquake science using Southern California as its principal natural laboratory. The region is data-rich and, with an urbanized population exceeding 20 million, it comprises the lion's share of national earthquake risk. According to the Uniform California Earthquake Rupture Forecast (UCERF2), the mean probability of an M > 7 earthquake in Southern California over the next 30 years is 82%. New research by the Southern San Andreas Fault Evaluation (SoSAFE) project has revised the recurrence interval for the Carrizo section of the San Andreas fault downward, to less than the open interval since its last rupture in 1857. The entire southern San Andreas is "locked and loaded."

SCEC Mission. SCEC's theme of *earthquake system science* is reflected in its mission statement, which emphasizes the connections between information gathering by sensor networks, fieldwork, and laboratory experiments; knowledge formulation through physics-based, system-level modeling; improved understanding of seismic hazard; and actions to reduce earthquake risk and promote community resilience. The Center is a large consortium of institutions with a national, and increasingly worldwide, distribution that coordinates earthquake system science within Southern California, and with research elsewhere. The 16 current core institutions have all committed resources to SCEC4, and three new core institutions are expected to join, including a consortium of 6 CalState campuses. More than 50 other institutions (11 foreign) are likely to participate, forming one of the largest research collaborations in geoscience. Several other characteristics describe the Center:

- A collaboratory for earthquake system science that includes the Community Modeling Environment (CME), which applies high-performance computing to large-scale earthquake modeling, and the Collaboratory for the Study of Earthquake Predictability (CSEP), a global infrastructure for the prospective testing of earthquake forecasts.
- An open "community of trust" that nurtures students and early-career scientists and shares information and ideas about how earthquakes work. The Center's working groups, workshops, field activities, and annual meeting enable scientists to collaborate over sustained periods, building strong interpersonal networks that promote intellectual exchange and mutual support. About two-thirds of the total SCEC science budget directly supports students and early-career scientists (Fig. S1).
- A reliable and trusted partner that collaborates with other organizations in reducing risk and promoting societal resilience to earthquake disasters. The SCEC Communication, Education, and Outreach (CEO) program has steadily grown a diverse network of partnerships. Its California-wide Earthquake Country Alliance (ECA)—now comprising more than 200 organizations—promotes preparedness through the popular publications that have branched from *Putting Down Roots in Earthquake Country* and involves millions of California citizens in earthquake awareness and readiness exercises through its annual ShakeOut exercises.

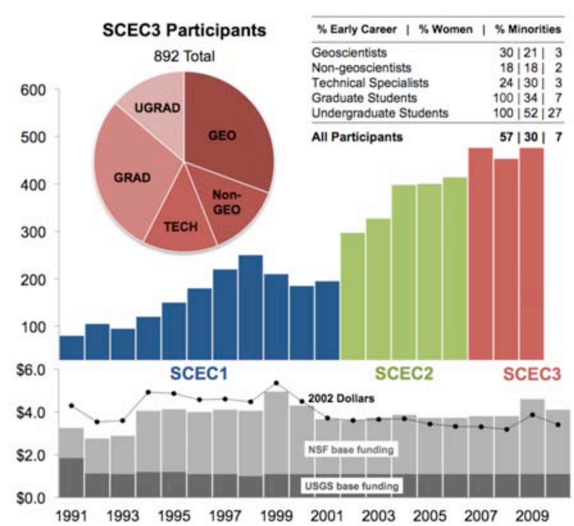


Figure S1. Colored bars show total registrants at SCEC Annual Meetings, one measure of how the collaboration has grown during its 20-year history, 1991-2009. Pie chart and table show the demographics of SCEC3. The lower bar chart is the history of SCEC base funding in as-spent dollars; the connected dots are the base-funding totals in 2002 dollars.

Intellectual Merit of the Proposed Research. 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. The proposed 5-year research program will pioneer time-dependent seismic hazard analysis—the geoscience required to track earthquake cascades. This science seeks to understand the unusual physics of how matter and energy interact during the extreme conditions of rock failure. No theory adequately describes the basic features of dynamic rupture, nor is one available that fully explains the dynamical interactions within networks of faults. Progress towards a comprehensive theory will improve the predictive capabilities of earthquake system science.

SCEC4 will move this science forward through highly integrated collaborations that are coordinated across scientific disciplines and research institutions and enabled by high-performance computing and advanced information technology. It will focus on six fundamental problems of earthquake physics:

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

Broader Impacts of the Proposed Research. The Center will translate basic research into practical products for reducing risk and improving community resilience in Southern California and elsewhere. The SCEC4 program will help to:

- 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 help communities prepare 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—and
- improve the delivery of post-event information about strong ground motions and secondary hazards.

The Center will create, prototype, and refine these operational capabilities in partnership with the USGS and other responsible government agencies. In addition to better earthquake forecasting and ground motion prediction models, important SCEC4 contributions will include the CSEP cyberinfrastructure needed to evaluate prospectively and continually the performance of the operational models and their components by comparing the forecast ground motions with those actually recorded. Its international leadership in system science and sustained efforts to educate a diverse scientific workforce will contribute to its broader impacts.

SCEC3 Accomplishments. The main goal of SCEC3 has been to transform probabilistic seismic hazard analysis into a physics-based science. The core research program has focused on improving the science basis for the two principal components of probabilistic seismic hazard analysis, earthquake rupture forecasting and ground motion prediction. SCEC's basic research in Southern California has led to important advances. This basic research has been applied to develop new seismic hazard products (UCERF2), conduct public emergency preparedness drills (ShakeOut), create new ways of assimilating data into models (full-3D waveform tomography), gain new insights into earthquake behavior (ground motion variability caused by dynamic source complexities), and create the first physics-based seismic hazard model (CyberShake).

SCEC3 has pioneered novel modes of collaboration, including self-organized Technical Activity Groups, the global CSEP, and the statewide Earthquake Country Alliance. The EPIcenters program network of "free-choice" learning institutions now involves more than 50 museums, science centers, and other informal education venues. The Center has developed intern programs that effectively recruit a diverse population of students into science and technology careers. SCEC3 research results are demonstrably impacting earthquake insurance and statewide preparedness activities (e.g., ShakeOut), and they are contributing new tools to earthquake engineering. SCEC's research initiatives and organizational innovations are being emulated in other regions of high seismic risk, including Japan, China, and the European Union.

SCEC4 Project Plan. Seismic hazards change dynamically in time, because earthquakes release energy on very short time scales and thereby alter the conditions within the fault system that will cause future earthquakes. The project's long-term goal is to understand how seismic hazards change across all time scales of scientific and societal interest, from millennia to seconds.

The six fundamental problems listed under Intellectual Merit will constitute the basic-research focus of the project. They are interrelated and require an interdisciplinary, multi-institutional approach. Each is described by a short problem statement, a set of SCEC4 objectives, and a listing of priorities and requirements. Interdisciplinary research initiatives 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 be a new platform where the various constraints on earthquake-producing stresses can begin to be integrated. Improvements will be made to SCEC's unified structural representation and its statewide extensions.

The proposed research program will address four major challenges of earthquake system science: (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.

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.* It 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. SCEC scientists collaborate in a rich programmatic environment; therefore, an acronym guide is provided in the last page of the supplementary documents section.

I. Introduction

The Southern California Earthquake Center (SCEC) was created as a Science & Technology Center (STC) on February 1, 1991, with joint funding by the National Science Foundation (NSF) and the U. S. Geological Survey (USGS). SCEC graduated from the STC Program in 2002, and was funded as a stand-alone center under cooperative agreements with both agencies in two consecutive phases, SCEC2 (1 Feb 2002 to 31 Jan 2007) and SCEC3 (1 Feb 2007 to 31 Jan 2012). This proposal requests an extension of those agreements for the 5-year period from 1 Feb 2012 to 31 Jan 2017 (SCEC4).

Box 1.1. SCEC Mission Statement

- **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 and improving community resilience

SCEC coordinates basic research in earthquake science using Southern California as its principal natural laboratory. The Center's theme of *earthquake system science* is reflected in its mission statement (**Box 1.1**), which emphasizes the connections between information gathering by sensor networks, fieldwork, and laboratory experiments; knowledge formulation through physics-based, system-level modeling; improved understanding of seismic hazard; and actions to reduce earthquake risk and promote community resilience. This mission statement will guide SCEC4.

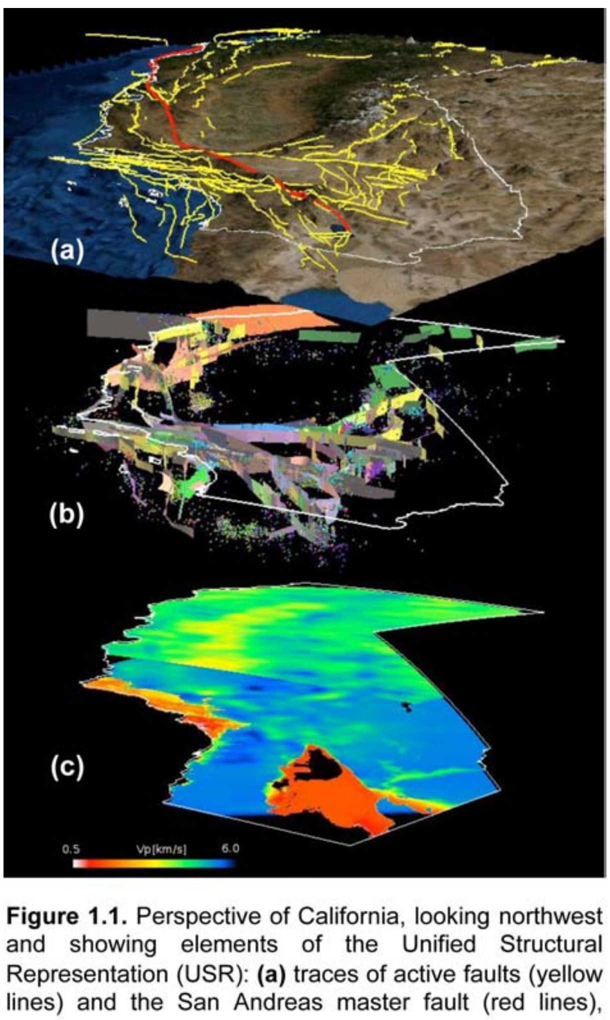


Figure 1.1. Perspective of California, looking northwest and showing elements of the Unified Structural Representation (USR): **(a)** traces of active faults (yellow lines) and the San Andreas master fault (red lines), **(b)** the statewide Community Fault Model (CFM), and (**c**) statewide Community Velocity Model (CVM).

This proposal is well aligned with the USGS strategic plan, specifically its National Hazards, Risk, and Resilience Assessment Program [*1*]. It will address the six "Grand Challenges for Disaster Reduction" articulated by the National Science and Technology Council [*2*] and the three grand challenges developed in the NSF 2009 *GeoVision* Report [*3*]: (a) *understanding and forecasting the behavior of a complex and evolving Earth system*, (b) *reducing vulnerability and sustaining life*, and (c) *growing the geosciences workforce of the future*. The SCEC4 program will coordinate research on the first three grand challenges in the 2009 Long-Range Science Plan for Seismology [*4*]: (1) How do faults slip? (2) How does the near-surface environment affect natural hazards and resources? (3) What is the relationship between stress and strain in the lithosphere?

A. Southern California as a Natural Laboratory

Southern California is SCEC's natural laboratory for the study of earthquake physics and geology. This tectonically diverse stretch of the Pacific-North America plate boundary contains a network of several hundred active faults organized around the right-lateral San Andreas master fault (**Fig. 1.1**). Its geographic dimensions are well-suited to system-level earthquake studies: big enough to contain the largest (M8) San Andreas events, which set the system's outer scale, but small enough for detailed surveys of seismicity and fault interactions. The entire fault network is seismically active, making the region one of the most data-rich, and hazardous, in the nation. Research on fundamental problems in

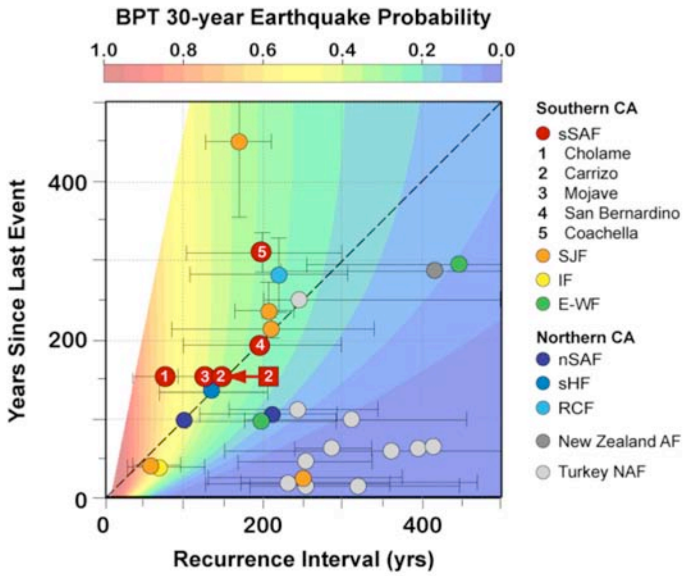


Figure 1.2. A plot of time since the last event vs. mean recurrence interval for sections of the southern San Andreas fault (red points) and other strike-slip faults in California and elsewhere. The arrow indicates the reduction in the mean recurrence interval for the Carrizo section implied by the new SoSAFE data. The color contours show the 30-year earthquake probabilities computed from a Brownian Passage Time (BPT) renewal model. The points for the five major southern San Andreas fault sections lie in the upper triangle; i.e., the entire fault is now "locked and loaded".

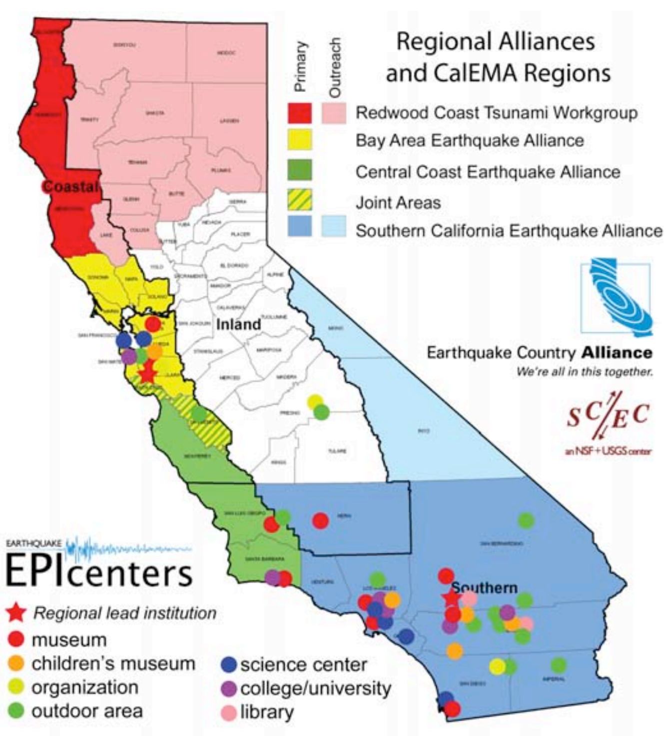


Figure 1.3. Four chapters of the Earthquake Country Alliance (colored areas) and locations of the EPIcenters (colored symbols), two key partnerships developed by the SCEC CEO program.

this well-instrumented natural laboratory has been progressing rapidly (see §II). SCEC coordinates a broad collaboration that builds across disciplines and enables a deeper understanding of system behavior than would be accessible by individual researchers or institutions working alone.

Catastrophes like the 12 Jan 2010 Haiti (M7.0) and the 27 Feb 2010 Chile (M8.8) earthquakes underline the urgency in SCEC's mission. Southern California is home to an urbanized population exceeding 20 million, and it comprises the lion's share of the national earthquake risk [*5*]. According to the Uniform California Earthquake Rupture Forecast (UCERF2), the chances of an $M > 7$ earthquake in Southern California over the next 30 years are 82% ± 14% [*6*]. Moreover, new research by the Southern San Andreas Fault Evaluation (SoSAFE) project has demonstrated that the seismic hazard from the southern San Andreas Fault is higher than even the recent UCERF2 estimates [*7*]. In particular, the recurrence interval for the Carrizo section of the fault has been revised from a previous estimate of over 200 years to 140 years or less [*8*,*9*], which compares to the 153-year interval since its last rupture (1857). Urgency comes from a recognition that the entire southern San Andreas is "locked and loaded" (**Fig. 1.2**).

SCEC's research in Southern California has led to the development of important advances, including a Unified Structural Representation (Fig. 1.1), the statewide UCERF2, and the CyberShake physics-based hazard model. The Center has pioneered novel modes of collaboration, including self-organized Technical Activity Groups (TAGs), the global Collaboratory for the Study of Earthquake Predictability (CSEP), and the statewide Earthquake Country Alliance (**Fig.1.3**). The EPIcenters program, coordinated through the Earthquake Country Alliance (ECA), now involves more than 50 museums, science centers, and other informal education venues (Fig.1.3). The research initiatives and organizational innovations developed by SCEC in Southern California are being emulated in other regions of high seismic risk and promoted by SCEC's growing network of national and international partnerships.

B. SCEC as a Virtual Organization

SCEC is a truly distributed organization, a realization of NSF's original vision of "centers-without-walls", and a prototype for the organizational structures needed to coordinate the interdisciplinary, multi-institutional science of complex natural systems ("system science"). SCEC's cyberinfrastructure has been highlighted by the NSF Cyberinfrastructure Council [*10*] and in other NSF reports on virtual organizations (VOs) [*11*]. The SCEC4 plan contains specific "smart & green VO" objectives that will contribute to a sustainable future for the Center (see §III.E and §IV). Here we describe five important dimensions of SCEC's organizational capabilities.

Table 1.1. SCEC3 Member Institutions (September 1, 2009)

Core Institutions (16)	Participating 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 University of California, Davis 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

1. SCEC is a ***large consortium of institutions*** with a national, and increasingly worldwide, distribution that coordinates earthquake science within Southern California, and with research elsewhere. Currently, there are 16 "core institutions" that commit sustained support to SCEC, as well as 57 "participating institutions", self-nominated through participation of their scientists and students in SCEC research (Table 1.1).

The current core institutions have all committed resources to SCEC4. Two new institutions have requested to join the core (see attached letters)—the California Geological Survey (CGS) and California State University Center for Collaborative Earthquake Science (CSUCCES), a consortium of 6 CalState campuses dedicated to the study of earthquakes and earthquake hazards—and the University of California at Davis is exploring becoming a core institution. We propose to include CalState—the nation's largest university system and one of its most diverse—as a "distributed" core institution. We will designate one seat on the SCEC4 Board of Directors for CSUCCES, and the participants will split the costs of the $35K per year matching funds. (As with all core institutions, these funds will be expended internally for SCEC-related activities.) This initiative, led by Prof. David Bowman of CalState Fullerton, will benefit an outstanding group of faculty and students who contribute substantially to the SCEC research program.

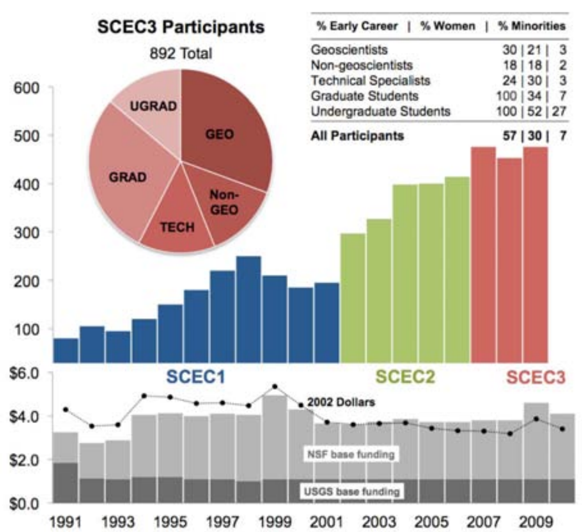


Figure 1.4. Colored bars show total registrants at SCEC Annual Meetings, one measure of how the collaboration has grown during its 20-year history, 1991-2009. Pie chart and table show the demographics of SCEC3. The lower bar chart is the history of SCEC base funding in as-spent dollars; the connected dots are the base-funding totals in 2002 dollars.

The SCEC community comprises one of the largest formal research collaborations in geoscience. Among the most useful measures of SCEC size are the number of people on the Center's email list (1186 on February 24, 2010), active SCEC participants on SCEC projects (892), and the registrants at the SCEC Annual Meeting (476 in 2009). Annual Meeting registrations for SCEC's entire 19-year history and other demographic information are shown in **Fig. 1.4**.

2. SCEC is a ***collaboratory for earthquake system science*** that uses advanced IT to synthesize and validate system-level models of earthquake processes. Components include the Community Modeling Environment (CME) and the Collaboratory for the Study of Earthquake Predictability (CSEP). SCEC strives to be a world-leading VO through the innovative use of "vertically integrated" platforms—cyberinfrastructure that combines hardware (equipment), software (knowledge tools), and wetware (professional expertise) to solve system-level problems. The functioning platforms of the CME collaboratory, which apply high-performance computing and communication (HPCC) to large-scale earthquake modeling, are diagrammed in Fig. 2.26. Further collaboratory innovations are proposed for SCEC4 (see §III.C).

3. SCEC is an ***open community of trust*** that nurtures early-career scientists and shares information and ideas about how earthquakes work. The Center's working groups, workshops, field activities, and annual meeting enable scientists to collaborate over sustained periods, building strong interpersonal networks that promote intellectual exchange and mutual support. In particular, SCEC encourages colleagues with creative physics-based ideas about earthquakes to formulate them as hypotheses that can be tested collectively. An advantage is that researchers with new hypotheses are quickly brought together with others who have observational insights, modeling skills, and knowledge of statistical testing methods.

Participation in SCEC is open, and the participants are constantly changing. At our 2009 Annual Meeting, 121 of the participants (1 in 4) were new registrants. About two-thirds of the total SCEC science budget directly supports students (over 400 in 2009) and early-career scientists (over 100). SCEC has also developed a set of undergraduate and graduate intern programs that recruit a diverse population of students into earthquake science and technology (see §II.B). More than 260 students have participated in these highly rated programs, which feed an effective career-development pipeline. About 30% of SCEC participants are women and 7% under-represented minorities. The number of women serving on the SCEC Planning Committee has increased from 3 in 2006 (13%) to 8 in 2010 (33%), consistent with SCEC's diversity plan, which calls for recruiting women scientists into leadership positions.

4. SCEC is a ***reliable and trusted partner*** that collaborates with other organizations in reducing risk and promoting societal resilience to earthquake disasters. SCEC has partnered with the USGS and CGS to create UCERF and coordinate SoSAFE, with UNAVCO to transfer 125 stations of the SCIGN array to the PBO in Southern California, and with the Computational Infrastructure for Geodynamics (CIG), the Geosciences Network (GEON), and the Incorporated Research Institutions for Seismology (IRIS) to develop user-friendly software packages, IT tools, and educational products. The SCEC Communication Education and Outreach (CEO) program has steadily grown a diverse network of partnerships. The statewide ECA now comprises more than 200 partner organizations, and has greatly increased public participation in earthquake awareness and readiness exercises. The ECA, managed through SCEC's Communication, Education and Outreach (CEO) program, now sponsors yearly preparedness exercises—the Great California ShakeOut—that involve millions of California citizens and expanding partnerships with government agencies, nongovernmental organizations, and commercial enterprises. The CEO program has used SCEC research in developing effective new mechanisms to promote community preparedness and resilience, including the many publications that have branched from the original SCEC publication, *Putting Down Roots in Earthquake Country* (see Fig. 2.24). Letters expressing the enthusiasm of some of our key partners in participating in SCEC4 are included in the supplementary documents section.

5. SCEC is an ***international leader*** that inspires interdisciplinary collaborations, and it involves many scientists from other countries. Currently, 11 leading foreign universities and research organizations are enrolled as participating institutions (Table 1.1), and others are involved through CSEP (**Fig. 1.5**), bilateral memoranda of understanding, and multinational collaborations, such as the Global Earthquake Model (GEM) program [*12*]. The SCEC program is heavily leveraged by contributions by the foreign participants who are supported through their own institutions.

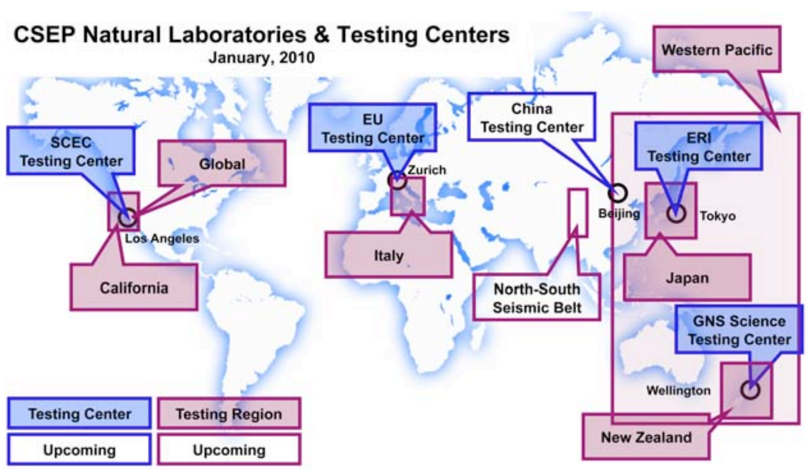


Figure 1.5. Map showing the worldwide distribution of activities developed under the Collaboratory for the Study of Earthquake Predictability (CSEP).

C. Earthquake System Science

Three main problems of earthquake system science are coupled through the complex and nonlinear processes of brittle and ductile deformation: (1) *Dynamics of fault systems*—how forces evolve within fractal fault networks on time scales of hours to millennia to generate sequences of earthquakes. (2) *Dynamics of fault rupture*—how forces produce slip on time scales of seconds to minutes when a fault breaks chaotically during an earthquake. (3) *Dynamics of ground motions*—how seismic waves propagate from the rupture volume and cause shaking at sites distributed over a strongly heterogeneous crust.

Solving these problems depends on a physics-based, interdisciplinary, multi-institutional approach. The proper use of system models to make valid scientific inferences about the real world requires an iterative process of model formulation and verification, physics-based predictions, validation against observations, and, where the model is wanting, data assimilation to improve the model—reinitiating the inference cycle at a higher level (**Fig. 1.6**). As we move outward on this "inference spiral", the data become more accurate and provide higher resolution of actual processes, and the models become more complex and encompass more information, requiring ever increasing computational resources and an improved arsenal of data and model analysis tools. SCEC provides these resources and tools to the earthquake science community through its core science program and its collaboratories.

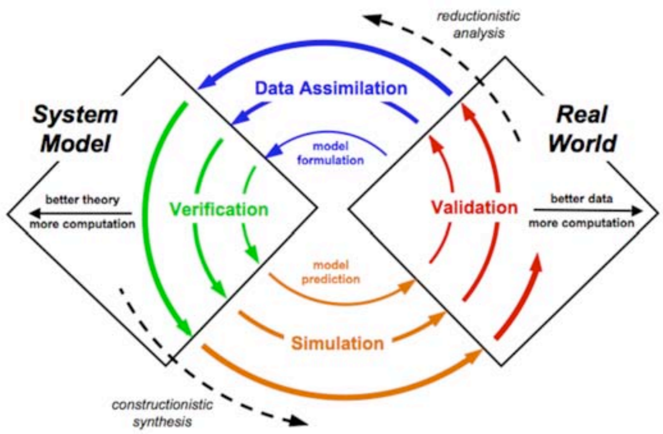


Figure 1.6. The inference spiral for system science, illustrating the improvement of system-level models through an iterated cycle of model formulation (blue), model verification (green), simulation-based prediction (orange), validation against observations (red), and data assimilation (blue). Verification occurs within the system-modeling domain: *does the model do what it's supposed to do at a specified level of precision?* Validation is done in the observational domain: *is the model a credible representation of the real system, adequate for predicting observed behaviors?* Simulation quantifies model predictions for comparisons with observations; data assimilation pulls empirical information into the modeling domain. Moving outward on the spiral involves more computations to incorporate better theories and better observations. Reductionistic analysis complements constructionistic synthesis throughout the process.

D. Intellectual Merit of the Proposed Research

System science seeks to represent nature in terms of models that can explain observations of system-level (emergent) phenomena and predict their future behavior. Earthquakes are system-level phenomena, and the intellectual challenges faced by SCEC4 exemplify those of system-level modeling in many other areas. The Center's research program will continue to guide other integrated studies of complex geosystems. (In a recent example, SCEC was used as an organizational model for the Center for Dark Energy Biosphere Interactions (C-DEBI), funded by NSF as an STC in 2010 [*13*].)

Earthquake system science is an especially difficult intellectual enterprise. 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 (**Fig. 1.8**), and are thus difficult to *predict*. The prediction of earthquake cascades in single events and during seismic sequences is one of the great unsolved problems of physical science. The main goal of SCEC4 program—to understand how seismic hazards change across all time scales of scientific and societal interest, from millennia to seconds—takes aim at this problem.

The fundamental science needed to understand earthquake system dynamics involves the unusual physics of how matter and energy interact during the extreme conditions of rock failure. No theory adequately describes the basic features of dynamic rupture, nor is one available that fully explains the dynamical interactions within networks of faults. Progress towards a comprehensive theory is essential to the improvement of our predictive capabilities. We will move in this direction by focusing on six fundamental problems of earthquake physics (see §III.B): (a) Stress transfer from plate motion to crustal faults: long-term fault slip rates. (b) Stress-mediated fault interactions and earthquake clustering: evaluation of mechanisms. (c) Evolution of fault resistance during seismic slip: scale-appropriate laws for rupture modeling. (d) Structure and evolution of fault zones and systems: relation to earthquake physics. (e) Causes and effects of transient deformations: slow slip events and tectonic tremor. (f) Seismic wave generation and scattering: prediction of strong ground motions.

A variety of evidence—new data, theories, and computations—suggests that progress on these basic problems can be made through interdisciplinary studies and system-level modeling. SCEC4 will move earthquake system science outward on the inference spiral of Fig. 1.6 through highly integrated collaborations that are (1) coordinated across scientific disciplines and research institutions, (2) enabled by high-performance computing and advanced information technology (IT), (3) capable of assimilating new theories and data into system-level models, and (4) can partner with other organizations in delivering practical knowledge to society, including predictions of future system behavior.

E. Broader Impacts of the Proposed Research

California comprises most of the nation's long-term earthquake risk, and Southern California nearly one half [*5*], perhaps even higher over the next few decades (Fig. 1.2). SCEC4 will translate basic research into practical products for reducing risk and improving community resilience in Southern California and elsewhere. As shown in Table 1.2, elements of the SCEC program score well in terms of the five major NSF criteria for broader impacts [*14*]. Its international leadership in system science and sustained efforts to educate a diverse scientific workforce will also contribute to its broader impacts.

SCEC4 will pioneer the geoscience required for time-dependent seismic hazard analysis—to track earthquake cascades (see Fig. 3.1). We are motivated to understand active fault systems on time scales of millennia to days to (a) develop long-term seismic hazard analysis, the basis for seismic safety engineering, into a physics-based science and (b) develop operational earthquake forecasting into a capability that can provide authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes.

Engineered systems in our civilization are driven by events happening on millisecond time scales. Therefore, losses unfold quickly during earthquake cascades. Because a smart and informed society can use real-time earthquake information to minimize its losses, we are motivated to understand fault ruptures on time scales of seconds to minutes. This research will (c) enable earthquake early warning—advanced notification that an earthquake is underway and predictions of when strong shaking will arrive at more distant sites—and (d) improve the delivery of post-event information about strong ground motions and secondary hazards, such as landsliding, liquefaction, and tsunami.

The Center will accomplish this research through an open geoscience collaboration, and its well-developed statewide, national, and international partnerships. Partnerships with Asian countries, especially Japan and China, and European countries, such as Switzerland and Italy, will help to support the SCEC4 program.

Significant efforts during SCEC3, especially the ShakeOut exercises, have helped prepare the Center for a large earthquake in Southern California. In SCEC4, we will continue to work towards an effective post-earthquake scientific response, in coordination with the USGS, CGS, EERI, and other organizations, with the goal of gaining scientific information and useful knowledge from future earthquakes.

Table 1.2. Scoring of SCEC Activities Against NSF Criteria for Broader Impacts

	Criterion				
SCEC Activity	**1**	**2**	**3**	**4**	**5**
Core research program	✓	✓	✓	✓	✓
UCERF2	✓		✓	✓	✓
Seismic Hazard & Risk Analysis	✓		✓	✓	✓
CSEP	✓		✓	✓	✓
SoSAFE			✓	✓	✓
Community Modeling Environment	✓		✓	✓	✓
Earthquake Country Alliance		✓	✓	✓	✓
ShakeOut (drill)	✓	✓		✓	✓
Putting Down Roots	✓			✓	✓
EPIcenters		✓	✓	✓	✓
Internships	✓	✓	✓	✓	✓
K-12 Programs	✓	✓		✓	✓
Media Relations				✓	✓

NSF Broader Impacts Criteria

1. Advance discovery and understanding while promoting teaching, training and learning
2. Broaden participation of underrepresented groups
3. Enhancing infrastructure for research and education
4. Broad dissemination to enhance scientific and technological understanding
5. Benefits to society

II. Research Accomplishments

Probabilistic seismic hazard analysis (PSHA) is the most important geotechnology for characterizing seismic hazards and reducing earthquake risk. The main goal of SCEC3 has been *to transform probabilistic seismic hazard analysis into a physics-based science*. Moving toward this goal has required implementing a series of computational pathways and moving the pathway models outward on the inference spiral of Fig. 1.6. As illustrated in **Fig. 2.1**, all five pathways have been populated with physics-based models, and they have been applied to develop new seismic hazard products (UCERF2), conduct public emergency preparedness drills (ShakeOut), create new ways of assimilating data into models (full-3D waveform tomography), gain new insights into earthquake behavior (ground motion variability caused by dynamic source complexities), and create the first physics-based seismic hazard model (CyberShake).

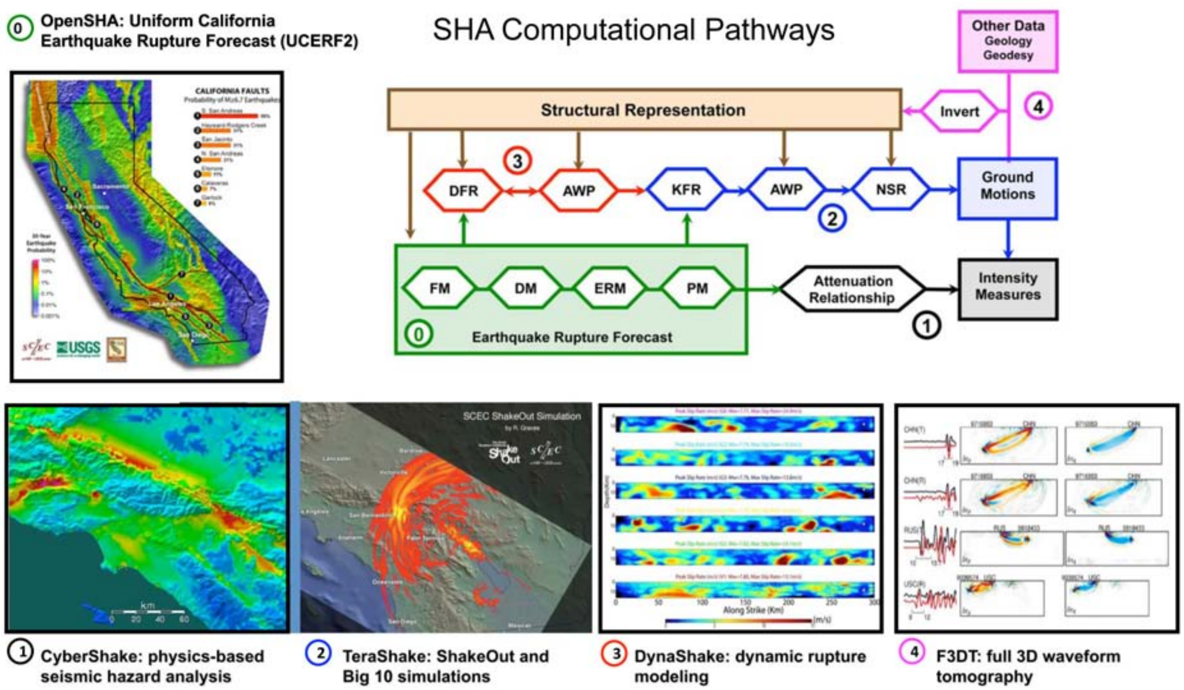


Figure 2.1. Computational pathways for physics-based ground motion prediction in the Community Modeling Environment. (0) UCERF2 empirical earthquake forecast. (1) Cybershake PSHA by ground motion simulation. (2) large earthquake simulation (ShakeOut scenario) using kinematic fault rupture (KFM), anelastic wave propagation (AWP) and nonlinear site-response model (NSR). (3) Dynashake simulation using dynamic fault rupture model (DFR). (4) Inversion of ground-motion data for parameters in the Unified Structural Representation (USR), including 3D information on faults, stresses, and wave speeds.

A. Science Accomplishments

The SCEC3 core research program has focused on improving the science basis for the two principal components of PSHA—earthquake rupture forecasts (ERFs) and ground motion prediction (GMP)—and developing system-specific ERF and GMP models for use in Southern California. Success in the latter activity is demonstrated by the results of three system-level modeling activities:

Uniform California Earthquake Rupture Forecast. The UCERF project is a partnership among SCEC, the USGS, and the California Geological Survey to sponsor the Working Group on California Earthquake Probabilities (WGCEP), and it has received substantial support from the California Earthquake Authority, the state-run earthquake insurance company. The UCERF2 model, released by WGCEP in April, 2008, is the first statewide time-dependent earthquake forecast for California [*6*]. It was developed on OpenSHA, a vertically integrated PSHA computational platform created by a SCEC-USGS partnership. Key UCERF2 components were built on the Community Fault Model (CFM) and other SCEC products. The high impact of UCERF2 on earthquake insurance, seismic safety engineering, and statewide preparedness activities (e.g., ShakeOut), as well as its substantial influence on seismic hazard analysis around the world, suggest that this project has accomplished "transformative science".

CyberShake. This is the first physics-based seismic hazard model that couples an extended earthquake rupture forecast with an anelastic wave propagation model to predict ground motion hazard using a full PSHA formulation. In the current implementation of CyberShake (panel 1 of Fig. 2.1), hazard curves for each site are constructed up to 0.3 Hz from very large ensembles of synthetic seismograms (> 800,000 per site), which sample the complete rupture set of the UCERF2 model [*15*]. For such calculations, UCERF2 needs to be extended to incorporate hypocenter distributions and pseudo-dynamic rupture models that can simulate rupture complexity. The first CyberShake calculations add strong support to a hypothesis motivated by previous SCEC simulations: in the densely populated basins of Southern California, the coupling between source directivity and basin response substantially increases the probability of strong shaking relative to standard PSHA. CyberShake will be an important computational platform for investigating time-dependent seismic hazards in SCEC4.

NGA Project. SCEC has also participated in the Next Generation Attenuation (NGA) project led by the Pacific Earthquake Engineering Research (PEER) Center, which has produced the 2008 set of attenuation relationships now used in the National Seismic Hazard Maps [*16*]. In particular, the SCEC Technical Activity Group on Basin Response provided numerical simulations employed directly by the NGA modelers [*17*].

Box 2.1 SCEC3 Priority Research Objectives

1. **Improve the unified structural representation and employ it to develop system-level models for earthquake forecasting and ground motion prediction.**
2. **Develop an extended earthquake rupture forecast to drive physics-based SHA.**
    3. Define slip rates 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 post-earthquake response strategies.**

The SCEC3 program has been guided by the 19 specific research objectives listed in **Box 2.1**, which are organized under four priority objectives: improve the unified structural representation and employ it to develop system level models for earthquake forecasting and ground motion prediction (objective 1); develop an extended earthquake rupture forecast (objective 2); predict broadband ground motions for a comprehensive set of large scenario earthquakes (objective 13); and prepare post-earthquake response strategies (objective19). In this framework, which will be used here to describe the SCEC3 accomplishments, objectives (3)-(12) are subsidiary to (2), the main ERF objective, and (14)-(18) are subsidiary to (13), the main GMP objective.

1. Develop the Unified Structural Representation

The Unified Structural Representation (USR) refers to a combined set of structural models, which include the Community Velocity Models (CVMs) and the Community Fault Models (CFMs). The USR Focus Group supports the development and improvement of these models using 3D tomography, seismic exploration data and other geophysical surveys, geologic field mapping, precise earthquake relocations, and fault-system modeling. Signal accomplishments in research focused on the USR in SCEC3 include implementation of waveform tomography and incorporation of those results into CVM-H; incorporation of mantle tomography and Moho depths from receiver functions into CVM-H; addition of a shallow geotechnical layer to CVM-H; development of a goodness-of-fit metric for evaluating accuracy of ground motion predictions; and extension of the Community Fault Model to encompass the entire state of California.

Tomography to Improve CVM-H. SCEC has developed two crust and upper mantle velocity models: CVM-S [*18*] and CVM-H [*19*]. These consist of basin descriptions, including structural representations of basin shapes and sediment velocity parameterizations, embedded in regional tomographic models. Development during SCEC3 focused on improvements to CVM-H, which include new v_P, v_S, and density parameterizations within the Santa Maria and Ventura basins, and the Salton Trough. They also include improved tomographic models [20] that extend to 35 km depth and a new upper mantle tomographic model that extends to 300 km depth.

SCEC has taken the lead in developing full-3D waveform tomography, in which the starting model is 3D and the full physics of 3D anelastic wave propagation is used to extract waveform information. Chen et al. [21] used the scattering integral approach to develop the first full-3D waveform inversion-based model of the Los Angeles Basin using finite-difference simulations, and Tape et al. [22] have developed a tomographic model for all of Southern California using adjoint methods and spectral-element simulations. The new model used 6800 wavefield simulations and nearly 1 million CPU hours, and shows strong velocity heterogeneity related to major tectonic features (**Fig. 2.2**). Changes in wave speeds are up to 30% of the background, and highlight basin structures not represented in the original model, such as the San Joaquin Basin. The scattering-integral method has also been extended to image the crustal structure of Southern California using waveform data from both local earthquakes and ambient-noise Green's functions. The first iteration used more than 3500 phase-delay measurements from local earthquakes and about 800 finite-difference wave-propagation simulations [23]. The model perturbation reveals strong contrast in S-wave speed across the San Andreas Fault in the upper- to mid-crust and the updated model provides significantly better fit to observed waveforms. CVM-H 6.2 is the first release that fully integrates 3D waveform tomography into the community velocity model.

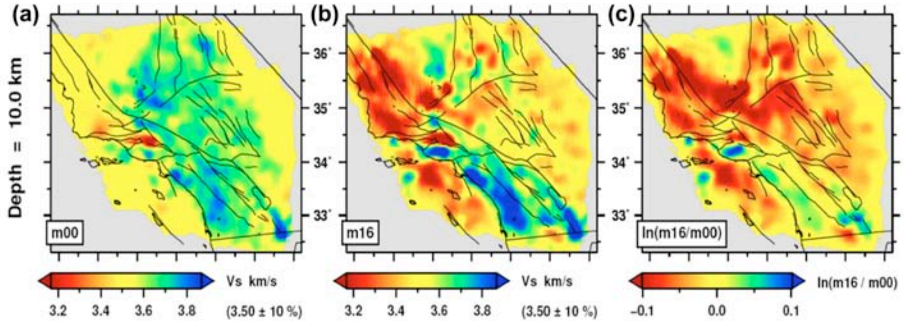


Figure 2.2 Horizontal sections of Vs adjoint tomographic model: (a) starting model CVM-H, (b) adjoint model after 16 iterations, (c) model differences. [22]

Additional Improvements to CVM-H. Additional improvements include a revised Moho (**Fig 2.3**) [24,25]. An important improvement for strong ground motion prediction is the implementation of a new bedrock geotechnical layer [26] based on the depth-velocity relations [27]. The cumulative effect of these changes is a dramatically improved CVM-H (**Fig. 2.4**).

Further improvements in the CVM should come rapidly now that waveform tomography is operational and a pathway into the velocity models is established. Green's functions from the ambient seismic field [28] will provide manifold new constraints on the velocity model [23] and attenuation model as well [29]. A key strength of the ambient-noise approach to CVM development is that it provides constraints in areas that are important for seismic hazard analysis, but that currently lack recordings of moderate earthquakes with which to validate the models (most notably for paths from the San Andreas Fault). SCEC is also developing eTree, and other representations, as well as parallel HPC codes to facilitate use of community models in large computational meshes and grids.

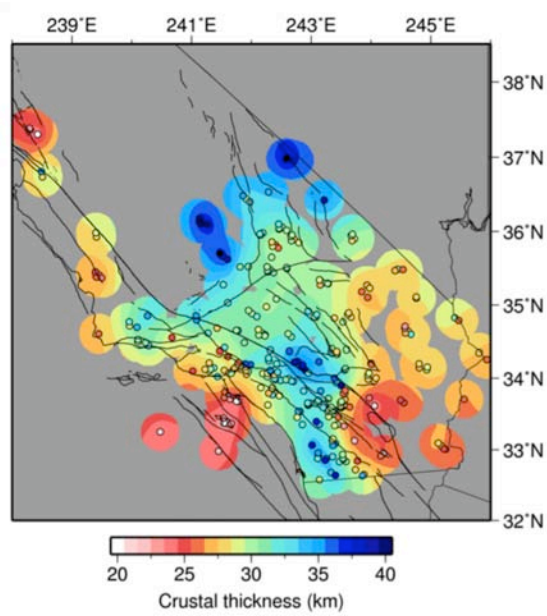


Figure 2.3 CVM-H was updated to include Moho depth from receiver functions [24].

Assessing the Accuracy of Ground Motion Predictions. The primary use of the CVM is to predict ground motion for physics-based seismic hazard analysis. To assess these ground motion predictions SCEC scientists developed a flexible goodness-of-fit metric that compares simulated and observed ground motions [30] according to criteria that can be tailored to specific applications. The method includes a set of user-weighted metrics such as peak ground motions, response spectrum, the Fourier spectrum, cross cor-

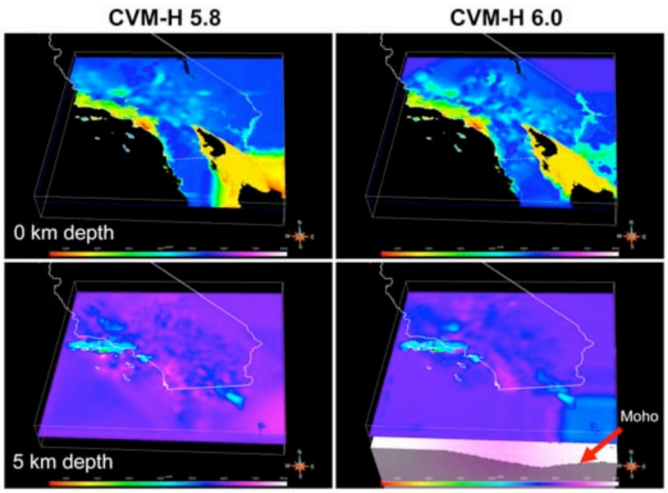


Figure 2.4. SCEC Community Velocity Model, CVM-H 6.0, and later revisions includes basin structures embedded in the 3D waveform inversion model, and an explicit representation of the Moho.

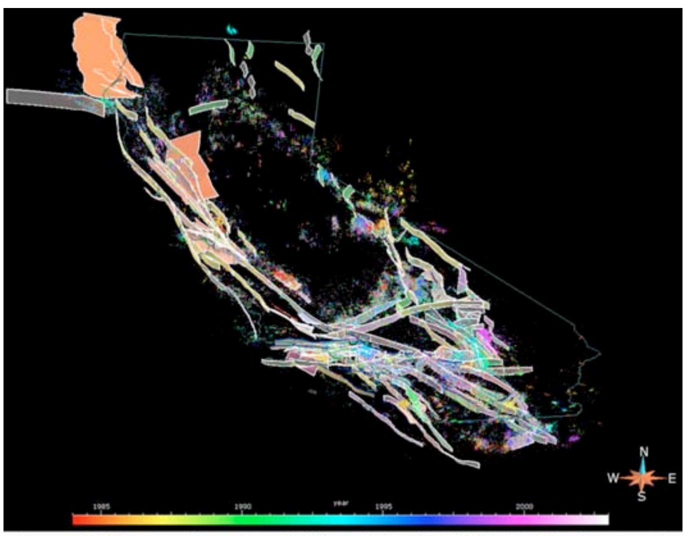


Figure 2.5 Perspective view of initial statewide CFM. Faults shown with hypocenters (colored coded by date) from [*31*].

relation, energy release measures, and inelastic elastic displacement ratios. It has been used to validate CVM-H and CVM-S simulations of the 2008 M5.4 Chino Hills earthquake.

<u>A Statewide Community Fault Model.</u> The community fault model has improved rapidly during SCEC3, and now extends statewide as the result of a joint effort with the USGS and CGS. The statewide model (SCFM) consists of the CFM in southern California [*26*] and new representations of faults in northern California (**Fig 2.5**). This was a key requirement for developing a statewide rupture forecast model in UCERF2, and for use in simulating seismicity catalogs. The CFM in southern California continues to be improved using relocated earthquake catalogs [*31*], which provide significantly improved resolution of many faults, particularly in areas of complex fault junctions [*32*]. The Uniform California Earthquake Rupture Forecast (UCERF3) project is critically dependent on the statewide CFM.

2. Develop an Extended Earthquake Rupture Forecast

Many elements of the SCEC3 research program contribute to the development of an "extended" earthquake rupture forecast; i.e., one with the requisite elements for physics-based simulations, as described above. Development of extended rupture forecasts draws on the full range of geoscience disciplines within SCEC and requires information from the entire range of temporal and spatial scales involved in the earthquake process. Signal accomplishments in developing and extended earthquake rupture forecast include: new understanding of the south-central San Andreas Fault that increases its seismic hazard; discovery and development of paleoseismic sites on the San Andreas system; progress in resolving geologic vs. geodetic slip-rate discrepancies; progress in modeling fault systems to include realistic geometry and loading; precision seismicity and source parameter catalogs; development of detection algorithms for aseismic transients; new infrastructure for earthquake predictability experiments; new understanding of the importance of off-fault deformation; and tests of dynamic fault-weakening mechanisms.

*<u>More Frequent Large Earthquakes on the South-Central San Andreas Fault</u>***.** A key to understanding the likely future behavior of the Southern California Fault System, is to refine our understanding of its past. A centerpiece of this effort is the Southern San Andreas Fault Evaluation (SoSAFE) special project, which receives support from the USGS Multi-Hazards Demonstration Project. This research venture, coordinated through SCEC, has led to fundamental advances in understanding of the size, frequency, and predictability of major earthquakes on the principal plate boundary structures in southern California. Progress in this area during SCEC3 has been profound to the point where we have a dramatically different view of the earthquake potential of the San Andreas Fault than we had just two years ago.

Research on slip-rate and slip-per-event blossomed with the release of the 'B4' lidar data set that imaged the entire southern San Andreas Fault. Results from the lidar data will be flowing in for the remainder of SCEC3 and beyond, but an early highlight of this work is the result from *Zielke et al.* [*9*] demonstrating that numerous, subtle 5m offsets are present along the Carrizo Plain section of the San Andreas Fault (**Fig. 2.6**). The youngest offsets cut by half the ~8m slip attributed to the 1857 Fort Tejon earthquake by Sieh [*33*]. This result agrees well with new paleoseismic results from the Bidart fan paleoeseismic site [*8*]. These findings imply that major events on the south-central San Andreas Fault are about *twice as frequent* as previously believed. The conclusion is that the entire southern San Andreas Fault is "locked and loaded" and could rupture in one, or a series, of large earthquakes at any time (Fig. 1.2).

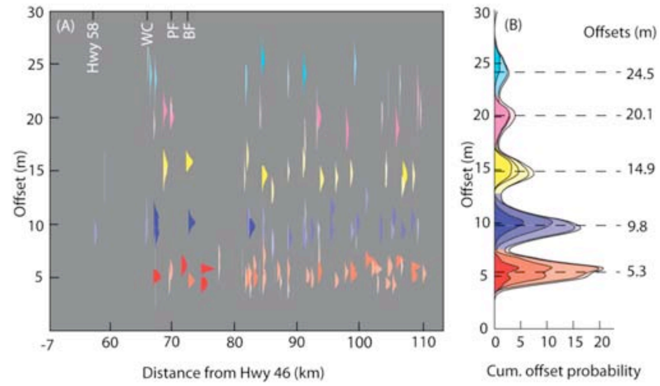


Figure 2.6. (A) Offset probability for slip from the 'B4' LiDAR along the Carrizo section of the San Andreas. Color based on respective optimal offset measurement (red=5±2.5 m, blue=10±2.5 m, yellow=15±2.5 m, magenta=20±2.5 m, cyan=25±2.5 m), indicating to which cumulative offset probability density (COPD) peak it contributes most. Intensity based on the quality of measurement. (B) COPD color intensity is based on the quality of the offset estimates in the stacking. The COPD forms narrow, well separated peaks [*9*].

<u>*Tests of Earthquake Recurrence and Slip-Rate Variations.*</u> **Fig 2.7** illustrates several critical paleoseismic data gaps have been filled and that new developments are unfolding from synthesis of paleoseismology, slip-rate, and slip-per-event data. New, deeper investigations at the Frazier Mountain site have begun to fill a critical data gap in the northern Big Bend of the San Andreas, which should allow correlation of records from the Carrizo Plain to the Mojave Section [*34*]. Preliminary findings support the idea that most of the prehistoric earthquakes that ruptured the Carrizo Plain reached Frazier Mountain and about half can be connected to Pallett Creek (Fig. 2.7). Work at the Frazier Mountain site continues, now externally supported by the NSF Tectonics program. Another focus of the SoSAFE project has been the Coachella Valley – the only portion of the San Andreas that has not ruptured historically [*35*]. The northern San Jacinto Fault was also identified as a target of interest because of the potential trade-off of activity with the nearby San Andreas [*36*]. The emerging view is that slip is approximately equally partitioned between the San Andreas and northern San Jacinto Faults (Fig. 2.7). The discovery of a new paleoseismic site along the San Jacinto Fault at Mystic Lake [*37*] has great potential to yield a long record of earthquake recurrence.

Ongoing work at sites on the San Andreas Fault will further refine event-dates and slip-per-event. New paleoseismic records from the eastern California shear zone and from large blind thrust fault systems that underlie the coastal basins will further test the size of potential earthquakes. The ongoing research will help to quantify the threat from

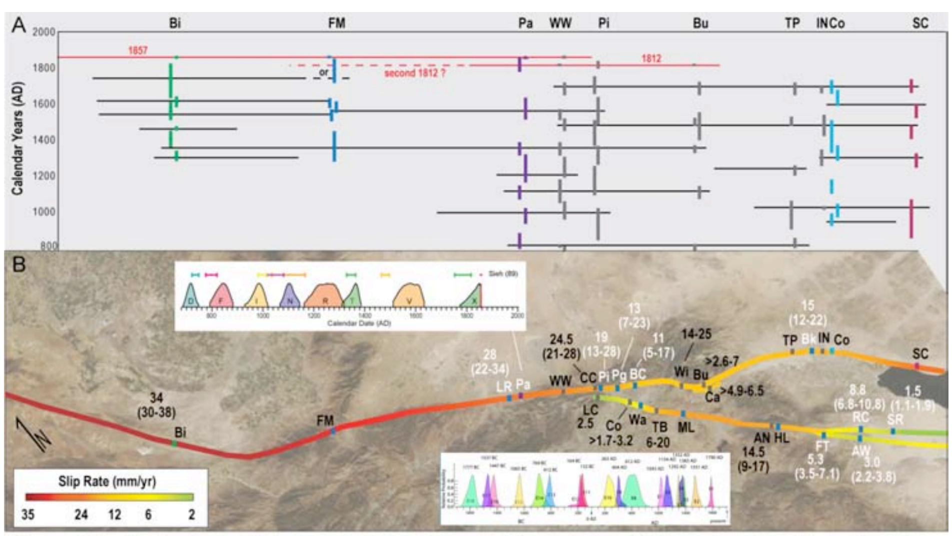


Figure 2.7. San Andreas Fault system data collected during SCEC3. (A) 2σ range for paleoearthquakes on the San Andreas identified/dated during SCEC3 (in color). Correlations based on age (black) suggest preference for N and S events. Color shows slip rate (mm/yr). Insets show PDFs for Hog Lake (lower) and Pallett Creek (upper).

faults that lie closest to urban centers; in particular, the large blind thrust systems directly beneath Los Angeles. Future work on the thrust systems of the western Transverse Ranges will examine the possibility that major faults could link into a very large event similar to the 2008 Wenchuan earthquake. Provocative results [*38*] indicate 6-7 m of coseismic uplift of the Ventura Anticline in a very large event about 1000 yrs ago.

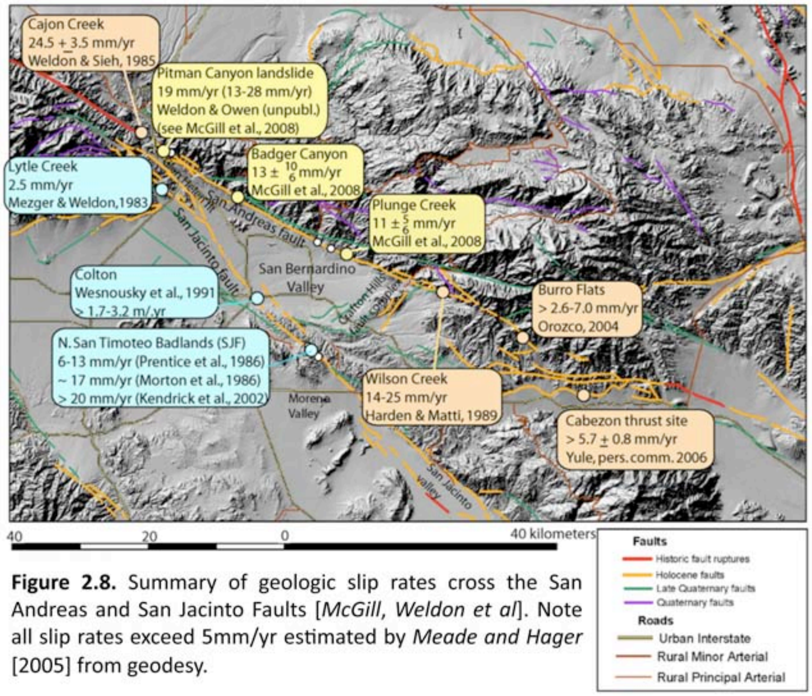


Figure 2.8. Summary of geologic slip rates cross the San Andreas and San Jacinto Faults [*McGill, Weldon et al*]. Note all slip rates exceed 5mm/yr estimated by *Meade and Hager* [2005] from geodesy.

<u>*Resolving Geologic vs. Geodetic Slip-Rate Discrepancies.*</u> At the end of SCEC2, some of the geodetic/geologic slip rate discrepancies were substantial and difficult to understand (**Fig. 2.8**). Work at several new sites on the San Jacinto Fault is testing for temporal variation of slip rate [*36*,*37*]. Geologically based slip-rate studies have focused on a possible trade-off in activity between the southernmost San Andreas and San Jacinto Faults. These include an intensive study of slip rate from the Biskra Palms site on the San Andreas [*39*], documentation of slip rates showing a gradient in activity on the San Bernardino section north of San Gorgonio Pass [*36*], and a multi-site investigation of slip rates on the San Jacinto [*37*,*40*]. Evidence for earthquake clustering [*41*] and temporal variation in slip rate of the San Jacinto [*40*] also suggest that its activity may oscillate with the southernmost San Andreas Fault.

SCEC played a central role in establishing continuously recording Global Positioning System (GPS) measurements in southern California with the Southern California Integrated GPS Network [*42*] (which, in many ways, was the prototype for EarthScope's Plate Boundary Observatory). SCEC continues to support new GPS observations, with a focus on campaign GPS data in strategically important locations that complement continuous GPS coverage. SCEC researchers are collecting data along the San Bernardino section of the San Andreas, in Joshua Tree National Park, near Anza, and in the Salton Trough to address discrepancies between geologically and geodetically determined slip rates and to characterize the important details of deformation in these high strain-rate regions.

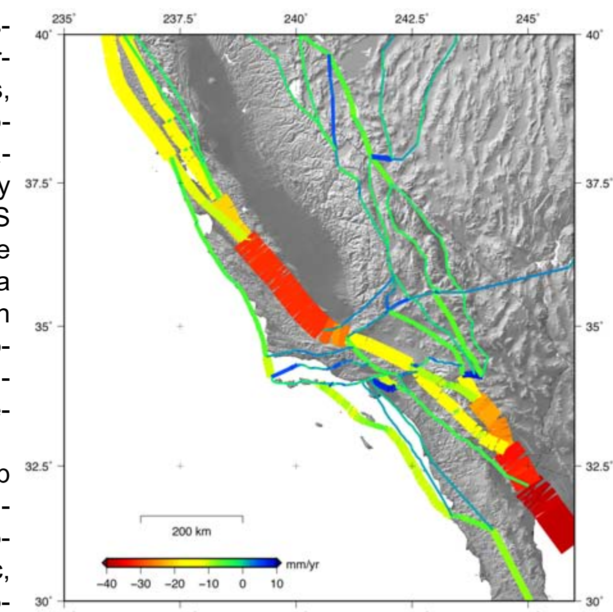


Figure 2.9. Geodetically constrained slip rates from 3D spherical block model, based on SCEC CFM, 1822 GPS velocities, and constrained by plate motion. Wider lines show higher slip rates, highlighting large variations along the San Andreas: from 35 mm/yr through the Carrizo segment to 9-11 mm/yr along the San Bernardino segment.

Geodetic observations can only be interpreted as slip rates through crustal deformation modeling. SCEC3 scientists have taken a number of different modeling approaches to infer fault slip rates from geodetic, geologic, and stress data. Of particular note are significant discrepancies between slip rates predicted by the elastic block model and geologic estimates of fault slip rates (Fig. 2.8). Relative to geologic rates, the elastic model predicts low rates on the Mojave and San Bernadino segments of the San Andreas as well as the Garlock fault, and high rates

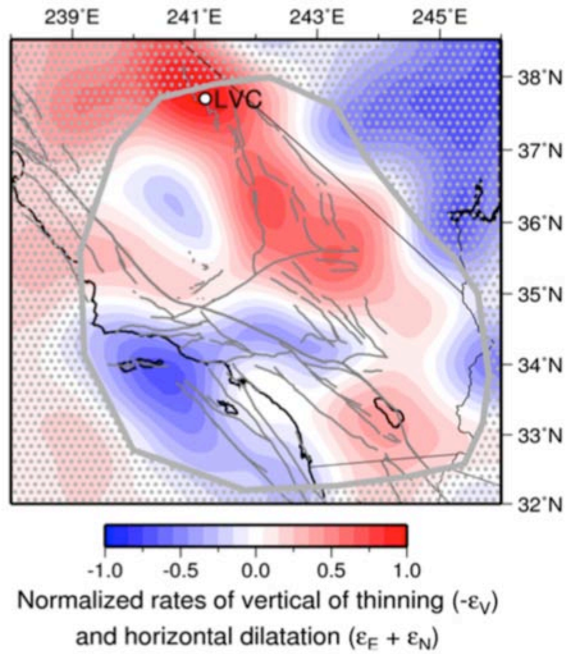


Figure 2.10. Predicted rates of vertical and horizontal strain, inferred from seismic tomography of the upper mantle [*46*].

in the Eastern California Shear Zone. These discrepancies with geologic measurements [*43*] have been largely resolved by more recent block modeling (**Fig. 2.9**); they now point to 9-11 mm/yr rates on the SBSAF, in agreement with the geologic rates. The slip rates from the block model (Fig. 2.9) increased largely due to changes in the representation of fault system geometry, pointing to the importance of an accurate CFM. This illustrates how interdisciplinary collaborations can resolve research questions.

In addition to the block modeling, viscoelastic earthquake cycle models for Southern California predict slip rates on the San Andreas and in the Eastern California shear zone that are largely consistent with geologic rates [*44*]. Thus, viscous relaxation between large earthquakes may account for the apparent low rates across the San Andreas and Garlock Faults, and high rates across the Eastern California shear zone.

Progress in Modeling Fault Systems. System-level deformation and stress-evolution modeling requires understanding heterogeneities in the stress, strain, geometry, and material properties. A goal is to determine how plate motion is resolved onto the San Andreas Fault system. An important element of this is resolving absolute stress levels acting across faults. A novel approach to this uses seismic tomography of the upper mantle, which can be interpreted in terms of density anomalies that exert known loading on the Southern California crust and upper mantle [*45*]. This load is substantial; resolving the predicted geodetic signal (**Fig 2.10**) provides an important constraint on absolute stress levels [*46*].

An emerging activity within SCEC3 is the development of earthquake simulators, aimed at generating synthetic earthquake catalogs over a range of spatial and temporal scales [*47*,*48*]. An Earthquake Simulator TAG has been formed, and results on a sequence of standardized simulation problems have been generated by the participating groups, intercomparisons have been made, and more complex problems formulated. An example of a simulated sequence of earthquakes on the San Andreas system is shown in **Fig. 2.11**. The simulator is based a quasi-static boundary-element calculation that employs a Dieterich nucleation model and can handle very complex fault geometries [*48*]**.** The vision for simulator-based seismicity catalogs is that they will provide important input into time-dependent earthquake rupture forecasts, such as the new UCERF3 project, by combining short-term triggering effects with long-term stress renewal effects.

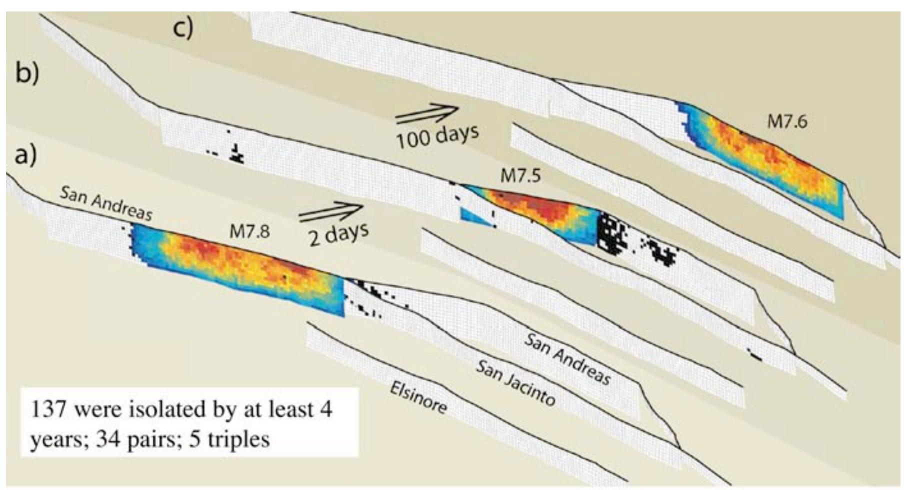


Figure 2.11. Example output from earthquake simulator showing a sequence of earthquakes on the San Andreas Fault. There were 72 aftershocks in the 2-day interval between the M 7.8 and M 7.5 events, and 183 aftershocks in the 100-day interval between that and the M 7.6 event. Over the long term, the simulation led to 227 M > 7 earthquakes on these faults [*48*].

Precision Catalogs. As earthquake rupture simulators show, fault geometry has a strong effect on earthquake size and occurrence. Much of what we know about fault structure at depth comes from earthquake locations. Recent development of precise location techniques, and their application to large Southern California catalogs [*31*], have allowed researchers to discern structures that were previously obscured by location uncertainties (**Fig. 2.12**). Incorporating this new information into the Community Fault Model is a major activity in SCEC3. Work is also underway to develop the capability for precise locations in near real time. Improved stress measurements from earthquakes is an important objective. We are working to improve and interpret both catalogs of stress drops and earthquake focal mechanisms that account for SH/P amplitude ratios as well as first motions to reduce uncertainty (Fig. 2.12). Algorithms for improved focal mechanism determination are currently being automated.

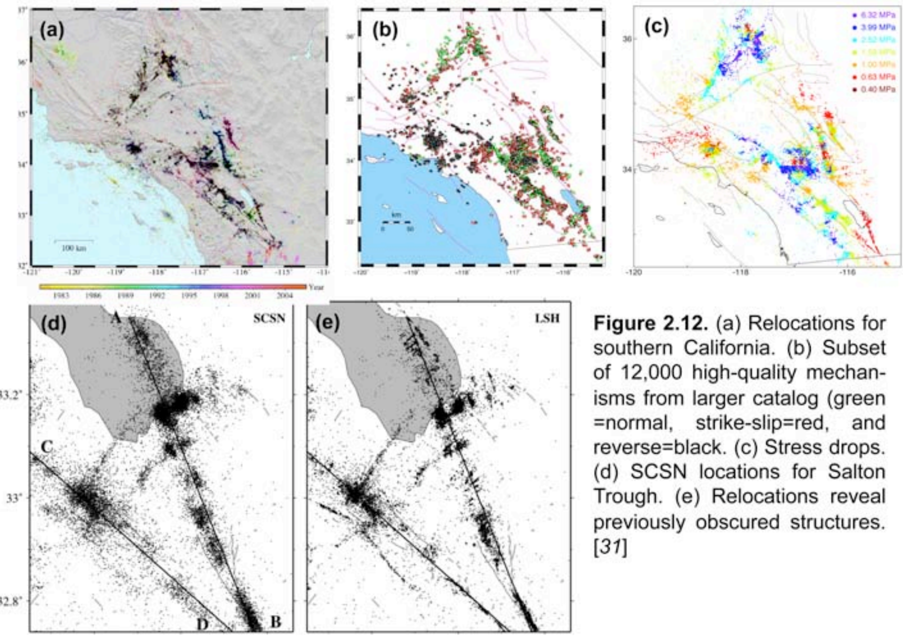


Figure 2.12. (a) Relocations for southern California. (b) Subset of 12,000 high-quality mechanisms from larger catalog (green =normal, strike-slip=red, and reverse=black. (c) Stress drops. (d) SCSN locations for Salton Trough. (e) Relocations reveal previously obscured structures. [*31*]

Aseismic Transient Detectors. A SCEC3 objective is to develop geodetic transient detectors, and a Transient Detector Technical Activity Group has been formed for this purpose. This group is organized like the Earthquake Simulators and Rupture Dynamics Code Verification TAGS, and their objective is to develop new approaches to geodetic transient detection. Test data are distributed to participants who apply their detection methodologies and report on any transient signals they find through an online forum and at small workshops (**Fig. 2.13**)**.** So far, test data have been time series of synthetic GPS observations possibly containing an unknown transient fault slip signal and contaminated by a realistic combination of noise sources. As the exercise progresses, more complexity will be added to the synthetic data, test datasets consisting of real GPS time series will be incorporated, and other data types such as InSAR and strainmeter observations will be included. The eventual goal is to make geodetic transient detection an operational capability.

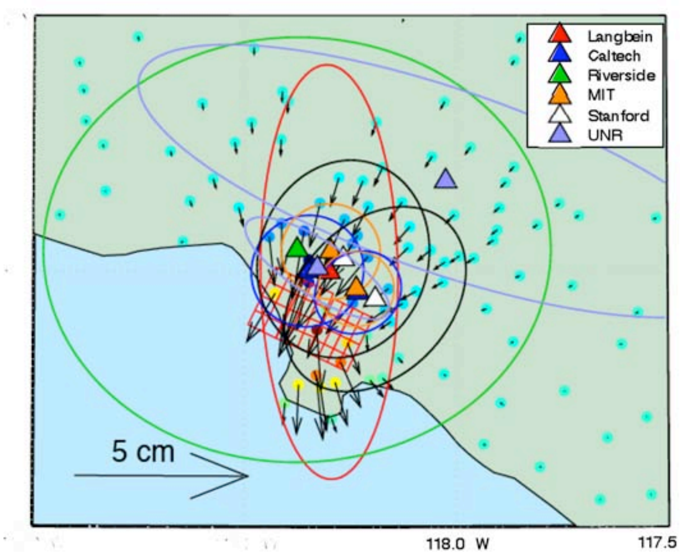


Figure 2.13. Summary of results from a test dataset used in the Transient Detection Test Exercise. Triangles with ellipses mark centroid location and extent of the transient cumulative displacement detected by each participating group. Cumulative noiseless synthetic displacements that were added to the test data are shown by the vectors, and the source fault geometry is shown by the red grid.

Earthquake Predictability Experiments. The Collaboratory for the Study of Earthquake Predictability (CSEP) is developing a virtual, distributed laboratory that supports a wide range of scientific prediction experiments in regional or global natural laboratories, and provides means for conducting and evaluating earthquake prediction experiments, with the goal of determining the extent to which the earthquake rupture process is predictable. CSEP has developed rigorous procedures for comparative testing of predictions as part of an infrastructure, including authorized data sets and monitoring products [*49*]. A major focus of CSEP is to develop international collaborations between regional testing centers and to accommodate a wide-ranging set of prediction experiments involving geographically distributed fault systems in diverse tectonic environments. Nucleated as a special project within SCEC with funding from the W. M. Keck Foundation, CSEP has rapidly become a large international organization, with testing centers in Switzerland, New Zealand, Japan, and, most recently, China (Fig. 1.6).

Work on short-term earthquake forecast models for CSEP testing has focused on models, such as the Epidemic Type Aftershock Sequence (ETAS), which are updated and tested on a daily schedule. Models based on ETAS have been submitted to CSEP, some with a focus on California, while others are global, including both long-term and short-term global earthquake forecasts based on earthquake branching models and estimates of tectonic deformation (**Fig. 2.14**). There are currently more than 100 earthquake forecasts being testing by CSEP, and the global forecasts are being evaluated at the SCEC testing center. Considerable work has gone into the development of appropriate statistical tests for alarm-based earthquake forecasts [*50*]. This represents an important expansion of CSEP's capabilities, as it allows CSEP to test classical earthquake predictions defined by a magnitude, time and location window.

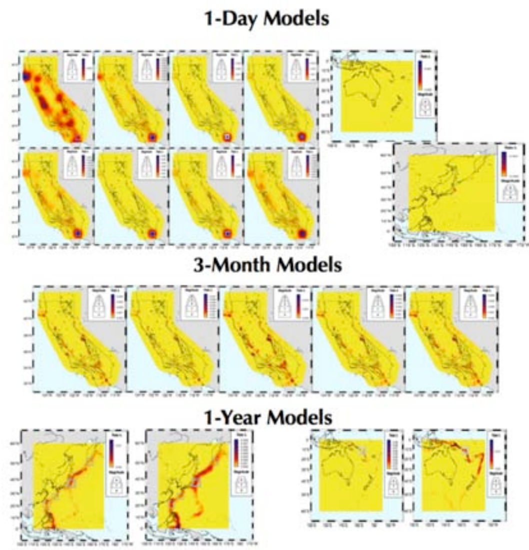


Figure 2.14. Example earthquake forecast models under evaluation at the CSEP testing center.

Importance of Off-Fault Deformation. The need to account for off-fault deformation in ground motion modeling, dynamic rupture modeling, and in crustal deformation modeling more broadly, has emerged as a major theme of SCEC3. This includes damage in the very near field, and there is great progress in understanding the origin and effects of damaged and pulverized rocks along faults. Shallow drilling and coring of the pulverized zone adjacent to the San Andreas at Little Rock is the first borehole sampling effort to disentangle the mechanism of pulverization from near-surface weathering. *Weschler et al.* [*51*] found clear evidence for pulverized rock that had undergone extensive tensile failure, and multiple fracture-healing cycles indicating they are earthquake-generated. Studies of pulverized rocks along major southern California faults [*52*] point to an origin caused by dynamic slip, but at relatively shallow depth. The need to assess the contribution of fracture and comminution to the earthquake energy budget also motivated improved techniques to determine particle size distributions in fine-grained fault rocks [*52*]. The presence of damage has been shown to have a strong effect on dynamic rupture in the laboratory [*53*].

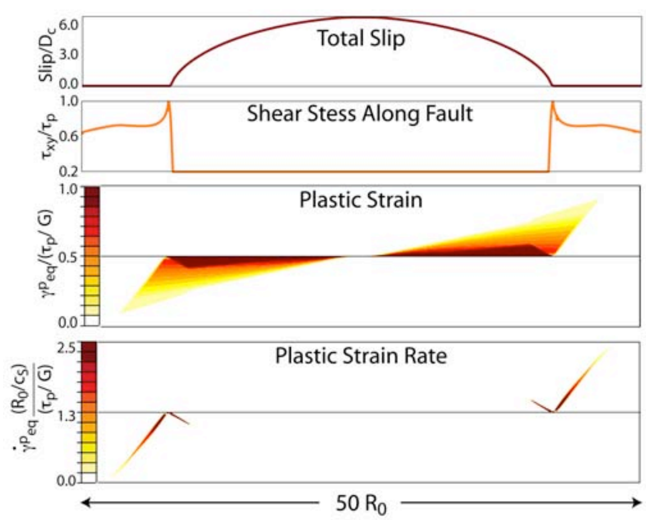


Figure 2.15. Accumulation and evolution of plastic strain during rupture propagation [*Templeton et al.*, 2009]. Plastic strain accumulates in a narrow zone near the crack tip.

Central to earthquake rupture forecasts is the ability to predict extent and direction of rupture on major faults. Fault geometry is thought to play a major role in the former, and there are indications that material contrasts across a fault might play a controlling role in the latter. Slip on non-planar faults leads to geometric incompatibilities that grow in proportion to slip if the crust is assumed to behave elastically. In SCEC2 almost all numerical simulations assumed elastic yielding, whereas in SCEC3 inelastic effects have been examined and found to be important.

Much of the initial impetus for modeling off-fault plasticity (**Fig. 2.15**) came from the Extreme Ground Motion (ExGM) special project, which is designed to understand absolute limits on maximum possible ground motion at the proposed Yucca Mountain Nuclear Waste Repository [*54*]. The most recent efforts of the SCEC Rupture Dynamics Code Validation TAG [*55*] tested the effects of elastic vs. plastic yielding during super-shear and complete stress-drop earthquakes (extreme events) in both 2D and 3D. The maximum vertical ground motion (velocity) at a 300-m deep repository site was produced when 2D elastic assumptions were adopted, while ground motions were lowest for 3D simulations with plastic-yielding. The importance of off-fault yielding extends far beyond the Extreme Ground Motion project, however. The potential "smoothing" effect of near crack tip plasticity may, for example, counteract the need to resolve finer and finer spatial details in numerical simulations due to Lorentzian contraction during high-speed rupture propagation.

Tests of Dynamic Fault-Weakening. Identifying new mechanisms of dynamic fault weakening was an important achievement of SCEC2. The same research area remains as a research thrust in SCEC3, but the focus now is on understanding which dynamic weakening effects are most important and, which are most likely to be operative on real faults, and how might their signature be expressed in the field, and during fault rupture. *Dunham and Rice* [*56*] and *Noda et al.* [*57*] developed numerical methods for incorporating flash heating and pore fluid pressurization into a boundary integral code for dynamic rupture propagation. Recent models simulating spontaneous ruptures, constrained by lab and field data and incorporating rate-and-state friction laws, show that flash heating on faults with initially low ratios of shear to effective normal stress promote self-healing slip pulse behavior and predict stress drops consistent with seismic observations. Critical to understanding the role of fault geometry on dynamic rupture is determining how strength changes with normal stress changes. Plate-impact experiments demonstrate that sudden changes in normal stress cause friction to gradually approach a new steady-state level [*58*], reflecting the current state of the interface.

Theory [*59*,*60*] indicates the velocity at the onset of weakening due to flash heating varies inversely with contact size. *Tullis and Goldsby* [*61*] tested this prediction, but found that samples of large initial roughness do not demonstrate dramatic weakening. The discrepancy reflects the development and shearing of a gouge layer. This emphasizes the importance of slip localization and contact size in determining the degree to which flash heating is an important weakening mechanism in nature. *Sagy et al.* [*62*] and *Sagy and Brodsky* [*63*] find that slip surfaces bound a cohesive layer that has undergone granular flow, that the topography of the surfaces reflects variations in the thickness of this layer, and that it thins with displacement. *Kitajima et al.* [*64*] developed a new understanding of the interactions between changing normal stress, temperature, and displacement in the formation and behavior of slip surfaces in high displacement fault zones using detailed microscopy and thermo-mechanical modeling. They found that dynamic weakening initiates above a critical temperature and is associated with slip localization and formation of a fluidized gouge layer (**Fig. 2.16**). These and related findings, have significant implications for improving models of slip on faults that incorporate realistic geological and geometrical complexities.

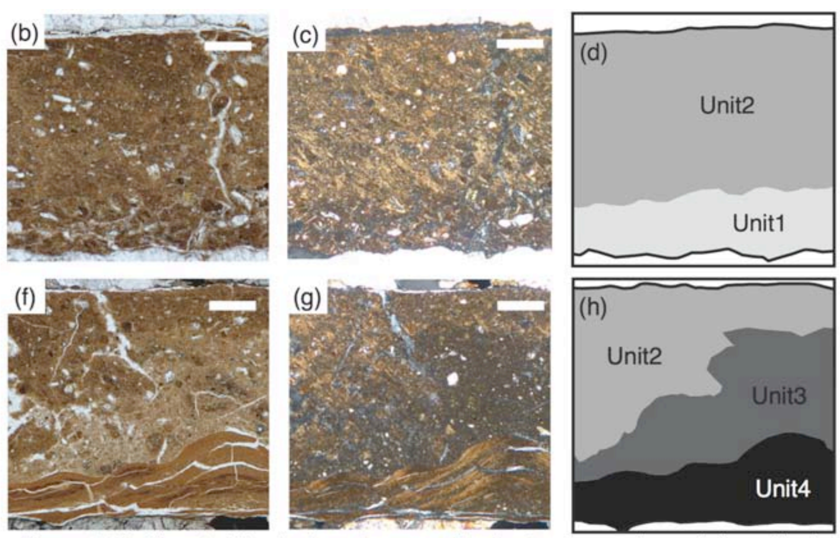


Figure 2.16. Characteristic structure of gouge units showing progressive evolution with slip. Unit 4 has been repeatedly imbricated and stacked [*64*].

3. Predict Broadband Ground Motions

The critical tie between improved earthquake rupture forecasts, and earthquake risk reduction is accurate ground motion prediction. SCEC's goal is the development of fully validated strong ground motion prediction based on a fundamental, physics-based understanding of earthquake rupture and seismic wave propagation. Simulating strong ground motion for large scenario earthquakes is one of the overarching research objectives of SCEC3, and there are a number of elements of the SCEC3 research program that contribute directly to this effort, including much of the research within the Community Modeling Environment (CME). Signal accomplishments in developing and extended earthquake rupture forecast include: verification of wave propagation and dynamic rupture algorithms; development of improved pseudo-dynamic representations; improved understanding of the possible effects of super-shear rupture; new ideas for modeling excitation of high-frequency ground motion; and new approaches to validations of strong ground motion simulations.

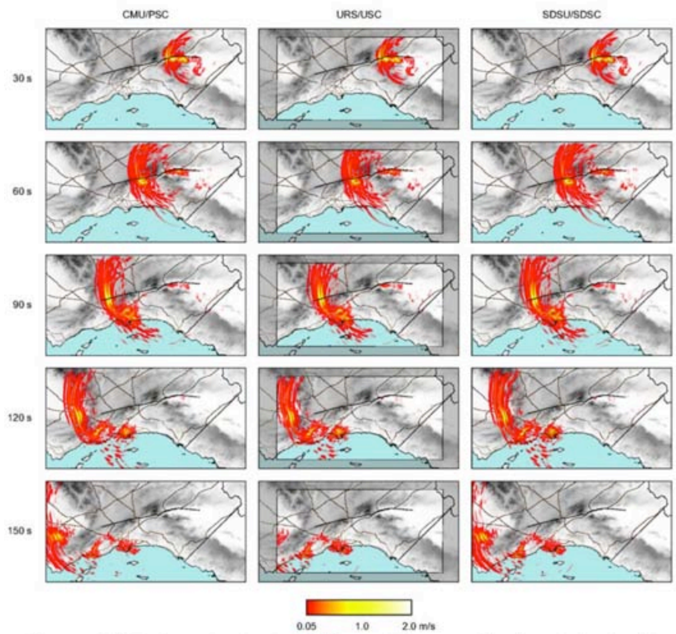


Figure 2.17. Snapshots at 5 different times, of horizontal velocity for 3 ShakeOut simulations. Groups/computer centers are from left to right: CMU/PSC, URS/USC, and SDSU/SDSC.

Another category of accomplishments in this area is the application of ground motion simulations for specific purposes. The Seismic Hazard and Risk Analysis focus group coordinates this research within SCEC. Here too, SCEC3 has an impressive list of accomplishments: ground motion simulations for extreme events, in support of NGA and the new National Seismic Hazard Maps, and for the PEER Tall Building Initiative; and for end-to-end simulations.

<u>Verification of Algorithms</u>. Simulating ground motions from complex ruptures in a 3D Earth is a task that absolutely *requires* high-performance computing (HPC). For that reason, SCEC3 has developed special projects that enable the requisite HPC, in particular the CME. These projects are a major success for SCEC in their own right (but not described here). As with any simulation, verification that algorithms are properly solving the wave propagation problem as posed is a challenge. SCEC has a long and successful history of code verification exercises, a history that is continuing not just with ground motion prediction, but with other tasks, such as dynamic rupture modeling [*55*] and ground motion modeling of large scenario earthquakes, such as the ShakeOut scenario [*65*] (**Fig. 2.17**).

<u>Improved Pseudo-Dynamic Rupture Models.</u> Dynamic rupture models incorporate the physics of earthquake rupture that can improve simulations for ground motion prediction; however, developing dynamic rupture models of sufficient spatial and temporal detail to simulate the full frequency range of engineering interest is not yet possible. For that reason, SCEC3 has an objective of developing kinematic rupture representations that are consistent with dynamic rupture models. These "pseudo-dynamic" models are kinematically prescribed, but incorporate the salient features of dynamic models required for strong ground motion prediction [*66*]. Multiple dynamic-rupture variations have been calculated for the ShakeOut scenario earthquake to estimate long-

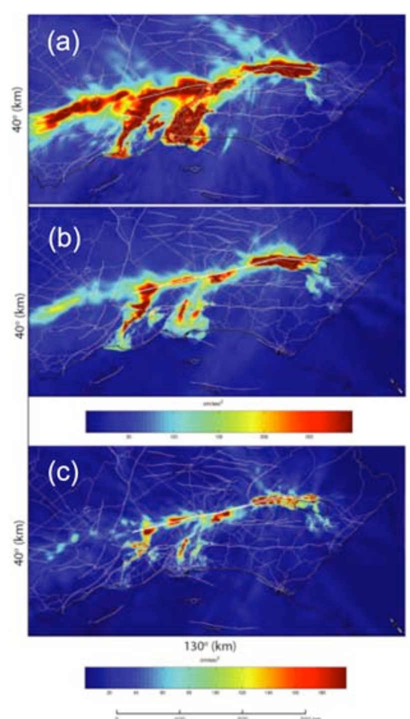


Figure 2.18. 3s SA for (a) kinematic, (b) mean dynamic, and (c) standard deviation of dynamic for ShakeOut scenario simulations.

period spectral acceleration within the basins of greater Los Angeles. Predicted ground motions were a factor of 2–3 lower than the corresponding kinematic predictions, which stems from the less coherent wavefield excited by the complex rupture paths of the dynamic sources. An unanticipated result of those simulations was that dynamic predictions (at a given site) were very stable (**Fig 2.18**). This suggests that simulation ensemble variances may be substantially reduced through use of sources based on spontaneous rupture simulations.

<u>*Effect of Super-shear Rupture.*</u> It has become apparent that super-shear rupture can occur over substantial parts of the fault in large strike-slip earthquakes. This is in line with theoretical predictions from decades ago [*67*], but we are still coming to grips with the implications for ground motion prediction because sub- and super-shear ruptures exhibit qualitatively different characteristics [*68*]. Super-shear rupture is observed in dynamic rupture simulations, such as the "wall-to-wall" earthquake rupture of the entire southern San Andreas Fault (**Fig 2.19**). The long, straight section of the Carrizo segment of the San Andreas is consistent with the conditions thought to be conducive to super-shear rupture [*69*] and the lack of on-fault seismicity on the San Andreas, here and elsewhere, is also suggestive [*70*]. Super-shear rupture adds a layer of complexity to ground motion simulation, because it may not occur in most earthquakes used to develop ground motion attenuation relations. It underscores the need for simulation-based ground motion predictions.

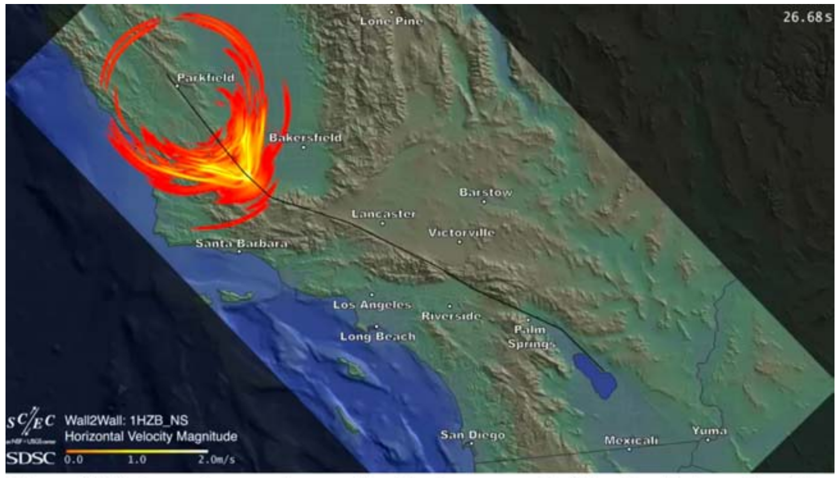


Figure 2.19. Supershear rupture on the Carrizo segment of the San Andreas Fault in this dynamic simulation of NW-SE rupture results in the formation of a classic Mach cone – the seismic equivalent of a sonic boom – behind the rupture front.

<u>*High-Frequency Excitation.*</u> We are working to address a pressing need in engineering seismology, *viz.,* to develop improved high-frequency simulation methods and investigate the upper frequency limit of deterministic ground motion predictions. Current methods to simulate high frequency ground motions use rather *ad hoc* approaches. It has long been known that high-frequency ground motion is generated by short scale-length variations in slip rate or rupture velocity. *Dunham et al.* [*71*] have pioneered a promising method that couples these phenomena in a physically realistic way. In their model, high-frequency ground motions are generated by normal stress variations that arise from dynamic rupture of a rough fault surface **(Fig. 2.20).** They include the effects of off-fault plasticity in their simulations. Plasticity enhances the effect due to its role as an energy sink.

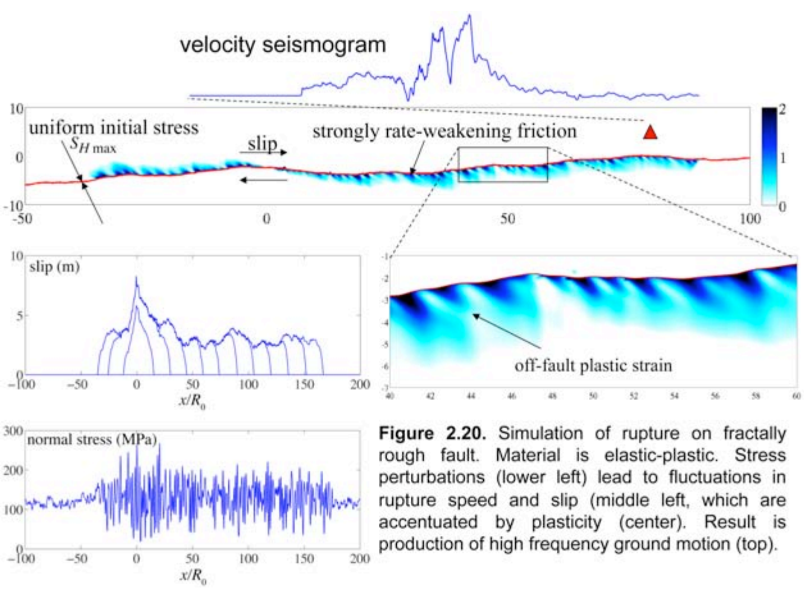
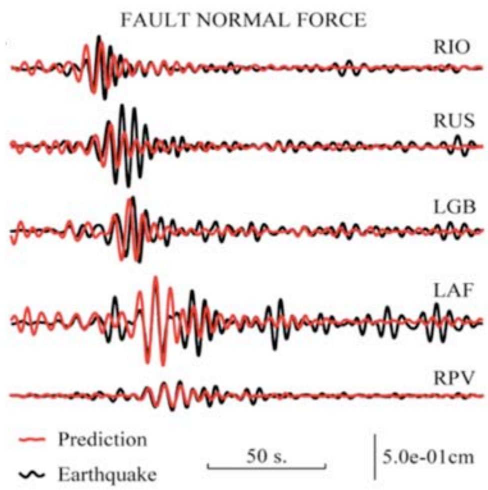


Figure 2.20. Simulation of rupture on fractally rough fault. Material is elastic-plastic. Stress perturbations (lower left) lead to fluctuations in rupture speed and slip (middle left, which are accentuated by plasticity (center). Result is production of high frequency ground motion (top).

<u>*New Approaches to Validation of Ground Motion Simulations.*</u> The need to validate simulated ground motions with data is listed explicitly as a SCEC3 priority. This is a challenge, however, because southern California has not suffered recent large earthquakes against which to compare simulations. SCEC has

attacked this problem creatively and pioneered new approaches. The wave propagation part of validation can be accomplished through ground motion predictions for smaller earthquakes. The goodness-of-fit analysis for the 2008 M5.4 Chino Hills earthquake [*30*] demonstrates this approach. This is not possible for many paths of interest, however, owing to the lack of appropriate earthquakes sources. *Prieto and Beroza* [*28*] showed it was possible to develop "virtual earthquakes," which can be constructed anywhere that a seismic station is available, using the ambient seismic field. As proof of concept, **Fig. 2.21** shows that a virtual earthquake for station BBR reproduces the amplification and duration of waves within the L.A. Basin in just the same way as a real earthquake. Using stations in areas of particular interest, such as along the San Andreas Fault, allows SCEC scientists to validate ground motion predictions and, where necessary, improve the Community Velocity Model.



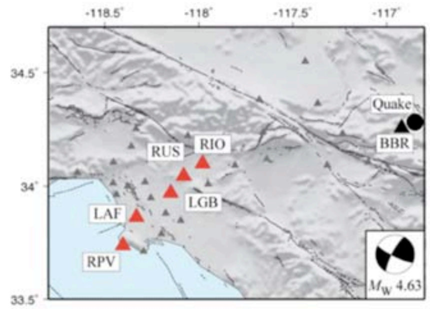


Figure 2.21. Proof of concept for the virtual earthquake approach. The ambient-field Green's functions for station BBR reproduce amplification and duration of the M 4.6 Big Bear earthquake shaking across the Los Angeles Basin. This approach can be used to validate predictions for any path of interest.

Uncertainties in the source are at least as large as those associated with wave propagation and the source characterization too must be validated. An obvious approach to this is to compare ground motion predictions with data from other large earthquakes. Perhaps the most directly relevant earthquake for which we have intensity data is the 1906 San Francisco earthquake. SCEC scientists were leaders in efforts to simulate of the 1906 San Francisco earthquake for its centennial [*72*]. Another approach to validation is the approach of using precariously balanced rocks (PBRs) to test probabilistic seismic hazard analysis. PBRs have the advantage of having been in place for thousands of years, and thus sample many earthquake cycles. There are challenges, of course, because to use them as quantitative constraints on hazard requires measurement of the age of their precarious state as well as their sensitivity to strong shaking. PBRs continue to be discovered in strategically important areas. The most recently recognized, and one of the most spectacular, is the Echo Cliffs PBR (**Fig. 2.22**).

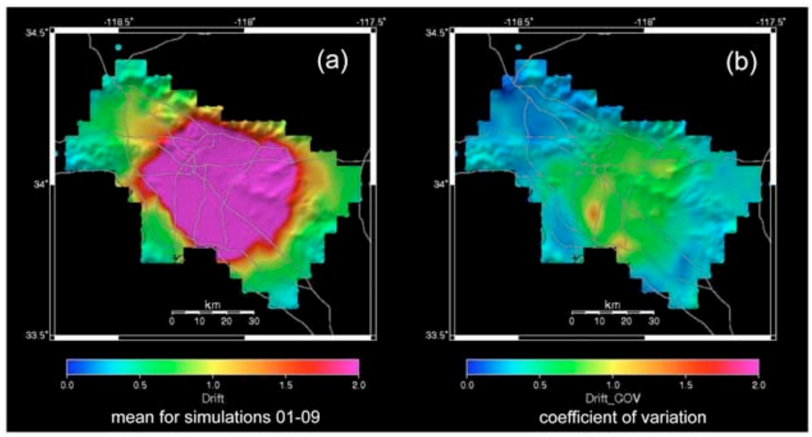
Figure 2.22. Echo Cliffs PBR in the Santa Monica Mountains is >14m high and has a 3-4s free period. This rock withstood ground motions estimated at 0.2g and 12 cm/s during the Northridge earthquake. Such fragile geologic features give important constraints on PSHA.

<u>*Simulation of Extreme Events.*</u> Recordings of large earthquakes at close distances are few, and are insufficient for assessing the range of motions for performance based design or evaluation of important structures (such as tall buildings and bridges in Los Angeles and San Francisco). SCEC3 has generated scientifically based representative ground motions via simulations to fill this void. SCEC simulated records have been utilized by practicing engineers and researchers dealing with design and evaluation of important structures [e.g., *73*]. A number of buildings and bridges have been designed or evaluated using such records as well.

<u>*Contributions to NGA and National Hazard Maps.*</u> The Next Generation Attenuation relations [*17*] are used in the calculation of the 2008 USGS National Seismic Hazard Maps, which form the basis for impending national seismic design standards, such as ASCE 7-10 (due in 2010) and International Building Code (due in 2012). Owing to the critical shortage of earthquake recordings, the NGA database has been supplemented with a number of SCEC simulated records for representation of motions produced by large nearby earthquakes. As a result, SCEC simulated records are having an impact on the building codes that will be used nationwide by practicing engineers.

Contributions to the PEER Tall Building Initiative. The Pacific Earthquake Engineering Research Center (PEER) is in the midst of a multi-year project sponsored by a variety of sources including NSF, USGS, California Seismic Safety Commission and Building Departments of Los Angeles and San Francisco, for establishing performance objectives and design guidelines for tall buildings. Numerous researchers and practicing engineers are actively involved in the PEER Tall Building Initiative. An important part of this research is a detailed parametric investigation of the performance of tall buildings designed by various methods, obtained by subjecting them to thousands of recorded and simulated earthquake ground motions. Another part of this research compares characteristics of recorded and simulated ground motions to validate the simulations. Tens of thousands of records generated by SCEC are being used in these exercises [*73*]. The PEER Tall Building Initiative project will result in a set of guidelines and source materials that will be widely used and referenced by practicing engineers and building officials. This illustrates how SCEC has been vital to advancing state of the art and practice of earthquake resistant design.

End-to-End Simulations. Ground motion predictions are only useful only if they inform engineering practice, disaster preparedness, or public policy. A priority for SCEC has been to work with earthquake engineers to develop rupture-to-rafters simulation capability for physics-based risk analysis. This type of end-to end simulation is illustrated in **Fig 2.23**. In such calculations, computer models of representative buildings (in the case of Fig. 2.23, a 2-story woodframe house) are spread throughout a geographical region and subjected to simulated ground motion scenarios, and the results are used to assess the performance of the representative buildings. The SCEC computational platforms such as TeraShake and CyberShake are especially suited for simulating ground motions appropriate for end-to-end calculations.



Figures 2.23 Peak interstory drift (inches) and coefficient of variation throughout the Los Angeles region in a 2-story 1980s-2000s index woodframe house from a magnitude 7.1 earthquake on the Puente Hills Blind Thrust. Values in excess of 2 inches (pink areas) would likely cause total loss and potential collapse.

4. Prepare Post-Earthquake Scientific Response Strategies

SCEC must be prepared to respond if a large earthquake strikes California. The last earthquake to have had a significant impact on Southern California was the 1994 Northridge earthquake (the M5.4 Chino Hills earthquake of 2008 doesn't really count). Thus, it has been a long time since we have responded to an earthquake in Southern California. SCEC has therefore conducted exercises to coordinate the post-event scientific response of the academic science community with USGS, CGS, and other organizations and constructed new tools to facilitate this response.

ShakeOut Scientific Response Exercises. To prepare the SCEC scientific community, we held simulated earthquake response exercises during the 2008 and 2009 ShakeOut scenario exercises. These featured realistic injects in real time, with the responses being largely simulated. The simulated responses uncovered a number of issues that we needed to resolve, and they have helped to enable a more effective response to the real thing. The exercise is now an annual event.

Earthquake Response Content Management System. We also tested communications over satellite phones at key SCEC institutions and exchanged information using a new SCEC Response Content Management System, which is hosted at USC and mirrored at Caltech and Stanford for redundancy (in the event a large earthquake renders one of the hosting sites inoperable). In developing the Earthquake Response CMS, we have gathered information on instrumental resources, and contacts, from UNAVCO, IRIS, and universities.

B. Communication, Education & Outreach Accomplishments

SCEC's Communication, Education, and Outreach (CEO) program is organized to facilitate learning, teaching, and application of earthquake research. SCEC CEO is integrated within the overall SCEC enterprise, and engages in a number of partnership-based programs with overarching goals of improving knowledge of earthquake science and encouraging actions to prevent, mitigate, respond to, and recover from earthquake losses. CEO programs seek to improve the knowledge and competencies of the general public, "gatekeepers" of knowledge (such as teachers and museums), and technical partners such as engineers and policy makers.

SCEC CEO has been very successful in leveraging its base funding ($2.7 million total over the last 7 years) with support from the California Earthquake Authority (CEA), FEMA, Cal-EMA, USGS, additional NSF grants, corporate sponsorships, and other sources. For its *Putting Down Roots in Earthquake Country* publication, SCEC CEO has leveraged an additional $4.4 million for advertising and printing. The 2007 *Dare to Prepare* campaign and ShakeOut drills in 2008 and 2009 benefited from more than $5 million in monetary and in-kind contributions by other organizations. SCEC's intern programs have been supported with more than $1 million in additional support from several NSF programs and a private donor.

1. 2009 Program Evaluation

At the recommendation of the SCEC External Advisory Council, an external evaluation team was hired in 2009 to conduct a mixed-methods program evaluation to assess selected programmatic areas and the broader impacts of the SCEC CEO program. The effort was led by Mehrnaz Davoudi, Davoudi Consulting Services, in consultation with Dr. Deborah Glik, UCLA School of Public Health, who combined have over 25 years of program evaluation. The evaluation used existing and newly collected primary data from key-informant interviews, online surveys, and observations. A detailed evaluation report was prepared and presented to an external review panel that met September 16-17, 2009.

The panel included participants that span the scope of the SCEC CEO programs: Farzad Naeim (EERI President, Engineering), Thalia Anagnos (San Jose State, Engineering), Diane Baxter (San Diego Supercomputer Center, Education Director), Carlyn Buckler (Museum of the Earth, Cornell University), Johanna Fenton (FEMA Region IX Earthquake Program Manager), Dennis Mileti (University of Colorado, Emeritus, Social Science), and Mary Lou Zoback (RMS, Inc., and Chair, SCEC Advisory Council).

The external review panel submitted a comprehensive report based on the evaluation team's findings and conclusions, and additional program review and data requested by the panel. Recommendations for each CEO area are included along with an analysis of the SCEC CEO program with regards to the NSF Broader Impacts criterion (see Table 1.2). The overall results are very positive and indicate that the SCEC CEO program plays an important role in earthquake education and preparedness in California and beyond (see **Box 2.2)**. The review panel recommendations have greatly influenced the CEO program plan for SCEC4 (see §III.D).

Box 2.2. Summary of Review Panel Findings

- Strong consensus that the SCEC CEO program has been an overwhelming success both in terms of breadth and impact
- CEO has succeeded in motivating the public to be better informed and prepared for the next big earthquake
- CEO has served as an honest broker and provided the leadership and trust to bring together a broad community of public, academic, and private groups
- At the same time they have created public outreach/museum programs, carried out effective K-12 teacher training, and have developed outstanding undergraduate internships which have become a magnet for attracting very bright and diverse students
- CEO should serve as a national model for other science centers
- CEO has effectively expanded and grown by leveraging dollars and strategic partnerships

2. Major Activities and Results

The primary SCEC3 CEO objective was to create reproducible "CEO frameworks" for using earthquake system science to inform and encourage preparedness and reduce earthquake risk. Research in the social sciences was applied during SCEC3, along with research and experience in K-12 education and undergraduate education and career advancement. The external review process documented several major accomplishments, which are summarized here.

a. Expansion of the Putting Down Roots in Earthquake Country portfolio

Putting Down Roots in Earthquake Country, a 32-page handbook, has provided earthquake science, mitigation, and preparedness information to the public since 1995. *Roots* was first updated in 2004, including the creation of the *Seven Steps to Earthquake Safety* to organize the preparedness content. Since then the handbook has undergone five additional revisions and printings totaling 3.5 million copies. The latest version (Fall 2008) includes overviews of the ShakeOut Earthquake Scenario and the Uniform California Earthquake Rupture Forecast study [*6*]. The first Spanish version of *Roots* was produced in 2006.

The booklet has spawned the development of region specific versions for the San Francisco Bay Area, California's North Coast, Nevada, and Utah (totaling an additional 4 million copies, see **Fig 2.24**). Versions for other parts of the country are in discussion. In Fall 2008, SCEC and its partners developed a new supplement to *Putting Down Roots* titled *The Seven Steps to an Earthquake Resilient Business,* a 16-page guide for businesses to develop comprehensive earthquake plans. It and other *Roots* handbooks can be downloaded and ordered from the main ECA website [*74*].

As part of the CEO evaluation, an online survey was conducted of people who recently ordered the southern California version of *Roots*, and compared to data collected when copies of the handbooks are requested. The survey indicates a clear increase in levels of household earthquake preparedness from the time they ordered the handbook to the time of the survey.

The *Putting Down Roots* framework (including the *Seven Steps to Earthquake Safety*) extends beyond the distribution of printed brochures and online versions. For example, the Birch Aquarium in San Diego and Fingerprints Youth Museum in Hemet both based earthquake exhibits on the booklet, and the Los Angeles County Emergency Survival Program based its 2006 and 2009 campaigns on the *Seven Steps.* Bogota, Colombia adapted the *Seven Steps* as the basis of the city's brilliant "Con Los Pies en la Tierra" (With Feet on the Ground) campaign [*75*]. This partnership resulted from SCEC CEO's involvement in the Earthquakes and Megacities initiative.

Figure 2.24. Related products of the *Putting Down Roots in Earthquake Country* series: (1) Original 1995 Southern California publication. (2) *Living with Earthquakes in Nevada* (1998). (3) *Echando Raices en Tierra de Terremotos* (So Cal, 2006). (4) *Seis Jugadas Maestras* (Bogota, Colombia campaign, 2007). (5) *Putting Down Roots* (Utah, 2008). (6) *Putting Down Roots* (Bay Area, 2005). (7) *Protecting Your Family From Earthquakes* (Bay Area Multi-Language booklets, 2006). (8) *7 Steps to an Earthquake Resilient Business* (2008). (9) *Living on Shaky Ground* (North Coast CA, 2009). (10) Fifth update since 2004 of the Southern California version (2008). Versions for the Central U.S., Pacific Northwest, and elsewhere are in discussion.

b. Creation and development of the Earthquake Country Alliance and its activities

SCEC created the Earthquake Country Alliance (ECA) in 2003 and continues to play a pivotal role in developing and sustaining this statewide (as of 2009) coalition [*74*]. Participants develop and disseminate common earthquake-related messages for the public, share or promote existing resources, and develop new activities and products. SCEC Associate Director for CEO Mark Benthien serves as Executive Director of the ECA.

Feedback from selected ECA members collected through key informant interviews, indicate that the foundation and development of the ECA very much rests upon SCEC leadership and its credibility and reputation as a trusted science and research consortium. SCEC is viewed as a 'neutral' and trusted leader, who employs a collaborative model to organizing stakeholders around a common cause and event. SCEC's "culture of collaboration" has provided for a bottom-up rather than a top down approach to building the ECA community.

Strategic planning in 2006 (just prior to SCEC3) identified the following six major projects for the ECA to implement. All have been completed or are continuing.

- *DARE to prepare*: ECA's 2007 Earthquake Readiness Campaign encouraged everyone to "secure your space" (so objects won't fall and cause injury or damage). A new website [*76*] was developed by SCEC, along with public events throughout the region and a comprehensive media campaign with commercials, on-air interviews, and more. In addition, a new Spanish-language website [*76*] was created and is also hosted by SCEC.
- *Policy Summits*: Two major earthquake policy conferences were coordinated by ECA partners. The first was led by the Southern California Association of Governments in August 2007, and the second by the City of Los Angeles in 2008 (*International Earthquake Conference* during ShakeOut).
- *USGS Southern San Andreas Shakeout Scenario*: This major study led by Dr. Lucy Jones (USGS) involved over 300 scientists, engineers, and decision makers, was completed in May, 2008 [*77*]. It portrays the consequences of a magnitude 7.8 earthquake on the southernmost San Andreas Fault. A SCEC simulation of the scenario earthquake [*78*] was used as basis for scenario development.
- *Major regional earthquake response exercise*: The ShakeOut Scenario became the basis of the State of California's Golden Guardian Exercise in November 2008, coordinated with the ECA-led first-ever regional public drill at the same time, *The Great Southern California ShakeOut* (**Box 2.3**).

Box 2.3 *ShakeOut: 2008, 2009, and beyond*

At 10 a.m. on November 13, 2008, **5.4 million** southern Californians participated in a massive "Drop, Cover, and Hold On" drill called *The Great Southern California ShakeOut*. Individuals, families, businesses, schools and organizations joined firefighters and other emergency responders in the United States' largest-ever earthquake preparedness activity. Organizers included the SCEC, USGS, California Office of Emergency Services, City of Los Angeles, Caltech, State Farm, and many others.

Participants were counted through a registration process at www.ShakeOut.org (hosted and maintained by SCEC). SCEC managed the recruitment of schools, whose staff and students accounted for nearly 4 million of the participants. Reports from participants showed that they engaged in a wide range of preparedness activities before, during, and after the drill, that they learned the value of practicing what to do during an earthquake. SCEC, UNAVCO, and other also use the drills to exercise post-earthquake research response plans.

Because of its success, the ShakeOut is now an annual event each October. More than **6.9 million** Californians participated in the 2009 drill, with participants from every county in the state. The 2009 drill was led by SCEC and involved over 200 Associates of the expanded Earthquake Country Alliance. As in 2008, many organizations provided significant in-kind support, and CalEMA and FEMA provided funding for many aspects, including the printing of over 1 million SCEC-developed ShakeOut flyers in five languages (English, Spanish, Vietnamese, Korean, and Chinese).

The ShakeOut is now being exported to other earthquake-prone regions. For example, SCEC hosted the website for "New Zealand's Great West Coast ShakeOut" on September 18, 2009 (which may be expanded nationwide in 2012). SCEC is now working with the Central United States Earthquake Consortia to organize an eight-state ShakeOut drill in April 2011, and with British Columbia on a ShakeOut drill in January 2011.

- *Comprehensive survey of earthquake awareness and readiness*: SCEC initiated the process that led to this largest-ever survey of California household earthquake readiness, conducted by Dr. Linda Bourque (UCLA) with state funding. The results of this survey will help shape future ECA activities.
- *Development of the Earthquake Country Alliance*: Because of the success of the 2008 ShakeOut, the ECA is now a statewide coalition of four regional alliances. "ECA Associates" work together to educate and inform the public and recruit their participation in the ShakeOut.

c. Development of the *EPIcenter* informal education network

SCEC CEO has developed exhibits and partnered with information education venues for many years, including an interpretive trail on the San Andreas fault at Wallace Creek, a permanent earthquake exhibit at a youth museum in Hemet, CA, and a temporary earthquake exhibit at the UCSD Birch Aquarium. The expansion of these partnerships, especially with the San Bernardino County Museum (SBCM) in 2007, led SCEC to create the Earthquake Education and Public Information Centers (EPIcenters) network in 2008. EPIcenters include museums, science centers, libraries, universities, parks, and other places visited by a variety of audiences including families, seniors, and school groups. Thus far, SCEC CEO has established relationships with over fifty institutional partners (Figure 1.3), who have implemented a variety of activities including displays and talks as part of earthquake exhibitions related to the ShakeOut, and other activities year round.

These partners share a commitment to 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, develop earthquake displays, or in other ways provide leadership in earthquake education and risk reduction.

Through key informant interviews, EPIcenter members have indicated that the EPIcenter model produces institutional and professional benefits which support collaboration among partners, such as a) access to innovative, cutting-edge earthquake science findings, educational materials, visualizations and other means of presenting information, b) technical assistance with exhibit and/or gallery design, c) earthquake science education training for educators and interpreters, d) resource-sharing for enhanced patron experiences and efficient use of funds, e) increased capacity for partnership development, f) enhanced ability to apply disaster preparedness training, g) increased credibility as perceived by institutional leadership and patrons, and h) opportunities to showcase achievements at professional meetings and EPIcenter meetings.

In 2009, the EPIcenter network collaborated with EarthScope in hosting an interpretive workshop at SBCM. This activity broadened participation and brought a new and diverse community to the network. SCEC is now serving as a regional coordinator for EarthScope's program as well as building membership among EPIcenters. The statewide EPIcenter network is part of the Earthquake Country Alliance.

d. Expansion and improvement of SCEC's internship programs

SCEC offers a set of internship opportunities that are connected into an intellectual pipeline that encourages students to choose STEM (Science, Technology, Engineering, and Math) careers and is improving the diversity of the scientific workforce. Since 2002, 265 internships have been provided in the three programs:

- The *Summer Undergraduate Research Experience (SURE)* internship places undergraduate students in research projects with SCEC scientists. Internships are supported from base SCEC funding and funding from internship mentors. 172 internships have been supported since 1994 (100 since 2002).
- The *Undergraduate Studies in Earthquake Information Technology (UseIT)* internship brings together undergraduates from many majors and from across the country in an NSF Research Experience for Undergraduates Site at USC. The eight-week program develops and enhances computer science skills while teaching the critical importance of collaboration for successful learning, scientific research and product development. UseIT interns tackle a scientific "Grand Challenge" that varies each year but always entails developing software and resources for use by earthquake scientists or outreach professionals, including SCEC-VDO (visualization software developed and refined each summer by UseIT interns). 145 students have participated since 2002.
- The *Advancing Cyberinfrastructure Careers through Earthquake System Science (ACCESS)* internship provides year-round opportunities for students to apply their advanced computational research skills within the earth sciences, including their ability to collaborate and network with other students and scientist-mentors, through an independent undergraduate or master's thesis research project. ACCESS is supported by the NSF Cyberinfrastructure Training, Education, Advancement, and Mentoring (CI-TEAM) program. 11 ACCESS-Undergraduate and 9 ACCESS-Graduate internships have been awarded.

Since 2002, 756 eligible applications for SCEC internship programs were submitted, with 265 (or approximately 35% of applicants) internships awarded among the three programs. Leveraging of additional funding has allowed SCEC to double the number of internships offered each year (from 23 in 2002 to 49 in 2009). Cumulatively 29% of interns from 2002 to 2009 were underrepresented minority students, with some years near 50%. A

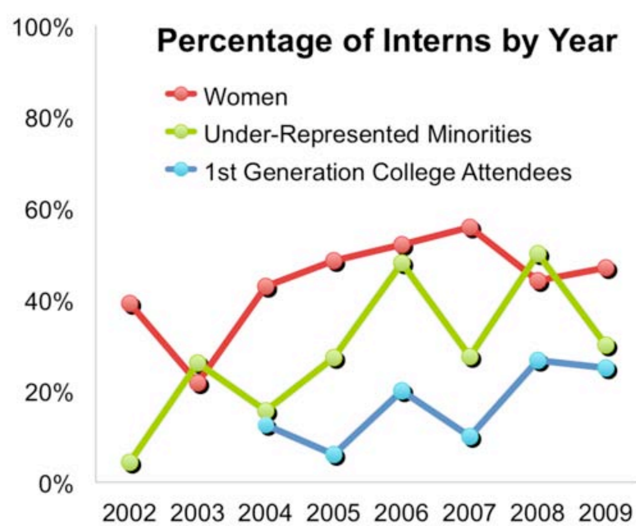


Figure 2.25. Participation of under-represented groups (as defined by NSF) in SCEC's three internship programs, 2002-2009, showing steady increases in each category.

22% gender gap in 2002 has effectively been erased with near-parity since 2005. First generation college attendees have also increased from 24% in 2004 to 33% in 2009, with a spike of 38% in 2006 (**Fig. 2.25**).

Much of the success in increasing diversity has come from increased efforts to recruit students from other states and also from community colleges, making the internship programs an educational resource that is available to a broader range of students.

Past interns report that their internship made lasting impacts on their course of study and career plans, often influencing students to pursue or continue to pursue earthquake science degrees and careers. By observing and participating in the daily activities of earth science research, interns reported having an increased knowledge about what it's like to work in research and education. When interns developed good relationships with their mentors, they reported an increased ability to work independently, which coupled with networking at the SCEC annual meeting, gave them the inspiration and confidence to pursue earth science and career options within the field. Interns also report that their experience with the SCEC network (fellow interns, students and mentors) has been rewarding in terms of community building and networking, and a key component in creating and retaining student interest in earthquake science and related fields.

e. Development of K-12 educational activities and products.

For the past eight years, SCEC has engaged in a number of activities – including educational workshops, materials development and distribution, field trips, school visits, and technical assistance – to provide K-12 educators with useful tools for teaching earthquake-related science, as well as to provide educators a direct connection to developers of these resources. SCEC uses a collaborative approach for two aspects of K–12 professional development: delivering workshops and developing materials. By building connections and coordinating with peer organizations, SCEC helps to ensure that educators are receiving the best resources available. SCEC has partnered with institutions such as USGS, IRIS, EarthScope, and USC to deliver workshops and develop curricula and materials.

From 2002 to 2009, SCEC led 2-3 workshops annually on earth science and earthquake science principles, with a focus on development of content knowledge and effective pedagogy. Participant data including grades and courses taught was collected during every workshop. For several of the workshops, SCEC implemented a content knowledge inventory. Based on selected pre/post test findings, teachers who participated in the trainings increased knowledge and confidence in teaching their students about earthquakes. The workshops give educators the opportunity to hear directly from SCEC scientists and often are scheduled to coincide with events such as the SCEC Annual Meeting.

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 of earth science education in general. Hence wherever possible, SCEC contributes to the community through participation on outreach committees, co-hosting meetings or workshops, and building long-term partnerships.

With the advent of the Great Southern California ShakeOut in 2008, SCEC CEO developed a suite of classroom materials focused primarily on preparedness to be used in conjunction with the drill. An important result of the ShakeOut is that it has enhanced and expanded SCEC's reach into schools at all levels from county administrators to individual classroom educators.

C. Information Technology Accomplishments

SCEC information technology supports administrative activities, collaborative activities, and research computing of the Center. The SCEC Community Information Systems (CIS), developed by SCEC's CEO program, has enabled SCEC's growth with automated project planning, collaborative proposal development, meeting planning, and the critical SCEC proposal submission and review system. Recently, the CIS introduced community-maintained, open-source, web-based, content management systems (Drupal [79]) to support communication between groups by providing easier contribution and distribution of project artifacts. Proven collaboration tools include Voice-over-IP, shared desktops, and shared calendar systems and SCEC IT will continue to introduce new collaboration tools into the community to increase collaboration and decrease meeting and travel expenses.

The SCEC Community Modeling Environment [80] (CME) provides advanced cyberinfrastructure in support of collaborative earthquake system science research. The interdisciplinary CME collaboration enables seismic hazard modeling projects that require computational and data resources beyond the capabilities of individual research group. The SCEC computational pathway diagram [Fig. 2.26] provides an organizational framework and a computational blueprint for improving ground motion forecasts on multiple time scales. CME research improves seismic hazard calculations through improved physical models, increased computational scale, increased regional scale, increased resolution, and higher frequencies.

SCEC seismic hazard calculations are computationally expensive and, when introduced into standard PSHA calculations, they will require extensive high performance computing. CME research has aggressively increased the scale and resolution of our deterministic wave propagation simulations advancing from TeraShake [81] at 0.5Hz, ShakeOut [82] at 1.0Hz, and 2009 Chino Hills [30] at 2.0Hz. SCEC's highly scalable parallel codes include AWP-Olsen [83] and Hercules [84]. Our highly parallel capability codes have run on the largest TeraGrid Track 2 HPC systems as well as on DOE Leadership Class supercomputers. CME ensemble for probabilistic seismic hazard research requires both parallel and high-throughput computing. SCEC implements high throughput computing using NSF-supported distributed computing and middleware that includes Globus [85] and advanced scientific workflow technology based on CondorDAG Manager [86], and Pegasus-WMS [87]. Through collaboration with computer scientists, SCEC's CyberShake 1.0 map calculation [88] is one of the largest scientific workflows ever performed on the NSF TeraGrid, running more than 190 million serial jobs over nearly 50 days. SCEC computational platforms are complex, vertically integrated research tools. SCEC's progress improving our computational scales has established the CME as a technology driver within an open-science HPC community [89]. CME researchers collaborate closely with NSF and DOE supercomputer resource providers on efficient and effective use of their systems as we push scientific and computational limits. SCEC has established itself as a leading HPC research organization and SCEC computer science research is presented at computer science conferences including NSF TeraGrid [90] and SC [91] conferences [92] as well as at geoscientific conferences.

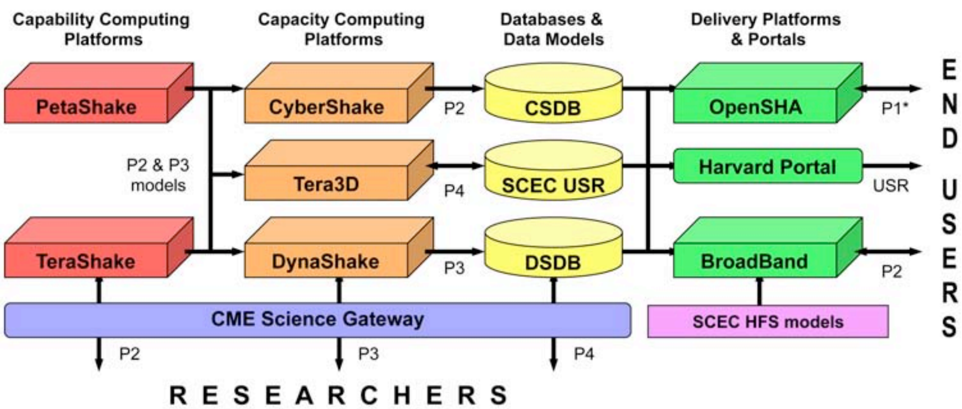


Figure 2.26. Computational platforms of the Community Modeling Environment. The capability computing platforms are shown as red boxes (*TeraShake* and *PetaShake*). The capacity computing platforms are in orange (*CyberShake, Tera3D* & *DynaShake*) and their databases in yellow. The delivery platforms are in green (*OpenSHA, Harvard USR Portal* & *Broadband*). The SCEC computational pathways are labeled *P1-P4*. Researchers access codes and results through the CME science gateway (blue), and users access validated models and data products from the delivery platforms. *BroadBand* produces broadband ground motion predictions by combining low-frequency deterministic simulations with SCEC High-Frequency Stochastic (*HFS*) models (purple).

The CME delivery platforms, including OpenSHA, Broadband, and the Harvard USR webservices, deliver PSHA information to non-CME researchers. OpenSHA [93] implements traditional PSHA components in computational form and it can calculate sites-specific PSHA hazard curves. OpenSHA was used by WGCEP during development of UCERF2 [6] and will be used in UCERF3 development. It will also be used in Global Earthquake Model [12] hazard processing. The SCEC Broadband platform delivers broadband synthetic seismograms to seismologists without HPC training. CME simulations require accurate structural models [19], so CME researchers are collaborating with the USR group to produce a general purpose, highly-scalable, geologically accurate 3D velocity models for southern California.

CME code and data management and automated software testing [94] techniques have been adapted for use in the CSEP forecast modeling testing infrastructure [49] and are being extended for use in SCEC's CISN ShakeAlert EEW testing project.

III. SCEC4 Project Plan

The SCEC3 program has quite appropriately focused on long-term PSHA, because that geotechnology remains the most important and cost-effective for seismic engineering and long-term disaster planning [*95*]. Progress at SCEC towards physics-based PSHA will be rapid in the next five years. For example, a series of studies currently underway will provide better earthquake rupture forecasts—e.g., the next version of Uniform California Earthquake Rupture Forecast (UCERF3)—as well as improved predictions of source-specific ground motions using large-scale simulations. The CyberShake seismic hazard models will have been tested against available data at low frequencies (< 0.5 Hz) and extended to a much larger region of California; developments aimed at creating and validating a 1-Hz CyberShake model will have been substantial.

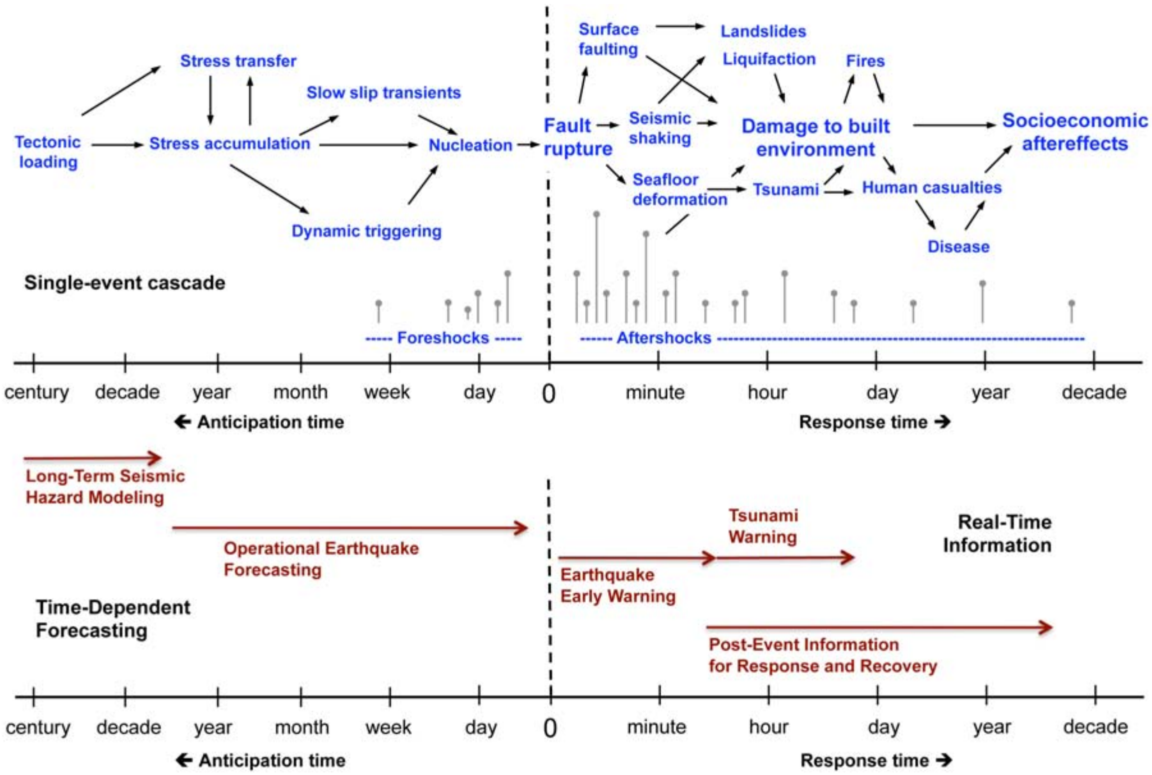


Figure 3.1. Earthquake processes (in blue) cascade through the natural and built environments, depicted here for a damaging event on a nonlinear time line. Red arrows indicate the time scales for long-term hazard modeling, operational forecasting, earthquake early warning, tsunami warning, and post-event information. Advancing the science that underlies these geotechnologies will help to reduce seismic risk and improve community resilience.

A. SCEC4 Vision Statement

SCEC3 will set the stage for a new SCEC4 program with the ambitious research goal of *understanding how seismic hazards change across all time scales of scientific and societal interest, from millennia to seconds*. Long-term PSHA treats seismic hazards as static quantities, but we know hazards change dynamically in time, because earthquakes release energy on very short time scales and thereby alter the conditions within the fault system that will cause future earthquakes. Statistical models of earthquake interactions have begun to capture many of the temporal and spatial features of natural seismicity, such as aftershock triggering and other aspects of clustered seismic sequences. Reliable and skillful earthquake prediction—i.e., casting high-probability space-time alarms with low false-alarm and failure-to-predict rates—is not yet (and may never be) possible. However, seismicity-based models can be used to estimate changes in the probabilities of future earthquakes over short to medium intervals, in some cases with gain factors of 1000 or more relative to long-term forecasts [*96*]. Providing authoritative information on time-dependent seismic hazards that communities can actually use to prepare for potential disasters is the objective of operational earthquake forecasting (OEF) [*97*]. A prototype system is the Short-Term

Earthquake Probability (STEP) webservice [*98*], an aftershock forecasting system developed by the USGS in partnership with SCEC [*99*].

Of course, seismic hazards evolve exceptionally rapidly during the active-rupture phase of the earthquake cascade (**Fig. 3.1**); if you feel a big *P* wave, you can bet that you are about to experience even bigger *S* waves and surface waves. Real-time seismology and geodesy offer the capability of tracking earthquake cascades during fault rupture by measuring how the rupture size is growing within a network of sensors, predicting the shaking at future times, and notifying the people and automatic control systems in the at-risk region. This is the objective of earthquake early warning (EEW) [*100*].

In the wake of widely felt earthquakes, the public and disaster management agencies need rapid and authoritative information about what has happened and might happen next in order to prioritize emergency response. Remarkable advances in seismic information capture and delivery have been made by the USGS and its partners, including the ShakeMap, Did-You-Feel-It?, ShakeCast, and PAGER [*101*]. Further improving the timely delivery of accurate post-event information remains a key objective of earthquake system science.

One can envisage a CyberShake-type system that will track information during earthquake cascades, beginning with long-term hazard maps that are modified dynamically by medium- to short-term probability models, such as the STEP prototype and the refinements we plan to embed in UCERF3 (**Fig. 3.2**). Once a significant rupture is underway, the probabilities of the candidate ruptures (which now combine to near unity) will rapidly evolve, eventually converging on a nearly deterministic ShakeMap constrained by the recorded ground motions. Enhancing the science knowledge and IT to enable such systems is the long-range vision of SCEC4, which is why this proposal is subtitled "Tracking Earthquake Cascades."

We emphasize that it is not SCEC's mission to provide operational information directly to the public, but rather to work in partnerships with the government agencies with such statutory responsibilities—the USGS, CGS, and the California Emergency Management Agency (CalEMA)—to create, prototype, and refine these capabilities. In addition to better earthquake forecasting and ground motion prediction models, important SCEC4 contributions will include the CSEP cyberinfrastructure needed to evaluate prospectively and continually the performance of the operational models and their components by comparing the forecast ground motions with those actually recorded.

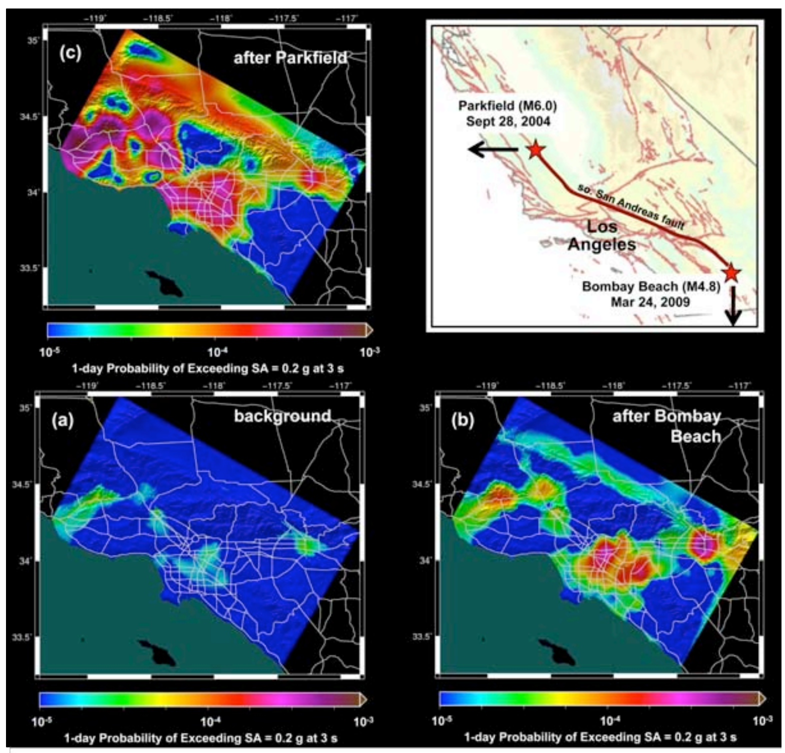


Figure 3.2. Comparison of **(a)** the CyberShake 1.0 long-term probability map for Los Angeles with short-term probability maps generated from the CyberShake database for **(b)** elevated probabilities associated with the 2009 Bombay Beach earthquake at the SE end of the southern San Andreas, and **(c)** the 2004 Parkfield earthquake at the NW end of the southern San Andreas (see map). In this demonstration calculation, the probabilities of ruptures with epicenters less than 10 km from these events were arbitrarily increased from their UCERF2 values by a gain factor of 1000. The ground-motion probabilities, here shown for 3-s spectral accelerations exceeding 0.2g at 0.3Hz, show gains up to 100, expressing the increased likelihood that activity near the San Andreas will trigger a large earthquake that subjects greater Los Angeles to ground motions >0.2g. This forecasting model accounts for rupture directivity and basin effects not adequately represented by standard empirical attenuation relationships.

B. Science Plan

The SCEC4 science plan was developed by the Center's Board of Directors and Planning Committee with broad input from the SCEC community. We assessed the basic research that will be needed to move towards the Center's scientific goals, identifying six fundamental problems in earthquake physics. We drafted five-year objectives in each of these problem areas and laid out the priorities and requirements for achieving them (§B.1). We developed four interdisciplinary research initiatives (§B.2) and reformulated our working group structure in accordance with the overall research plan, which is organized around a set of four system-level challenges (§B.3).

1. Fundamental Problems of Earthquake Physics

SCEC4 will focus its basic science program on solving six fundamental problems that are interrelated and require an interdisciplinary, multi-institutional approach. We describe each of these problems in terms of a short *Problem Statement*, a set of *SCEC4 Objectives*, which include answering basic questions and testing key hypotheses, and a listing of *Priorities & Requirements*.

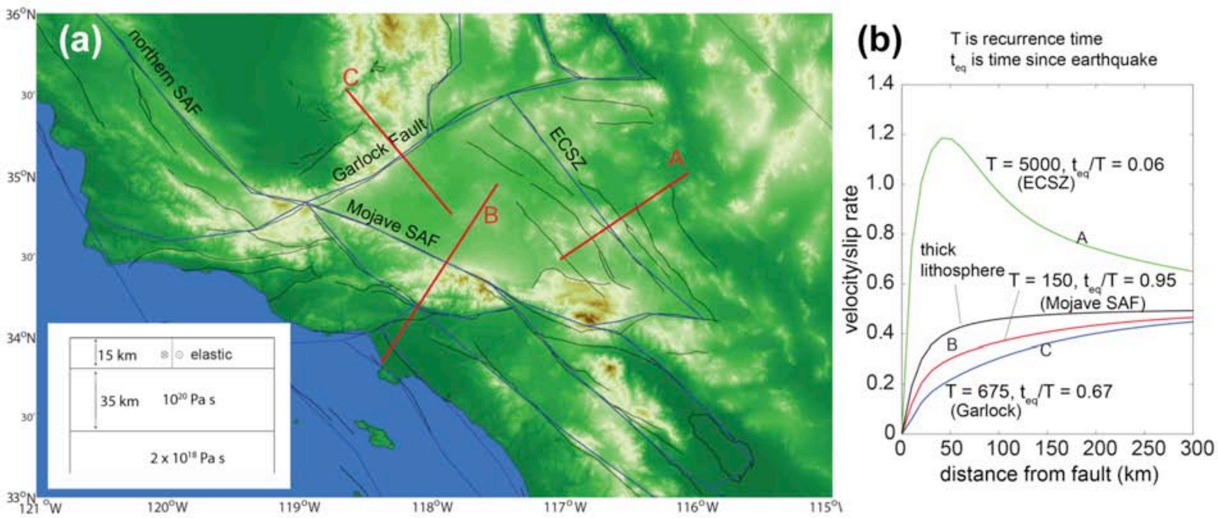


Figure 3.3. Profiles of surface velocities across selected southern California faults predicted by thin- and thick-lithosphere end-member models of crustal deformation. Velocities plotted as a fraction of long-term geologic slip rate for a strike-slip fault overlying viscoelastic crust and upper mantle using viscosities shown in the inset on the left (thin-lithosphere model) and for an elastic model with faults extending deep into the mantle (thick-lithosphere model). Late in the strain-accumulation cycle, the apparent slip rate can be less than its long-term average and early in the cycle the apparent slip rate can be higher. The viscosities illustrated here are controversial and require further testing. [K. Johnson]

a. Stress transfer from plate motion to crustal faults: long-term fault slip rates

<u>Problem Statement</u>**.** The energy for shallow tectonic earthquakes in plate boundary zones comes from elastic strain accumulating due to steady relative plate motion, and the long-term seismicity rate of a fault should thus be proportional to its long-term slip rate, which can be estimated from geologic and geodetic data. However, SCEC research has identified significant discrepancies: geodetic rates exceed geologic in the Eastern California shear zone [*102*], while geologic rates exceed geodetic for the Garlock fault and the Mojave section of the San Andreas [*103*]. These stubborn discrepancies suggest deficiencies in the traditional "thick lithosphere" model for strain accumulation, in which a thin planar fault in an elastic half-space is locked at seismogenic depths and creeps steadily in the lower crust and upper mantle.

An alternative hypothesis is that rapid and continuous viscous relaxation of the lower crust leads to a broad shear zone at depth, and a broad, shallow zone of time-dependent stress accumulation that is less strongly focused along the fault trace ("thin lithosphere" model) [*104*]. This effect, if not included,

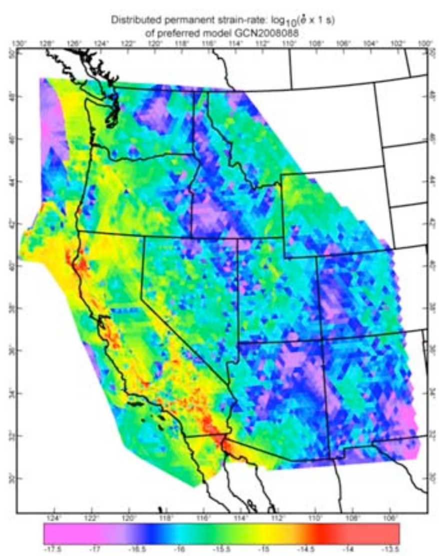


Figure 3.4. Estimated long-term-average rates of permanent (non-elastic) straining in the western U.S., showing only the contribution from the blocks between modeled faults. These high rates of permanent straining are controversial and require further testing. [P. Bird]

would bias geodetic inferences of slip rates to less than the actual geologic slip rate (**Fig. 3.3)**. An alternative may be that not all of the strain accumulating in the shallow crust between faults is elastic; some is permanent. For example, a recent kinematic model of the western U.S. [*105*] suggests that 1/3 of Pacific-North America relative velocity goes into distributed permanent strain (**Fig. 3.4**). This could explain why some geodetic networks record more relative velocity than is measured in the geologic slip rate.

SCEC4 Objectives. We propose to test these hypotheses by conducting research on deformation of the lower crust and upper mantle. One objective will be to determine whether deformation in the lower crust is localized across narrow crustal shear zones, or broadly distributed as flow. If deformation is primarily on aseismic lower-crustal extensions of faults, how variable are their shear rates during the post-, inter-, and pre-seismic phases? Key to answering these questions is quantifying the rates of permanent straining around and below the seismogenic portions of faults, and quantifying any time-dependence of deformation between major earthquakes. Geodetic benchmarks show post-seismic motions that decay over years or decades; is this due to afterslip on aseismic deep extensions of a planar fault, or regional viscoelastic relaxation in the lower crust and mantle?

In the traditional planar-fault model, deviatoric stress accumulation rate should peak along the fault trace [*106*], while in the weak-lower-crust model the accumulation could be regional. We will compare rates of stress accumulation with local rates of strain to test if the ratio is equal to the elastic shear modulus from wave speeds. If not, some of the shallow strain must be permanent rather than elastic.

These strain and stress observations will be unified in computer models that are consistent with laboratory flow laws. Models of lower-crustal strain may need to be upgraded from simple Maxwell viscoelasticity [*e.g. 107*,*103*] to more realistic nonlinear (power-law) dislocation-creep models for the long-term tectonic deformation process [*108*,*109*]. In the superposition of transient earthquake effects, there may be a role for a second dislocation-bowing viscosity. Poroelastic effects in the upper crust will also be considered, as otherwise they could be misinterpreted as lower crustal flow. One test of such models would be whether they can match slip distributions inferred in large earthquakes. In particular, do large earthquakes have coseismic slip extending deeper than the deepest hypocenters of regional microearthquakes, as implied by the observed scaling of seismic moment as the cube of rupture length [*110*,*111*]?

As we test these hypotheses, we will keep in mind that faults differ in net offset, heat-flow, and bulk crustal composition. For example, if ductile flow below the seismogenic zone involves recrystallization to finer grain sizes, it would probably favor strain localization into thinner faults with increasing net offset.

Priorities and Requirements. The priorities for SCEC4 activities include:

a1. Mapping and studying faults for which brittle/ductile transitions have been exposed by detachment faulting or erosion.

a2. Focused laboratory, numerical, and geophysical studies of the character of the lower crust, its rheology, stress state, and expression in surface deformation. We will use surface-wave dispersion to improve depth resolution relative to teleseismic studies [*112*].

a3. Regional searches for seismic tremor at depth in Southern California to observe if (some) deformation occurs by slip on discrete structures [*113*].

a4. Development of a Community Geodetic Model (CGM) for California, in collaboration with the UNAVCO community, to constrain long-term deformation and fault-slip models.

a5. Combined modeling/inversion studies to interpret GPS and InSAR geodetic results on postseismic transient deformation without traditional simplifying assumptions.

b. Stress-mediated fault interactions and earthquake clustering: evaluation of mechanisms.

Problem Statement. Earthquakes cluster in space and time. Aftershocks are one of the most common observations of seismicity and also one of the least understood physically. Clustering can result from triggering of one earthquake by another or triggering by aseismic strain transients. Within each of these broad categories is a variety of specific physical processes, including dynamic triggering [*114*,*115*,*116*], poroelastic interactions [*117*] and static stress change triggering [*118*,*119*,*120*], viscoelastic creep [*121*], and afterslip [*122*]. Other processes such as earthquake nucleation and fault zone healing may also play a role in the evolution of seismicity rate with time. Discriminating the relative roles of each of these processes and how they vary with time and space is a fundamental challenge to earthquake physics.

The proposed research will be critical to incorporating clustering and triggering into forecasting models and validating their utility. Current time-dependent forecasts (e.g. UCERF2) are based on characteristic recurrence time (renewal) models, which imply that large events are less clustered than time-independent (Poisson) behavior, whereas we know that earthquakes are much more clustered than Poisson on short time scales. The problem is to develop physical models that can accurately replicate and explain this time-dependent behavior.

SCEC4 Objectives. Statistical models that describe earthquake clustering have been developed and are beginning to be incorporated into operational earthquake forecasting (e.g. STEP, UCERF3). However, the statistical models contain little, if any, physics. To meet SCEC4 objectives in physics-based earthquake forecasting, we will develop physically based clustering models by addressing four key questions:

What physical triggering mechanisms dominate under which circumstances? How do the mechanisms interact? More than one triggering mechanism may be required, at least for near-field triggering (**Fig. 3.5**). A major challenge is to formulate tests to determine the relative roles of the proposed physical triggering mechanisms. A related challenge is to translate the various proposed triggering mechanisms into probabilistic forecast models that can be directly tested against each other in the CSEP prospective testing environment.

What can statistical models of earthquake clustering tell us about the underlying physics? Statistical models of earthquake clustering contain a number of parameters that must be found by fitting them to a particular dataset [*123*,*124*]. How do we physically interpret the parameters of the statistical models, and how are the observed parameter values related to properties of the crust? Are there aspects of earthquake clustering that are not fully captured by the current statistical models; if so, how is this behavior best modeled?

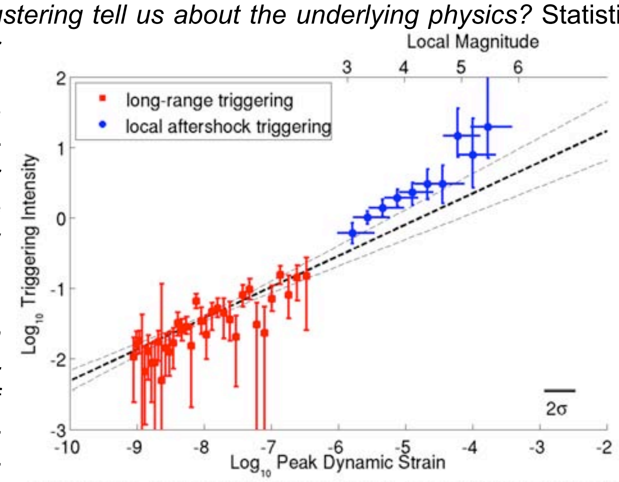


Figure 3.5. Comparison of long-range and near-field triggering. Triggering intensity measures the change in seismicity rate normalized by the background rate. Peak dynamic strain is inferred from the peak amplitudes of seismic waves. Long-range triggering is expected to be entirely due to dynamic stress changes; fit to the red points (dashed line) thus estimates the relationship between triggering and peak dynamic strain. This linear relationship can account for much, but not all, of the observed triggering in the near field (blue points, suggesting at least one other triggering mechanism operates in the near field. [van der Elst and Brodsky, in revision.]

Are current models of earthquake nucleation adequate to describe the time-scales of earthquake clustering? Since the temporal behavior of triggered earthquakes may be diagnostic in discriminating between physical triggering mechanisms, it is important to separate the time-delay due to earthquake nucleation from the timescales of the triggering process. Therefore, the current models of earthquake nucleation as a small-scale, quasi-static process described by rate/state-dependent friction laws consistent laboratory measurements of rock friction, must be tested.

What properties of the crust and/or fault system affect earthquake clustering and earthquake triggering? The relative amount of triggering can be mapped in time and space and then can be correlated with a range of other observations (**Fig. 3.6)** Observed correlations between earthquake clustering and other physical properties may give us insight into the physics of triggering, and may provide tests of the various proposed triggering models.

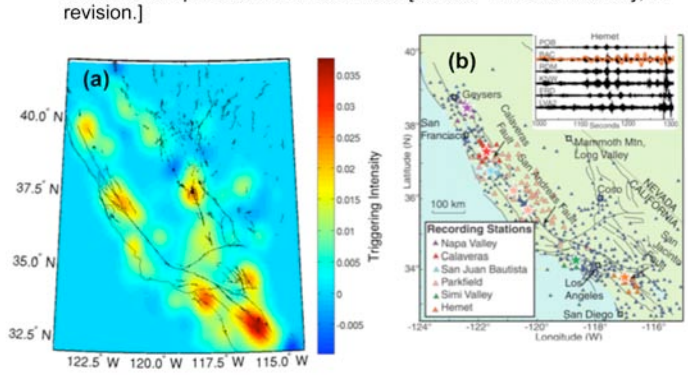


Figure 3.6. (a) Map of triggering intensity in California based on the aftershock productivity of earthquakes cataloged from 1984-2008 [Van der Elst and Brodsky, in revision]. **(b)** Areas of triggered tremor [Gomberg et al., 2008].

Priorities and Requirements.

b1. Improvement of earthquake catalogs, including non-point-source source descriptions, over a range of scales. Traditional aftershock catalogs can be improved through better detection of early aftershocks. Long-term (2000-yr) earthquake chronologies, including slip-per-event data, for the San Andreas Fault system are necessary to constrain long-term clustering behavior.

b2. Improved descriptions of triggered earthquakes. While temporal earthquake clustering behavior (Omori's Law) is well-known, the spatial and coupled temporal-spatial behavior of triggered earthquakes, potentially key diagnostics, are not well constrained.

b3. Lowered thresholds for detecting aseismic and infraseismic transients, and improved methods for separating triggering by aseismic transients from triggering by other earthquakes.

b4. Development of a Community Stress Model (CSM) for Southern California, based on merging information from borehole measurements, focal mechanisms, paleoslip indicators, observations of damage, topographic loading, geodynamic and earthquake-cycle modeling, and induced seismicity. We will use seismicity to constrain CSM and investigate how stress may control earthquake clustering and triggering. We plan to collaborate with other organizations in fault-drilling projects for *in situ* hypothesis testing of stress levels.

b5. Development of physics-based earthquake simulators that can unify short-term clustering statistics with long-term renewal statistics, including the quasi-static simulators that incorporate laboratory-based nucleation models [e.g.*125*].

b6. Better understanding of induced seismicity, specifically induced by geothermal power production in the Salton Sea area [*126*,*127*], which warrant study as potential hazards [*128*,*129*,*130*]. Recent research suggests that microseismicity in the geothermal fields near the Brawley seismic zone may affect and be affected by seismicity on tectonic faults at these distances.

c. Evolution of fault resistance during seismic slip: scale-appropriate laws for rupture modeling

Problem statement. Fault processes that determine fault resistance and its evolution at small spatiotemporal scales during co-seismic slip are critical to the large-scale physics of the earthquake failure cascade, because they dictate how, when, and where earthquake ruptures initiate, propagate, and stop [*57*,*131*,*132*,*133*,*134*]. Multiple lines of field evidence—lack of heat-flow anomalies [*135*,*136*,*137*,*138*], principal stress directions and their rotations due to earthquake stress drops [*139*,*140*,*141*,*142*], and geometry of thrust-belt wedges [*143*]—show that the effective friction during the bulk of slip on mature, well-developed faults is below 0.2, while static friction coefficients for most rock materials are 0.6-0.8 [e.g.,*144*]. We seek to test the null hypothesis that mature faults are statically weak, owing to their structure, composition and/or elevated pore pressure, against the alternative that they are statically strong but operate at low average shear stresses owing to dynamic weakening during rupture.

Several dynamic weakening mechanisms have been proposed, including thermal pressurization of pore fluids [*59*,*145*,*146*,*147*,*148*,*149*], flash heating of the contacting asperities [*58*,*59*,*60*,*150*,*151*], normal stress changes due to bimaterial effects [*152*,*153*], partial or full melting of the shearing zone [*151*,*154*], elastohydrodynamic lubrication [*155*], and silica gel formation [*156*].

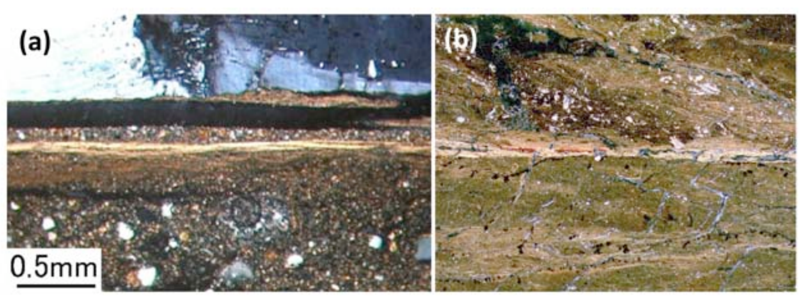


Figure 3.7. Extreme localization of slip zones (light horizontal strips in the middle of both panels) to sub-millimeter scale in **(a)** a high-speed friction experiment on fault gouge [Mizoguchi, 2004] and **(b)** ultracataclasite layer of the Punchbowl fault, California [Chester & Chester, 1998]. Both experimental and natural slip zones consist of thin strips with uniform birefringence reflecting crystallographic preferred orientation of phyllosilicates.

Field observations of mature faults suggest that large shear deformation, and therefore heat generation, in individual earthquakes is extremely localized in a finely granulated fault core less than 1–5 mm wide (**Fig. 3.7**). Such localization implies significant local heat input, and fault weakening processes during large crustal events are therefore likely to be thermal. SCEC3 research has significantly advanced our understanding of two such processes: flash heating at highly stressed frictional micro-contacts and thermal pressurization of fault-zone pore fluid (**Fig. 3.8**).

Another thermal weakening process, thermal decomposition, has recently been proposed (**Fig. 3.9**). Laboratory experiments suggest that, as temperature rises during shear in experimental fault zones containing clays [*157*], carbonates [*158*] or serpentine [*159*], conditions for thermal decomposition of mineral constituents are reached. This can weaken the fault by liberating a fluid product phase at high pore pressure and by creating a low-friction product (e.g., lime, when calcite decomposes and releases CO_2). In such processes, the latent heat demand may temporarily buffer the fault zone against further temperature rise towards melting as decomposition occurs. Mineral compositions have been discovered in natural fault zones that are consistent with this mechanism, such as reduced kaolinite content in shear zone [*157*] and calcite fault gouge decomposed to lime [*158*].

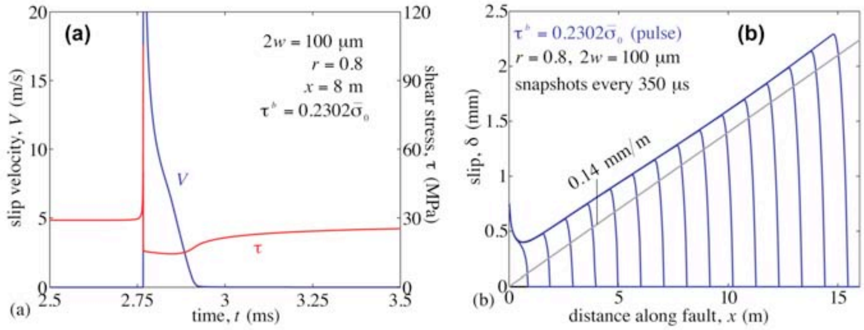


Figure 3.8. Simulation of rupture propagation on faults that dynamically weaken under the combined effects of flash heating and thermal pressurization [*52*]. Constitutive parameters are taken from laboratory measurements. Example shows properties of a growing slip pulse. **(a)** History of slip velocity (blue) reveals a self-healing slip pulse. The corresponding evolution of shear stress (red) shows dramatic variations, from the prestress of about 30 MPa, to the static friction strength level of more than 100 MPa, to low dynamic resistance of less than 20 MPa, with the final stress change of about 3 MPa. **(b)** Snapshots of slip on the fault indicate a linear increase of slip with distance at a rate of 0.14 m/km, consistent with geological measurements. Owing to computational limitations, only 15 m of rupture propagation is simulated. Such detailed modeling will be used to develop parameterized fault rheologies suitable for coarse-grained numerical modeling of rupture dynamics during large earthquakes.

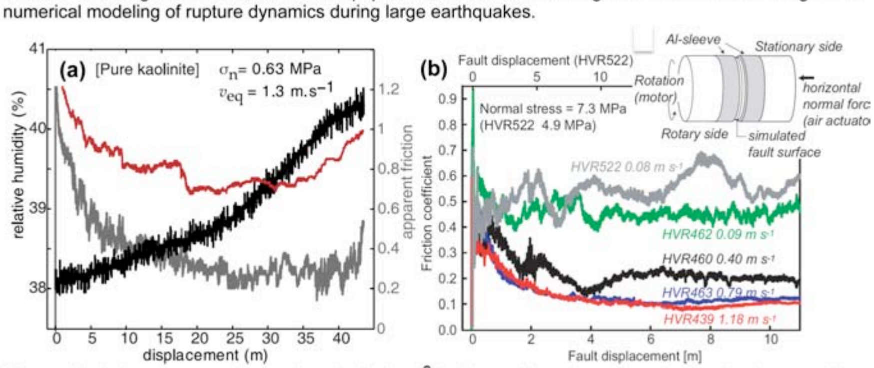


Figure 3.9. Laboratory results on dynamic fault weakening attributed to pressurization by decomposition products. **(a)** Evolution of friction (gray) and relative humidity (black) due to high-rate slip (1.3 m/s) for pure kaolinite gouge samples [Brantut et al., 2008]. Friction decreases from high peak values of about 1.0 to low dynamic values of about 0.3, while relative humidity increases more than 2% in the sample chamber, indicating release of decomposition products. The large weakening distance (~10 m) is due to low normal stress (0.63 MPa). **(b)** Frictional properties of simulated faults in Carrara marble show similar behavior, with steady-state friction coefficients of ~0.1 for seismic slip rates of 1 m/s. These experiments have much shorter slip weakening distances, of the order of 1 m, due to higher normal stress (7.3 MPa) and hence more rapid heat input. Even higher normal stresses, as appropriate for typical seismogenic depths, would raise the heating rate and further shorten the slip weakening distances, to centimeters or less.

<u>SCEC4 objectives</u>. Encouraging progress has been made in SCEC2 and SCEC3 in understanding the constitutive relations for rupture propagation and co-seismic fault slip, both in the laboratory and on natural faults [*57*, *58*,*59*,*60*,*132*,*133*,*134*,*144*,*149*,*160*,*161*,*162*]. The emphasis in SCEC4 will be on (1) identifying the resistance mechanisms dominating during seismic slip, and (2) formulating parameterizations of them that are suitable for large-scale models of dynamic ruptures and multiple earthquake failures on interacting faults. We will address the following key questions:

What is the underlying physics for each of the proposed weakening mechanisms, what are the fault conditions that would lead to them, and how do the mechanisms combine to determine fault resistance? Different weakening mechanisms may be dominant at different stages of seismic slip; e.g., flash heating of contacting asperities at relatively small slips, followed at larger slips by pore pressurization of native pore fluids, or those created by decomposition reactions, and finally, when those thermal buffering mechanisms are overcome, by partial melting.

What seismic and field observations can constrain the dynamic variation of fault resistance during seismic events? Significant co-seismic fault weakening would lead to substantial dynamic stress variations near propagating rupture tips, as stresses increase from low pre-stress values to high static-friction values and then back to low dynamic resistance (Fig. 3.8). Such variations may leave identifiable signatures in high-frequency, near-fault ground motion and as near-fault damage. In particular, we seek to understand how dynamic weakening mechanisms interact with local fault roughness and damaged bulk layers surrounding the fault.

How do faults restrengthen after dynamic weakening? Observations of short local rupture durations [*163*] suggest that, in most large earthquakes, rapid dynamic weakening is followed by rapid strengthening, but the microphysics of the restrengthening is not well understood.

Priorities and Requirements.

c1. Laboratory experiments on fault materials under appropriate confining stresses, temperatures, and fluid presence through targeted experiments in collaboration with rock mechanics laboratories.

c2. Search for geological, geochemical, paleotemperature, and hydrological indicators of specific resistance mechanisms that can be measured in the field. In particular, we will look for evidence of thermal decomposition in exhumed fault zones.

c3. Theoretical and numerical modeling of specific fault resistance mechanisms for seismic radiation and rupture propagation, including interaction with fault roughness and damage-zone properties. At the scale of meters to hundreds of meters, the behavior of the near-fault layer with evolving damage may have to be included in the fault constitutive relations.

c4. Development of parameterized fault rheologies suitable for coarse-grained numerical modeling of rupture dynamics and for simulations of earthquake cycles on interacting fault systems. Currently, the constitutive laws for co-seismic slip are often represented as complex coupled systems of partial differential equations, contain slip scales of the order of microns to millimeters, and hence allow detailed simulations of only small fault stretches (Fig. 3.8).

c5. Dynamic rupture modeling to constrain stress levels along major faults, explain the heat-flow paradox, and understand extreme slip localization and the dynamics of self-healing ruptures. We will use improved seismic slip inversions to constrain the local rupture durations and evolution of fault friction. We will collaborate with other organizations in fault-drilling projects to measure temperature on faults before and after earthquakes and thus constrain co-seismic resistance.

c6. Development of earthquake simulators that can incorporate realistic models of fault-resistance evolution during the earthquake cycle.

d. Structure and evolution of fault zones and systems: relation to earthquake physics

Problem Statement**.** Faults and fault systems are geometrically complex (see Fig. 1.1). A plate-boundary fault system can be represented as a hierarchical fractal network organized around a master-fault spine, which takes up most of the plate motion and on which most large earthquakes occur (e.g. the San Andreas and San Jacinto faults in Southern California). A major problem in earthquake physics is how the distribution of large ruptures depends on the geometrical complexities, such as step-overs, bends, branches, and intersections. Traditional seismic hazard analysis has relied on the characteristic earthquake model, where ruptures are confined to well-defined fault segments. In many cases, geometrical irregularities appear to control rupture lengths and may also have important effects on the fault slip and rupture velocity [*164*,*165*,*166*,*167*,*168*,*169*,*170*,*171*,172,*173*]. Yet the ability of ruptures to break across segment boundaries, as well as branch to and from subsidiary faults, is well documented for large earthquakes. Numerical simulations of fault step-overs [*170*, *172*,*174*,*175*,*176*,*177*] indicate that details of the stress pattern in the vicinity of the step-over region, the degree of fault overlap, and step-over width all affect the ability of rupture to jump the step-over. Simulations of branched fault systems [*178*,*179*,*180*,*181*,*182*,*183*,*184*,*185*] have shown that the path that rupture takes at a fault branch depends on the branch angle and the interaction between the dynamic and static stress field. Finally, simulations of earthquakes on geometrically complex fault systems over multiple cycles [*172*,*176*,*185*,*186*,*187*,*188*,] suggest that the buildup of stress at geometrical heterogeneities has an important impact on the earthquake process and slip complexity. Ways to account for this stress buildup include simple forms of viscoelasticity [e.g., *186*,*187*] and plasticity [e.g.,*189*]. Recent workers have emphasized the importance of these stress perturbations in developing slip partitioning [*190*,*191*]. How the rupture probabilities in such cascades depend on fault geometry has not been quantified and is thus a critical problem for earthquake forecasting.

On a smaller scale, faults are rough surfaces embedded in damage zones that comprise damaged and altered rock up to hundreds of meters wide. The properties and behavior of these damage zones have the potential to affect the dynamics of fault rupture, as discussed for problem (c). Some mature faults show extreme slip localization, but the evolution of this localization with total fault offset, the main measure of maturity, is not yet understood. The 3D structure of fault zones that accommodates steady creep and aseismic transients is also not understood.

<u>SCEC4 Objectives</u>. The objective for SCEC4 will be to develop realistic representations of fault zone and fault system complexity and the spatial and temporal heterogeneity in stress and strain associated with such complexity. This research will improve our understanding of how these complexities evolve and to what extent they control earthquake probabilities.

Research conducted during SCEC4 will address the following key questions: What are appropriate representations of fault-system and fault-surface geometries? What are the fault-surface geometries in regions of major fault complexity? How do large-scale geometrical complications affect rupture nucleation, propagation, and arrest? How is deformation distributed in damage zones and how does it vary with depth during seismic and aseismic slip? How do the properties of damage zones evolve during cycles of dynamic failure and interseismic healing, and how does this evolution affect rupture nucleation, propagation, and arrest?

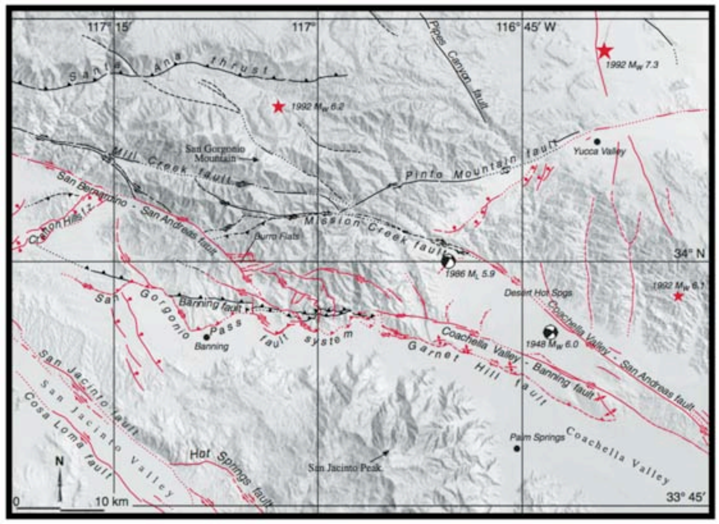


Figure 3.10. Topographic map of San Gorgonio Pass region, showing the complexity in surface fault traces. Active faults are shown in red, inactive faults in black. Beach balls and stars are epicenters of earthquakes. [D. Yule]

In SCEC4, we will focus on the effects of complex fault geometry on earthquake size and rupture variation and thus move toward more realistic earthquake source models. Specifically, interdisciplinary efforts will be concentrated in a series of "special fault study areas", such as the San Gorgonio knot (**Fig. 3.10**). We will also examine the role of small-scale geometrical heterogeneity on the earthquake rupture process. On a smaller scale, faults are rough surfaces [*e.g., 63,192*], embedded in damage zones. Impacts of small-scale fault roughness on stress complexity and aftershocks [*48,63*] (**Fig. 3.11**) and high frequency radiation [*193*] are some of the fundamental behaviors now being examined. Initial results suggest even small levels of roughness may play a dominant role for each. Finer scale complexities, such as fault branches, segment linking structures, and variations in off-fault damage also influence rupture energetics [*e.g., 185,194*]. Quantifying and understanding the characteristics of these small-scale geometrical features are key goals of proposed SCEC4 research. Understanding along-strike variations in roughness and complexity, the degree of localization and damage perpendicular to the fault, and the dependence with depth and connection to creep and aseismic transients, are priorities for SCEC4.

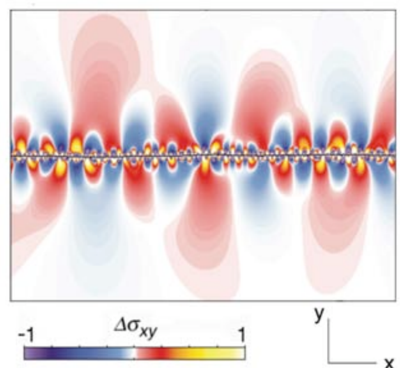


Figure 3.11. Example of shear stress changes (arbitrary scale) resulting from uniform slip of planar fault with random fractal (self-affine) roughness [Dieterich & Smith, 2009]. In purely elastic materials, these interaction stresses increase with slip, but in real materials with finite strength, off-fault yielding halts the growth of these interaction stresses. In the brittle seismogenic portion of the earth's crust this yielding can result in fault formation and seismicity off of major faults.

<u>Priorities and Requirements</u>. SCEC4 will conduct interdisciplinary studies of fault system complexities, including the variation in mechanical properties along fault surfaces, geometric irregularities and discontinuities of fault surfaces, and the associated spatial and temporal heterogeneity in stress and strain. Among the priorities are:

d1. Establishment of special fault study areas for detailed geologic, seismic, geodetic, and hydrologic investigations of fault complexities. Examples of areas especially suitable for such studies are shown in **Fig 3.12**. We will integrate the results of these special studies into the CFM.

d2. Investigations of along-strike variations in fault roughness and complexity as well as the degree of localization and damage perpendicular to the fault.

d3. Improvements to the CFM using better mapping, including lidar, and precise earthquake relocations. We will also extend the CFM to include spatial uncertainties and stochastic descriptions of fault heterogeneity.

d4. Use of special fault study areas to model stress heterogeneities both deterministically and stochastically. We will integrate the results of these special studies into the CSM.

d5. Use of earthquake simulators and other modeling tools, together with the CFM and CSM, to quantify how large-scale fault system complexities govern the probabilities of large earthquakes and rupture sequences.

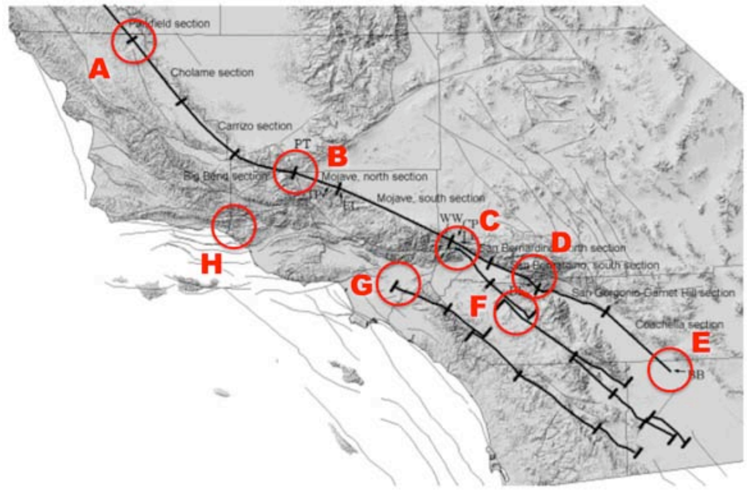


Figure 3.12. Map of the UCERF2 Type-A faults (long black lines) and their section boundaries (short black lines). Red circles A-F identify regions of fault complexity that will be considered as "special fault study areas" in SCEC4. For example, Area D is the San Gorgonio region shown in Fig. 3.10.

e. Causes and effects of transient deformations: slow slip events and tectonic tremor

Problem Statement**.** The last decade has witnessed the discovery of a new mode of behavior of major seismogenic faults: episodic tremor and slip (ETS). First identified in the Cascadia and Japan subduction zones, ETS was subsequently found in other subduction zones around the world [e.g., *195*,*196*,*197*,*198*,*199*,*200*]. ETS involves periodic slip of several centimeters on what is believed to be a transition zone between the velocity-strengthening (creeping) and velocity-weakening (seismogenic) part of the subduction zone megathrust. Recent theoretical work suggests that such behavior implies high pore fluid pressure and low effective normal stress [*201*,*202*,*203*,*204*]. Presence of highly pressurized pore fluids is supported by observations of tremor that correlates with aseismic slip both spatially and temporally [*205*]. ETS events on strike-slip faults such as the San Andreas fault in California have not yet been reported, but a growing number of studies have separately revealed both slow-slip events (**Fig. 3.13**) [*206*,*207*,*208*,*209*] and tectonic tremor [*210*,*211*].

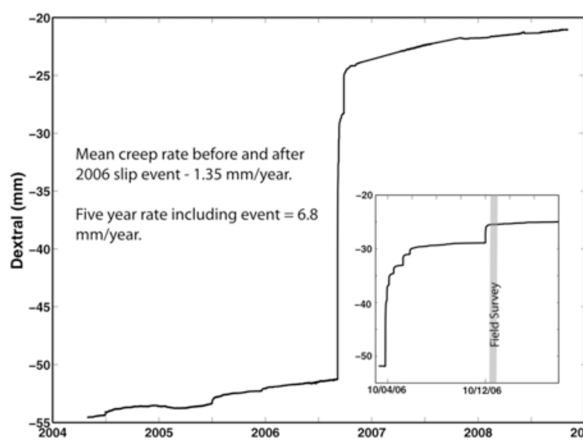


Figure 3.13. Transient surface deformation on the Superstition Hills Fault in Southern California. A nearly steady creep at an average rate of ~1.4 mm/yr suddenly accelerated by several orders of magnitude, resulting in more than 3 cm of slip over several days. Inset shows the subevent structure of the slow slip event, which suggests a complex dynamics [Wei *et al.* 2009].

Tremor in California exhibits remarkable behavior. *Shelly* [*212*] demonstrated that, as in subduction zones [*213*], tremor in California is comprised of a superposition of low-frequency earthquakes (LFEs) that resemble streaks of micro-earthquakes observed on the shallower portions of the fault (**Fig. 3.14**). The depths of these LFEs, at ~25 km, is greater than any previously observed seismicity on the San Andreas. In subduction zones, LFEs have been shown to be shear slip [*214*], which suggests that tremor in California occurs as shear slip on the deep extension of active faults. *Shelly* [*215*] identified thousands of LFEs in the lower crust deep underneath a nearly 100km stretch of the San Andreas Fault, suggesting the fault remains localized through the entire crust. *Shelly* [*215*] showed that increased tremor activity near Parkfield in the 3 months before the 2004 M 6 earthquake is consistent with accelerated slip

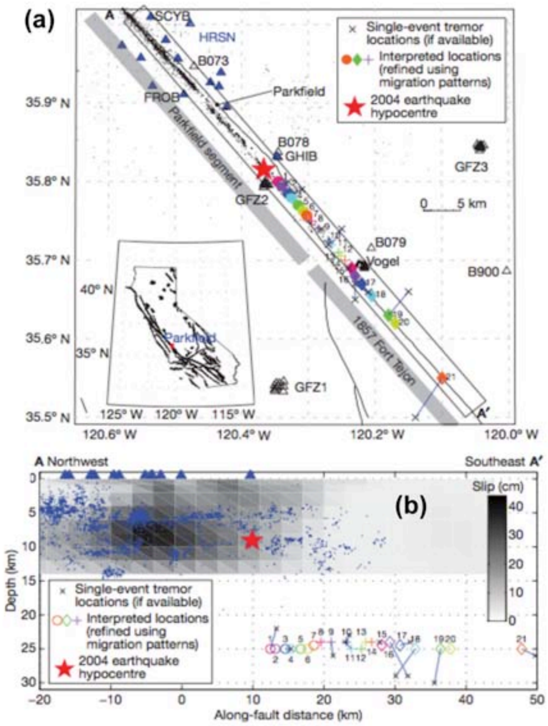


Figure 3.14. Tremor locations near Cholame in map view **(a)** and cross-section **(b)**. Star is 2004 Parkfield hypocenter. Circle, plus, and diamonds show LFE locations. Single-event travel-time-based locations for each family are shown as 'x'. Filled triangles are seismic stations used in detection, while black triangles are additional stations used for location. Dots are earthquakes. Shaded regions denote the 2004 Parkfield rupture, and the presumed northern end of the 1857 rupture. Slip model in (b) includes coseismic slip and the first 230 days of afterslip from the 2004 earthquake.

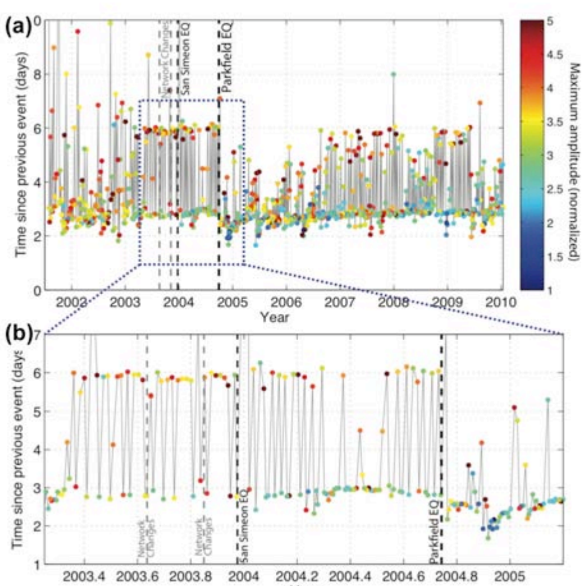


Figure 3.15. Recurrence interval vs. time for a family of low-frequency earthquakes under the San Andreas Fault near Cholame. **(a)** Recurrence history, mid-2001-2010. Colors indicate maximum amplitude in each episode, normalized to the 1st percentile amplitude. Gray lines connect consecutive events. **(b)** Zoomed view, highlighting dual periodicity and dramatic changes following the 2004 M 6 Parkfield earthquake.

on the fault below the eventual hypocenter. The latest result, not yet published, indicates remarkable behavior in LFE activity, including one that occurs every three days – except when its period doubles to 6 days (**Fig. 3.15**). There are currently ~540,000 LFEs detected for the period where continuous data are available, from mid-2001 to present. This is ~2.5 times as many earthquakes (216,000) as there are in the entire Northern California Seismic Network catalog during that period.

These findings present a new opportunity to learn how the deep crust operates, and raise some interesting questions. *What are the conditions conducive to tremor and slow slip events?* Proposed mechanisms include a transitional behavior near the velocity-neutral ends of the velocity-weakening zone [*202,204*], and a transition from velocity weakening to velocity strengthening behavior with increasing slip speed, e.g., due to dilatant strengthening [*216*], among others. *How important are lithologies, fluid saturation, and poroelastic properties of fault zone materials, and structure of fault zones, in regulating slow slip?* Addressing whether slow-slip instabilities are a long-lasting behavior or one that changes with time will help answer this. *What are the mechanics of tectonic tremor and what controls the propagation of tremor?* The balance of evidence for tremor in a subduction zone indicates that it is comprised of a swarm of thousands of small, slow earthquakes. *Is the deep SAF tremor accompanied by geodetically detectable slow slip? Is tremor always accompanied by slow slip events and vice versa? How are slow slip events and tectonic tremor related to earthquake occurrence?* It has been recognized that such events may increase stress on the locked portion of a fault, presumably bringing it closer to failure. In some areas slow slip events are associated with swarms of small to moderate seismicity [e.g., *197*,*208*], but this behavior does not appear to be universal [e.g., *209*]. Given the strong sensitivity of tremor to weak tidal stressing, might some attributes of tremor and slow slip events (period, depth extent, amplitude) vary with time as the next large earthquake approaches?

<u>SCEC4 Objectives</u>. Exploring tremor and its implications will be an important research thrust in SCEC4. A second will be the application of geodetic transient detectors to dense networks of permanent GPS stations and InSAR time series to search for slow slip events throughout and beyond the seismogenic zones.

The SCEC4 research program will test a number of relevant hypotheses against interesting alternatives: (1) Tectonic tremor on the SAF system is caused by swarms of small shear slip events on the downward extensions of strike-slip faults. (2) Slow slip events occur in regions that generate tectonic tremor. (3) Scaling laws that govern slow slip transients in the SAF system are the same as in subduction zones. (4) A fault patch has a single mode of slip (i.e., is either fully-seismic or fully aseismic) rather than exhibiting multi-mode behavior (slipping both seismically and aseismically, depending on conditions) [*e.g., 217,218*].

<u>Priorities and Requirements</u>.

e1. Improvement of detection and mapping of the distribution of tremor across southern California by applying better instrumentation and signal-processing techniques to data collected in the special study areas, including the Cholame segment of the San Andreas fault (Area A of Fig. 3.12), where the tectonic tremor was first identified in California [*210*] and the southern termination of the San Andreas fault near Bombay Beach (Area E of Fig. 3.12), which is the locus of an intense swarm activity [*219*].

e2. Application of geodetic detectors to the search for aseismic transients across southern California. We will use the CGM as the time-dependent geodetic reference frame for detecting geodetic anomalies.

e3. Collaboration with rock mechanics laboratories on laboratory experiments to understand the mechanisms of slow slip and tremor.

e4. Development of physics-based models of slow slip and tectonic tremor. We will constrain these models using features of tremor occurrence and its relationship to seismicity, geodetic deformation, and tectonic environment, as well as laboratory data.

e5. Use of physics-based models to understand how slow slip events and tremor activity affect earthquake probabilities in Southern California.

The goal of the proposed research will be the development of detailed quantitative understanding of the role of tremor and slow slip events in the operation of active seismogenic faults in California and elsewhere.

f. Seismic wave generation and scattering: prediction of strong ground motions

<u>Problem Statement</u>. Ground motion predictions are the main product of seismic hazard analysis and essential input to risk mitigation activities, such as performance-based engineering and nonlinear structural response analysis [*e.g., 220,221,222,223,224*], operational earthquake forecasting [*97,99*], earthquake early warning [*100*]. Numerical simulations validated by data are an effective means for incorporating rupture directivity, sedimentary basins and other volumetric near-surface heterogeneities [*e.g., 225,226,227,228,229,230,231*], structural boundaries, and steep topography [*e.g., 230,232,233*] into ground motion predictions, and they provide meaningful ground motion estimates for conditions poorly represented in the empirical database.

Dynamic rupture models predict complex behaviors such as focused/defocused rupture fronts [e.g., *234*], rupture jumps [*e.g., 235*], back rupture [*e.g., 236,237*] and supershear transitions [*e.g., 238,239,240,241*]. These and other rupture phenomena have important effects on ground motion, yet have proven difficult to parameterize kinematically for use in simulations of ground motion [*e.g.,242*]. That difficulty is evident even at relatively long periods [*81*]. For example, **Fig. 3.16** compares kinematic and dynamic ground motion simulations of the 2008 ShakeOut scenario, showing that the kinematic model adopted for the official ShakeOut scenario is an outlier relative to an ensemble of dynamic simulations [*82*].

Current models are inadequate for predicting high frequency (> 1 Hz) ground motion. In that regime, we

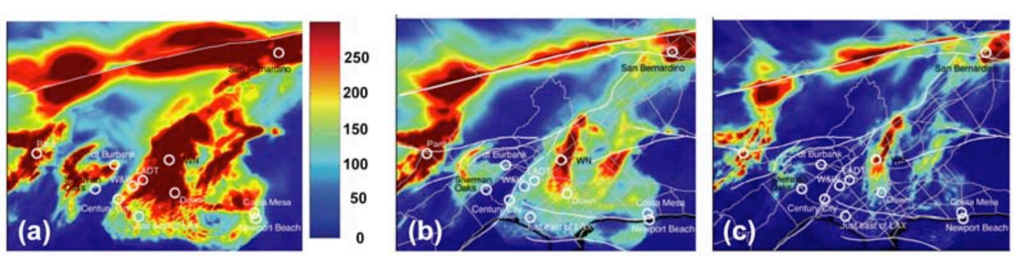


Figure 3.16. Spectral acceleration at 0.3 Hz (color scale in cm/s^2) for the LA region from ShakeOut simulations, comparing the kinematic source model **(a)** with the mean **(b)** and standard deviation **(c)** computed from a suite of dynamic source models [Olsen *et al.*, 2009]. The simulations indicate that the low-frequency ground motions predicted by the kinematic source are biased high relative to the mean of the dynamic source. Panels in this figure were extracted from Fig. 2.18. This example illustrates how we will use suites of dynamic rupture simulations to quantify aleatory uncertainties in ground motion predictions.

face the dual challenge of characterizing the source at high spatiotemporal resolution, and modeling wave propagation at short wavelengths, for which ground motion is sensitive to poorly-resolved small-scale crustal structure. As a result, high-frequency ground motion simulation is currently done with (1) kinematic source models that include stochastic components [e.*g., 243,244,245*] for which we currently lack a well-founded physical interpretation; (2) crustal velocity models [*18,19,246*] with few observational constraints on their short-wavelength components (even though high-frequency, shallow profiles [*247*] show power-law velocity heterogeneity down to the shortest resolvable wavelength); and (3) scattering operators [*248,249,250*] to represent unmodeled small-scale structural heterogeneity. The kinematic/stochastic source can be tuned to agree in the mean with available empirical ground motion metrics [*e.g. 243*], but such an approach typically leads to high-variance predictions (because we lack a physical basis to constrain parameter ranges and correlations) and provides an inadequate basis for scaling up to the largest earthquakes (for which relevant empirical measurements are scarce). Likewise, scattering-model formulations are uncertain, and depend upon assumptions about the scattering process, e.g., whether coda is due to trapping within layers or scattering from heterogeneities, whether intrinsic Q is frequency dependent, whether scattering is uniform or anisotropic, whether it is concentrated near the surface [*251,252,253,254*], and in what regimes single-scattering and multiple-scattering processes, respectively, dominate.

An essential component of ground motion simulation is the estimation of aleatory uncertainties (due to natural variability) and epistemic uncertainties (due to lack of knowledge). It is now technically possible to simulate very large suites of earthquake scenarios (>10^6) and to sample a wide range of plausible models for rupture physics [*255*] and Earth structure. Uncertainties can be propagated by means of simulation ensembles, and such brute-force sampling can also be supplemented by adjoint-based sensitivity estimates [*e.g.,256*]. Careful application of these strategies may enable us to obtain simulation-based ground motion estimates with lower uncertainties than conventional empirical estimates.

<u>SCEC4 objectives</u>. We will address an interrelated set of seven questions:

What quantitative limits can be placed on strong motions using plausible limits on key physical parameters? For example, the shear stresses that initiate and drive fault slip have evolved over multiple past episodes of co-seismic slip, abetted by interseismic interactions with nearby faults. Improved understanding of fault system behavior may lead to statistical models for the spatial structure of these stress fields at the initiation of large ruptures, and simulation ensembles can map such statistical models into probability distributions for ground motion.

What dynamic weakening mechanisms are relevant for modeling strong ground motion, and how can those mechanisms be accurately represented in models of large earthquakes? Weakening mechanisms that are potentially important in natural earthquakes can be explored in high-resolution numerical simulations (e.g., Fig. 3.8). It remains unclear whether these small-scale processes have important effects on the larger-scale dynamics relevant to ground motion excitation, and if they do, how the full spectrum of weakening processes can be parameterized effectively in numerical models for large earthquakes (see priority c4 above).

What controls the generation of high-frequency (> 1 Hz) ground motions? Both stress heterogeneity [*257*] and fault roughness [*e.g.,258,259*] are likely to play fundamental roles [*260*]. Discrete fault irregularities like bends and fault intersections may induce damage localization [*261,262*] and fault branching [*180,182,263*] that affect high-frequency excitation; more diffuse roughness enhances overall high-frequency generation while promoting off-fault damage [*264*]. At high frequency, model validation by deterministic matching of seismic phases is not realistic, so model validation with seismic data will emphasize other metrics, including those based on the Fourier and response spectra and the waveform envelope [*e.g., 30,243,265,*]. We will also explore approaches to model validation that focus on matching statistical distributions over event ensembles.

How common is supershear rupture, and is it limited to strike-slip earthquakes or associated preferentially with mature and/or geometrically simple faults [*70*]*?* Current theoretical models predict elevated high-frequency spectral levels of near-fault ground motion from supershear rupture [*266*], yet observational studies of supershear events have thus far found little evidence of this effect [*267*]. It is a high priority to determine whether this lack of high-frequency enrichment reflects limited observational sampling, incoherence during rupture propagation, or masking by other effects, such as nonlinear deformation induced by high stresses at the Mach front [*263,267*].

How do fault frictional parameters and initial stress state vary with depth, how can we parameterize these in numerical models, and what seismic observables provide sensitive tests of those models? Of particular importance is a better understanding of the conditions under which the shallow parts of faults may become diminished in their capacity to undergo abrupt dynamic stress drops—e.g., by a transition to velocity-strengthening behavior [*268*]—because shallow dynamics disproportionately affects near-fault ground motion amplitudes [*269*,*270*].

What is the upper spectral limit to which we can make useful deterministic predictions of the seismic wavefield, and how can we extend ground motion predictions to 10 Hz, as needed for engineering applications? We are only now able to explore the upper frequency limitations on deterministic predictions (**Fig. 3.17**). A significant issue will be the "partition of unity" problem—how the stochastic wavefield components are added to deterministic calculations to conserve energy—which may be challenging, because the boundary between the two regimes can be complex in time-frequency space. In formulating stochastic representations, various scattering approximations (e.g., single-scattering, multiple-scattering, radiative transport models) will be appropriate in different regimes.

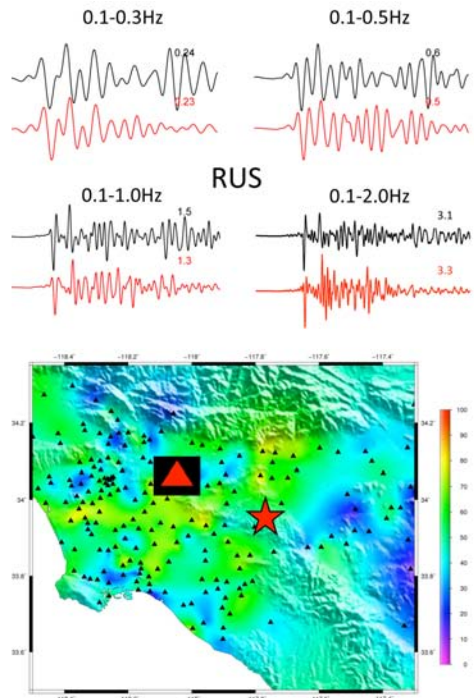


Figure 3.17. Deterministic simulations of the 29 Jul 2008 Chino Hills earthquake (M 5.4, red star) at station RUS (red triangle). Top traces compare observed seismograms (black) with synthetics (red) at lower frequencies; bottom traces at high frequencies. This test shows that this CVM can predict early-arriving phases with some success up to 2 Hz but less well for later phases.

What are the dominant scattering and attenuation mechanisms at high frequencies? Representation of attenuation in terms of anelastic Q (with or without frequency dependence) is technically straightforward, but the integration of nonlinear attenuation into ground motion simulations presents significant technical challenges best addressed through collaboration with experts in the geotechnical engineering community. Seismic networks that include down-hole sensors, such as SAFOD, offer new opportunities to calibrate scattering and attenuation effects [*e.g. 271,272*].

<u>Priorities and requirements</u>.

f1. Development of a statewide anelastic Community Velocity Model (CVM) that can be iteratively refined through 3D waveform tomography. We will extend current methods of full-3D tomography [*21,22*] to include ambient-noise data and to estimate seismic attenuation, and we will develop methods for estimating and representing CVM uncertainties.

f2. Modeling of ruptures that includes realistic dynamic weakening mechanisms, off-fault plastic deformation, and is constrained by source inversions. The priority is to produce physically consistent source models for broadband ground motion simulation. An important issue is how to treat multiscale processes; specifically, does off-fault plasticity regularize the Lorentzian scale collapse associated with strong dynamic weakening? If not, how can adaptive meshing strategies be most effectively used to make full-physics simulations feasible?

f3. Develop stochastic representations of small-scale velocity and attenuation structure [e.g.,*273*] in the CVM for use in modeling high-frequency (> 1 Hz) ground motions. We will test the stochastic models with seismic and borehole logging data and evaluate their transportability to regions of comparable geology.

f4. Measure earthquakes with unprecedented station density using emerging sensor technologies (e.g., MEMS). The SCEC Portable Broadband Instrument Center will work with IRIS to make large portable arrays available for aftershock and flexible array studies.

f5. Collaborate with the engineering community in validation of ground motion simulations. We will establish confidence in the simulation-based predictions by continuing to work with engineers in validating the simulations against empirical attenuation models [e.g.,*274*] and exploring coherency [*275*] and other standard engineering measures of ground motion properties.

2. Interdisciplinary Research Initiatives

The six *Problem Statements* span a wide range of scientific issues that will drive our next five-year program in earthquake system science and will guide progress towards our overarching goal of understanding time-dependent seismic hazards. The *SCEC4 Objectives*, taken together, are a suitable reformulation and extension of those that have guided SCEC3 (Box 2.1), and *Priorities and Requirements* lay out the interrelated elements of a coherent research plan. Here we describe four research initiatives that figure prominently in the organizational structure of SCEC4 system-level research.

a. Special Fault Study Areas

We propose to focus interdisciplinary research in special fault study areas to address priorities (d1)-(d5), as well as (a1), (a3), (b3), (b6), (c2), and (e1). Complexities associated with high slip-rate faults provide excellent targets because they are where seismic, geodetic, and geologic signals tend to be strong. A prime example is the San Gorgonio Pass (**Fig 3.18**), where slip is partitioned onto multiple thrust- and oblique-slip strands through a compressive, 10-km double-bend [*276*]. High topography and rapid uplift [*277*] indicate the distributed, 3D nature of the deformation. Slip-rates diminish on the San Andreas approaching this bend [*278*,*279*], suggesting that it may act as a persistent barrier to rupture. Understanding whether large earthquake ruptures might propagate through the San Gorgonio Pass is particularly important for predicting ground motions from a major earthquake on the southern San Andreas [*280*]. Nearby in Cajon Pass, the intersection of the San Jacinto fault with the San Andreas (Fig. 3.18) hosts strain-rate gradients and geometrical complexities that may also control large ruptures [*e.g.34,35,36,37,39,40,41*]. Other potential sites for focused study of fault-zone complexity are identified in Fig. 3.12.

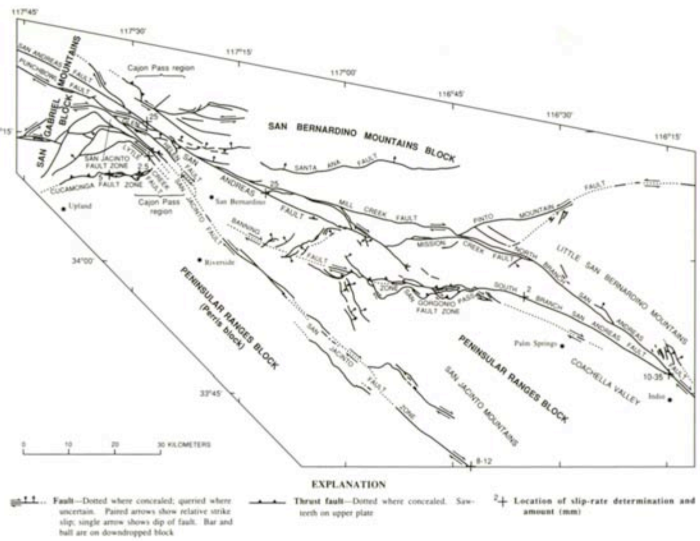


Figure 3.18. Complexity of San Andreas fault system in the vicinity of the San Gorgonio structural "knot", on the right (Area D of Fig. 3.12) and the confluence of the San Jacinto fault with the San Andreas near Cajon Pass, on the left (Area C). We propose to designated these regions as special fault study areas. Figure from *Wallace* (1990).

The growing inventory of lidar data will provide high-resolution surface morphology. We will combine detailed geologic studies based on these data and field mapping with high-resolution seismology to resolve the 3D structure of fault complexities. We will constrain the deformation field in regions of strong fault interaction using a combination of geodetic, geologic, and seismic methods.

b. Community Geodetic Model

To address priorities (a4), (a5), and (e2), we propose to develop a SCEC Community Geodetic Model (CGM), which will combine data from continuous and survey-mode Global Positioning System (GPS) data with Interferometric Synthetic Aperture Radar (InSAR) for Southern California. Development of a CGM is motivated by the densification of GPS arrays as part of Earthscope, the rapidly growing volumes of InSAR data from various satellites, and the development of time series analysis for InSAR data [*281*,*282*,*283*]. It will improve the geodetic studies of non-secular strain phenomena observed in Southern California, including post-seismic deformation [e.g., *121*,*284*] and events for which no trigger has been established [e.g., *209*] (Fig. 3.13). The new CGM will be distinct from the past SCEC Crustal Motion Map (CMM) [*285*] because it will be time dependent and will incorporate InSAR data to constrain the vertical deformation field and resolve small-scale details of the regional deformation. This will provide a greatly improved picture of vertical deformation in Southern California during the past two decades, as well as produce refined and improved tectonic geodesy data products for use in modeling.

Permanent GPS yields temporally dense and spatially sparse three-component time series data, and research is needed to determine how to merge these data with spatially dense but temporally sparse line-of-sight InSAR measurements (**Fig 3.19**). For both systems, methods of reducing non-tectonic signals from noise and other sources, such as hydrology, need to be investigated. InSAR and GPS data are highly complementary, and the data integration strategy will take advantage of the strength of each technique. In particular, uncertainties in InSAR measurements at long (>100 km) spatial wavelengths can be efficiently reduced using a low-resolution time series model derived from data provided by a continuous GPS network. The availability of InSAR measurements from more than one vantage point (e.g., from ascending and descending satellite orbits) allows accurate measurement of the subtle vertical component of deformation [e.g., *286*], for which GPS is noisiest. The SCEC CGM will be a cutting-edge experiment in developing optimal methods for combining such data. Once established, these methods can be applied to other regions.

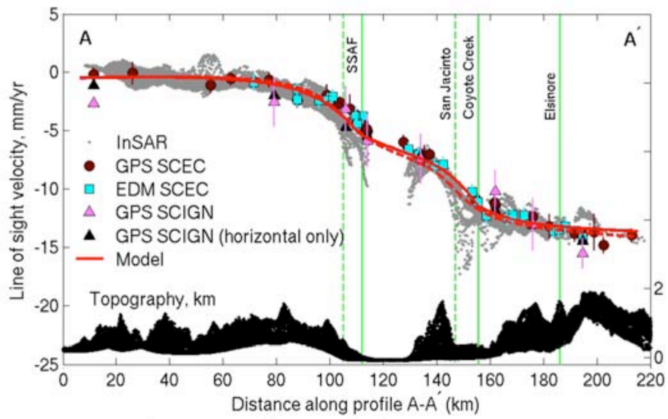


Figure 3.19. Combining InSAR and GPS data to constrain interseismic deformation across Southern San Andreas system (*Fialko*, 2006). Grey dots show InSAR line-of-sight (los) velocities from ERS-1 and 2 images for 1992-2000. Colored symbols show velocities from ground measurements (projected onto satellite los), including GPS (triangles & circles) and EDM (squares). Red curves show best-fitting velocity models. Solid and dashed green lines show surface traces of faults, and inferred fault locations at brittle-ductile transition respectively. The proposed Community Geodetic Model (CGM) will provide geodetic framework for this type of data integration.

The initial CGM product is likely to consist of spatially sparse, temporally dense 3D GPS time series and spatially dense, temporally sparse InSAR line-of-site time series consistent with GPS time series in the appropriate projection. Both the GPS and InSAR products would have temporal and spatial filters applied (separately) so that products contain spectral content that can be modeled. The CGM would be used in combination with other SCEC community models to infer the evolution of sub-surface processes. For example, the CGM, once developed, would provide a time-dependent reference frame for transient detection algorithms, as well as models of interseismic loading to evaluate stress changes and update rupture forecast models as tectonic conditions evolve in California.

c. Community Stress Model

State of stress is fundamental to the earthquake problem. We propose to begin the challenging task of developing Community Stress Models (CSMs) to constrain the physics of earthquakes—an initiative that will address priorities (b4), (c5), (c6), (d4), and (e4). Building CSMs will provide a platform where different constraints on stress can begin to be integrated and agreements and conflicts between models examined in a quantitative and comprehensive way. The range of potential uses for CSMs includes seismic hazard estimates, crustal seismicity modeling, tectonic studies, and earthquake simulators.

CSMs will bear many similarities to other SCEC community models, such as the CFMs and CVMs. At long wavelengths, we can use observations from seismology and geodesy to constrain the tectonic components of CSMs deterministically. A variety of observations are relevant: focal mechanisms [*287*,*288*,*289*,*290*,*291*,*292*], fault orientations, shear wave splitting [*293*], heat flow [*294*], stress orientations in boreholes [*295*,*296*,*297*], and topography [*286*]. Numerous modeling approaches are available: block [*298*] and viscoelastic loading *299*,*300*] models to constrain stressing rates, and joint inversions that combine geodetic and focal-mechanism data [e.g. *301*,*302*,*303*] with gravimetric [e.g. *304*,*305*] and tectonic [e.g., *306*] modeling to constrain absolute stress. At short wavelengths, the stress field is thought to become highly heterogeneous [*307*], and it will be necessary to employ stochastic descriptions. Constraints are available through the observable effects of stress heterogeneity on larger scale behaviors, such as on aftershock decay rates [*308*], aftershock locations [e.g. *309*,*310*], and focal mechanism diversity.

One of the primary sources of uncertainty in dynamic rupture modeling is the initial stress state along faults. The CSM will provide modelers with constraints on the orientation of the stress field around faults in the CFM. Dynamic rupture models can then be used to investigate issues of super-shear propagation [*238*], the possibility of branching [*311*,*312*], and complex rupture processes involving multiple faults or fault segments. Even more sensitivity to the stress state is expected when physics-based friction laws are used in place of the standard slip-weakening friction law.

Because this dependency works both ways, dynamic rupture models have the potential to provide new constraints on the state of stress, including its absolute level. Absolute stress determines the frictional heat produced during faulting, which influences the efficiency of thermal pressurization of pore fluid, the rate of thermal decomposition reactions, and whether or not the fault ultimately melts. Simulations incorporating dynamic weakening due to flash heating and thermal pressurization by *Noda et al.* [*57*] (Fig. 3.8) reveal a highly nonlinear dependence of the overall rupture process on the background stress level. In models that account for off-fault yielding, the initial stress state influences the extent and location of inelastic deformation [*313*,*314*].

While fault dynamics is a nonlinear function of stress, the fundamental elastic equations are linear, and short-wavelength stress variations, described stochastically, can be superposed on long-wavelength stress models, described deterministically. We are particularly interested in testing models with scale separation in the spectrum of stress variations against those with scale invariance. An important consideration is that the CSMs properly reflect "uncertainties" in an extensive and systematic fashion, both in terms of measurement and inversion robustness issues, and in terms of alternative physical descriptions (e.g. fractal vs. deterministic). The representation of such alternative hypotheses and uncertainties should ideally be in terms of (spatiotemporally variable) probability density functions for all relevant tensorial components, as a function of model assumptions and priors. Approximations and judicious parameterizations will have to be made, but the challenges will be synergistic with other SCEC4 objectives, such as to better characterize the uncertainties in our other community models.

d. Unified Structural Representation

The initiative to combine the Community Fault and Velocity Models into a self-consistent Unified Structural Representation (USR) began in SCEC2 and has continued as an important activity in SCEC3 (see §II.A). In SCEC4, the USR will be improved and extended in directions critical to our goals. Versions of the CVM are now beginning to directly incorporate results from full-3D waveform tomography based on both the scattering-integral [*21*] and adjoint formulations [*22*]. These powerful methods offer clear paths for improving the CVM's, which are critical in ground motion simulations and, will remain a key focus for SCEC4 (priorities f1 and f3-f5). The expected proliferation of candidate models and an emphasis on characterizing model uncertainties (priority f1) will require new USR representations to maintain and distribute alternative models in ways that facilitate direct comparisons. We will synthesize the best of these results into formally versioned CVM models to support better seismic hazard models and ground motion predictions.

The extension of ground motion simulations to higher frequencies (priority f3) will require an increased precision in velocity representations within the CVM's. Most critical, perhaps, is the need to improve representations of near-surface wavespeeds. These are currently incorporated using Geotechnical Layers (GTL's) draped on top of the crust and upper mantle models. The current GTL's are rule-based parameterizations that use sediment maps and local borehole data to specify velocities within the upper 300 m. While effective for certain applications, they are currently inadequate for simulations above about 1 Hz (Fig. 3.17), and we will need to explore both deterministic and stochastic representations. Deterministic approaches will involve the acquisition and implementation of new data constraints, including multi-component active source experiments and geotechnical borehole observations. Stochastic approaches will seek to describe the natural range and variability of wavespeeds in the shallow sediments. The performance of these alternative parameterizations will be measured through direct comparisons of observed and synthetic waveforms at higher frequencies [*30*].

Progress will also be rapid in improving and extending the Community Fault Models in ways needed to address priorities (a1)-(a2), (d1)-(d3), and (e1). Lidar techniques will provide enhanced resolution of near-surface fault traces, and various seismologic data products (relocated seismicity [*31*,*315*] and focal-mechanism catalogs [*316*]) will improve fault geometries, especially in regions of fault complexity. Tomographic refinements will offer new constraints on fault geometries at depth. The CFM will need to incorporate revised, alternative representations of fault geometries that properly reflect these new constraints in hazard calculations and fault system models (**Fig. 3.20**). A new emphasis will be on representing smaller scale features, such as the detailed representations expected from the special fault study areas. At local scales, representations will be developed for the constraints on variable elastic and frictional properties of the near-fault zones important to dynamic rupture simulations, such as cross-fault contrasts and the characteristics of fault damage zones [*317*].

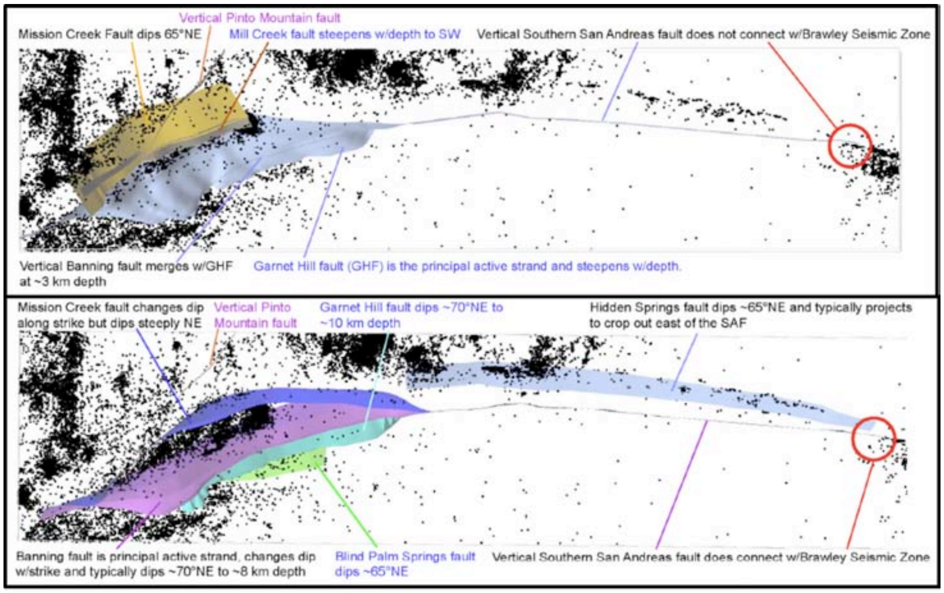


Figure 3.20. Comparison of current SCEC CFM-3 fault representations **(top)** for principal strands of the southern SAF with new, alternative 3D fault representations (**bottom**) that better account for distribution of relocated hypocenters and improved focal mechanisms (*Nicholson*, 2009). Three active, and distinct strands (Mission Creek, Banning, and Garnet Hill) define the San Andreas through the northern Coachella Valley.

Finally, the USR will support other community modeling efforts, including proposed development of CGMs and CSMs, ensuring that the models are consistent with the best fault and velocity representations; in collaboration with the CME, it will help facilitate the archiving, versioning, and distribution of the various community models for their collective use in a wide range of SCEC4 activities.

2. System-Science Challenges and SCEC4 Organization

The proposed research program will address four major challenges of earthquake system science: (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. Addressing these system-level challenges provides a roadmap for moving towards the goal articulated in the SCEC4 Vision Statement.

Over its 19-year history, the Center has adapted its modes of collaboration to become more effective in coordinating system-level earthquake research through both its internal projects and external partnerships. We will continue this evolution with the organizational structure diagrammed in **Fig. 3.21**; it will comprise disciplinary working groups (green boxes), interdisciplinary focus groups (yellow boxes), special projects (pink boxes), and elements of the CEO program (orange boxes). Leaders of the major working groups will form the SCEC Planning Committee, chaired by the Deputy Director, and they will be charged with developing the Center's Annual Collaboration Plan (see §IV). We will also sponsor a set of smaller, self-organized Technical Activity Groups (TAGs).

a. Disciplinary Groups

In SCEC3, disciplinary science and related data-gathering activities are carried out through standing committees in Geology, Geodesy, and Seismology. In SCEC4, we propose to retain this disciplinary structure but add a new disciplinary group in Computational Science. The CME special project has been very successful in using NSF supercomputing resources to simulate large earthquake ruptures and their associated ground motions, apply 3D waveform tomography to the imaging of crustal structure, and model other types of earthquake observations. This usage will increase in SCEC4 as we move outward on the "inference spiral" of Fig. 1.5. The CME has attracted some very talented computer scientists, and they are interacting strongly with geoscientists on some of the basic issues of computational science (e.g., formulation of scientific workflows, algorithms suitable for execution on multi-core processors). This disciplinary group will encourage such research, and it will also encourage students from both geoscience and computer science to develop their skills in an area considered to be a "third pillar" of modern science.

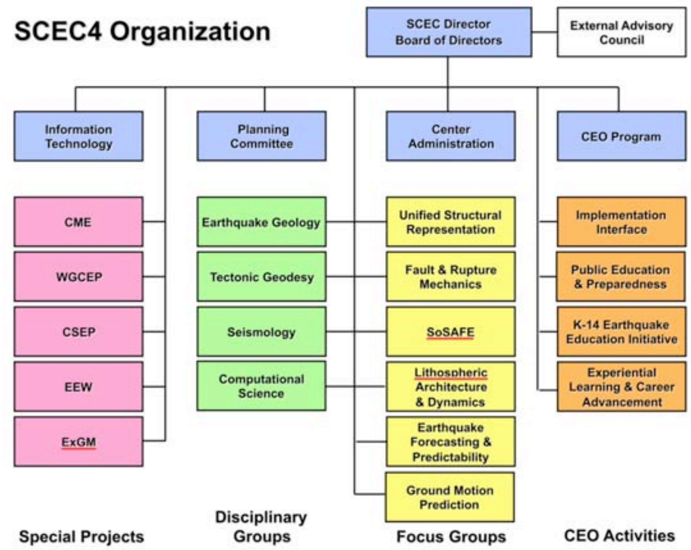


Figure 3.21. Proposed SCEC4 organization, showing Disciplinary Groups (green boxes), interdisciplinary Focus Groups (yellow boxes), CEO activities (orange boxes), and Special Project (pink boxes). The management structure for the Center is described in §IV.

b. Interdisciplinary Focus Groups

The interdisciplinary research activities required to address the fundamental problems of earthquake physics will be organized into collaborative projects by six focus groups that span the SCEC4 research program in earthquake system science. Interdisciplinary focus groups were first instituted in SCEC2, and they were reconstituted in SCEC3. Here we propose a reconstitution of the focus groups adapted to the SCEC4 science plan (Fig. 3.21).

Currently, seven focus groups are active: Unified Structural Representation (USR), Lithospheric Architecture and Dynamics (LAD), Crustal Deformation Modeling (CDM), Fault and Rupture Mechanics (FARM), Earthquake Forecasting and Predictability (EFP), Ground Motion Prediction (GMP), and Seismic Hazard and Risk Analysis (SHRA). We will merge CDM with LAD, create a new SoSAFE focus group, and strength SHRA through a reconstituted Implementation Interface.

Merger of CDM with LAD. The LAD and CDM focus groups have largely overlapping goals in fault-system research, although they tend to focus on different scales and explore different approaches. For example, CDM has emphasized modeling of small-scale deformation using geodetic data, whereas LAD has emphasized the use of structural models in understanding fault system loading by large-scale plate motions. Merging these groups recognizes that a unified approach to fault-system modeling is the best way to address problems (a) and (d) outlined in the previous section.

SoSAFE as an Interdisciplinary Focus Group. The Southern San Andreas Fault Evaluation (SoSAFE) project has been funded at SCEC by the USGS Multi-Hazards Demonstration Project for the last four years. The primary goal of the project has been to improve understanding of the past behavior of the San Andreas fault and San Jacinto fault by funding field-based projects to constrain the frequency and magnitude of past earthquakes. The results have been outstanding (e.g. Figs. 2.7 & 2.8). In SCEC4, SoSAFE will be transformed from a special project to an interdisciplinary group focused on understanding the master faults of the San Andreas system—specifically, the southern San Andreas fault and the San Jacinto fault. The group will continue to emphasize research on the geologic record of these faults; despite all that has been done, much more geologic information is required to improve time-dependent earthquake forecasts. This strong geologic program will be tied to activities involving other disciplines. The Southern California Seismic Network is expanding its instrumentation along the San Andreas Fault (also funded by the MHDP) to develop an operational earthquake early warning system, and this densification can be used for research on earthquake source processes and ground motion prediction. The USGS and SCEC will collaborate in the siting of the expanded network to optimize both early warning capabilities and scientific impact. The SoSAFE group will examine deformation along the San Andreas system on all time scales using all available information—geologic, geodetic, and seismic.

Reconstitution of the Implementation Interface. Within SCEC3, the collaborations with PEER and other earthquake engineering partners are coordinated through the Seismic Hazard & Risk Analysis focus group. Owing to its emphasis on partnerships and technology transfer, SHRA is situated in the CEO program, and its leadership has been specifically tasked with coordinating engineering-oriented research across the entire SCEC program. As described in §II.A.3, progress in the application of SCEC ground motion predictions to engineering problems—NGA development, the Tall Buildings program, rupture-to-rafters simulation—has been encouraging. We recognize, however, that the advanced SHA technologies currently being developed in SCEC3, such as CyberShake, will have to be thoroughly validated in collaboration with earthquake engineers before they can be applied in practice. Moreover, transferring these technologies will require that practicing engineers be informed about the utility and limitations of these developments. We therefore propose to bolster SHRA activities by extending them in an Implementation Interface that will include educational as well as research partnerships. The research and educational aspects are described in more detail in §III.C.1. As with SHRA in SCEC3, the Implementation Interface will have the status of an interdisciplinary focus group and its leadership will participate in the SCEC4 Planning Committee.

c. Technical Activity Groups

The SCEC4 Technical Activity Groups (TAGs) will self-organize to develop and test critical methodologies for solving specific types of forward and inverse problems. In SCEC3, various groups of experts have formed TAGs 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 (see §II.A). Successful groups share a *modus operandi:* the posing of well-defined "standard problems", solution of these problems by different researchers using different algorithms or codes, a common cyberspace for comparing solutions, and meetings to discuss discrepancies and potential improvements. We will apply our experience in encouraging and supporting TAGs to meet some of the challenges posed in the SCEC4 science plan, specifically CGM and CSM development. Providing "mini-collaboratories" for TAGs is part of our Information Technology plan (§III.4).

d. Special Projects

As shown in the lower graph in Fig. 1.4, the core funding for SCEC from the NSF and USGS has remained essentially flat in as-spent dollars over the entire history of the Center. Consequently, the growth in SCEC's activities (indicated by the upper graph of Fig. 1,4) has largely come through special projects funded separately by the NSF or USGS, or by other agencies. We have been careful to undertake only projects consistent with our mission (Box 1.1), and we have required that the research objectives of these projects be built into our annual science plans to ensure that the entire SCEC community has an opportunity to participate in this research. This coordinated science plan has been extremely effective, as the results in Fig. 2.1 illustrate. Here we describe the current special projects that may continue into SCEC4.

Community Modeling Environment (CME). CME is an HPC collaboratory for investigating earthquake systems using NSF's TeraGrid and other supercomputing facilities. The CME has developed an integrated cyberfacility for physics-based SHA computations (Fig. 2.26) and managed the output using NSF's most capable computing centers, including the petascale Blue Waters machine in development. The CME has been supported jointly by NSF-OCI and the Cyberinfrastructure Program in the Instrumentation and Facilities section of NSF-EAR. It began in 2001 as an NSF Large ITR project; the two current projects, PetaSHA (Petascale Cyberfacility for Physics-Based Seismic Hazard Analysis) and PetaShake (Petascale Inference in Earthquake System Science) are funded at a combined level of ~$1.6M/year. Funding is split between geoscientists who provide the earthquake system models and software engineers who develop the high-performance computing capabilities. The current focus areas are: (1) development of techniques to support both deterministic and stochastic high frequency simulations; (2) development of dynamic rupture simulations that include complexity including non-planar faults, a variety of friction-based behaviors that require higher inner/outer scale ratios; and (3) physics-based PSHA that includes probabilistic hazard based on 3D waveform modeling. All of these modeling efforts are accompanied by verification and validation efforts.

Working Group on California Earthquake Probabilities (WGCEP). WGCEP is a joint project of SCEC, USGS, and CGS funded in part by the California Earthquake Authority (CEA). CEA is required by law to use the "best available science" to establish its insurance-premium rates. SCEC is the lead on a $2M contract with CEA through 2012 to support the WGCEP group in the development of UCERF3, version 3 of the Uniform California Earthquake Rupture Forecast. The new WGCEP will consider (a) the effects of relaxing fault segmentation and including fault-to-fault ruptures on long-term earthquake probabilities, (b) methods for incorporating earthquake clustering and triggering statistics into time-dependent rupture forecasts, and (c) procedures for updating the UCERF immediately after a large earthquake.

Collaboratory for the Study of Earthquake Predictability (CSEP). In 2006, the W. M. Keck Foundation awarded SCEC a 5-year grant of $1.3M to fund CSEP to test earthquake prediction and forecasting models using standardized methods. CSEP has 1) established rigorous methods for registering prediction procedures, 2) erected community-endorsed standards for assessing probability-based and alarm-based predictions, 3) developed hardware and software support that allows individual researchers and groups to participate in prediction experiments and update procedures as results become available, 4) provided prediction experiments with access to data and monitoring products, authorized through agreements with the agencies producing them, and 5) accommodated a wide-ranging set of prediction experiments involving fault systems in different geologic environments. CSEP is headquartered at SCEC, but testing centers have been established In Japan, Switzerland, and New Zealand, with a new testing center coming online in China shortly. SCEC has been asked to submit a proposal to the USGS to continue CSEP operations after the Keck funding ends this year.

Earthquake Early Warning (EEW). EEW is a joint project of UCB, Caltech, and SCEC, also funded by the USGS. Currently, SCEC funding is ~$45K/year. The earthquake alert system (EAS) will provide a continuum of earthquake alert information ranging from the earliest shaking predictions based on *P*-wave detections near the epicenter, through *S*-wave detection and integration into warnings, to peak shaking observations at the epicenter and integration into warnings at greater distances. The goal is to provide "alerts" as prototype earthquake early warnings, i.e. before peak shaking. SCEC's role is to compare the performance of the EEW algorithms against ANSS observations and to update a secure website on a daily basis with EEW algorithm performance summaries. In this respect, SCEC activities in EEW are similar to CSEP's in time-dependent earthquake forecasting.

Extreme Ground Motion (ExGM). EXGM has been funded at a total of $1.2M to date, both by the Department of Energy (DOE) and Pacific Gas and Electric Company (PG&E). It is a collaborative project between PG&E, the USGS, and SCEC to determine physical limits on the amplitude of strong ground motion in rock, and is motivated by the need to bound very large ground motion levels predicted to occur at very low exceedence probabilities at the proposed Yucca Mountain Nuclear Waste Repository. There are also applications to the Diablo Canyon Nuclear Power Plant near San Luis Obispo. This project investigates the credibility of very high ground motions through studies of physical limits to earthquake motions and the observed frequency of very large ground motions or of exceptional earthquake source parameters (e.g., stress drop or faulting displacement) that might cause them.

C. Communication, Education & Outreach Plan

SCEC's Communication, Education, and Outreach (CEO) program is an important complement to the SCEC4 Science Plan. Through its engagement with many external partners, SCEC CEO fosters new research opportunities and ensures the delivery of research and educational products to the Center's customers, which include the general public, government offices, businesses, academic institutions, students, research and practicing engineers, and the media. SCEC CEO addresses the third element of SCEC's mission: *Communicate understanding of earthquake phenomena to the world at large as useful knowledge for reducing earthquake risk and improving community resilience*. The programs and resources developed during SCEC3, and planned for SCEC4, provide an expanded capacity for accomplishing this mission.

In SCEC4, the Center will continue to expand its CEO activities through partnerships with groups in academia and practice. The letters of support from many of our existing partners (see Supplementary Documents) portray strong and effective partnerships that anticipate many years of continuing collaboration. The Earthquake Country Alliance (ECA), created by SCEC, will continue to grow and serve as a model for multi-organizational partnerships that we plan to establish within education and among practicing and research engineers. Much of this interaction is virtual, in line with SCEC's "smart and green" Virtual Organization objectives.

The theme of the CEO program during SCEC4 will be *Creating an Earthquake and Tsunami Resilient California.* This includes: increased levels of preparedness and mitigation; routine training and drills; financial preparedness; and other ways to speed recovery. Each of these areas builds on improved earthquake science understanding. In particular, we will prepare individuals and organizations for making decisions (split-second through long-term) about how to respond appropriately to changing seismic hazards, including new technologies such as operational earthquake forecasts and earthquake early warning.

While tsunami research will not be a focus of SCEC, tsunami education and preparedness is now an element of the CEO program and the ECA. Awareness of tsunami risk along the coast will grow rapidly as new maps of inundation zones produced by the California Geological Survey [*318*] lead to posted signs along the coast, and local warning systems are put in place. The activities of the Redwood Coast Tsunami Workgroup will be replicated in the other regional ECA alliances. This will also bring potential new funding to SCEC and the ECA for outreach activities from NOAA and other sources.

The CEO program has evolved and expanded considerably during the first half of SCEC3, and is likely to continue to grow between now and the start of SCEC4 (including activities beyond California), with additional funding from FEMA, California State Agencies, and other sources. The SCEC4 program builds upon our expected progress and also introduces several new elements. The program will require additional resources, and a 50% increase in CEO funding relative to SCEC3 is requested (see budget justification). This increase will be leveraged against additional funding from many sources, as in SCEC3 (see §II.B). The plan addresses recommendations resulting from the 2009 SCEC CEO evaluation (see §II.B). The plan also address the challenges of the NSF 2009 *GeoVision* Report, particularly (2) reducing vulnerability and sustaining life and (3) growing the geosciences workforce of the future.

In SCEC4, the CEO program will continue to manage and expand a suite of successful activities along with new initiatives, within four CEO interconnected thrust areas. The *Implementation Interface* connects SCEC scientists with partners in earthquake engineering research, and communicates with and trains practicing engineers and other professionals. The *Public Education and Preparedness* thrust area educates people of all ages about earthquakes, and motivates them to become prepared. The *K-14 Earthquake Education Initiative* seeks to improve earth science education and school earthquake safety. Finally, the *Experiential Learning and Career Advancement* program provides research opportunities, networking, and more to encourage and sustain careers in science and engineering.

1. Implementation Interface

The implementation of SCEC research for practical purposes depends on effective interactions with engineering researchers and organizations, and with practicing engineers, building officials, insurers, utilities, emergency managers, and other technical users of earthquake information. These are most effective as partnerships towards common objectives, although trainings, tools, and other resources are also needed.

a. Research Engineering Partnerships

SCEC3 has produced a large body of knowledge about the seismic hazard in California that will enhance the seismic hazard maps currently used in building codes and engineering risk assessments (see §II.A). For example, Cybershake results will be fed into the USGS's National Seismic Hazard Mapping Program for use in its 2013 revisions (a process that starts next year). In the long term, we will collaborate with research engineers to test enhanced CyberShake models as an alternative to the empirical ground motion prediction equations and also as a database of simulated time histories for the design of critical facilities and other structures (e.g., tall buildings).

As described in the previous section, the SCEC4 Implementation Interface will provide the organizational structure for creating and maintaining collaborations with research engineers, much as the SHRA focus group has done in SCEC3. These activities will include rupture-to-rafters simulations of building response as well as the end-to-end analysis of large-scale, distributed risk (e.g., ShakeOut-type scenarios). Analysis of the performance of very tall buildings in Los Angeles using end-to-end simulation remains a continuing task that requires collaboration with both research and practicing engineers through PEER and other organizations. Our goal of impacting engineering practice and large-scale risk assessments require even broader partnerships with the engineering and risk-modeling communities, which motivates the activities described next.

b. Activities with Technical Audiences

The Implementation Interface will also develop effective mechanisms for interacting with technical audiences that make decisions based on understanding of earthquake hazards and risk, including practicing engineers, geotechnical consultants, building officials, emergency managers, financial institutions, and insurers. This will include expansion of the Earthquake Country Alliance to include members focused on mitigation, policy, and other technical issues. SCEC, perhaps with one or more partner organizations, will develop training sessions and seminars for practicing engineers and building officials to introduce new technologies (including time-dependent earthquake forecasts), discuss interpretation and application of simulation records, and provide a forum for SCEC scientists to learn what professionals need to improve their practice. These activities will increasingly be online, with frequent webinars and presentations and discussions videotaped and available for viewing online.

To understand SCEC's effectiveness in this area, we will track and document use of our technical resources and information, and their impact on practice and codes, guidelines, and standards. Those who utilize SCEC products and information may be asked to notify us, especially partners who understand the value to both SCEC and themselves.

2. Public Education and Preparedness

This thrust area spans a suite of partnerships, activities, and products for educating the public about earthquakes, and motivating them to become prepared for earthquakes and tsunamis. To work towards these goals, we will increase the application of social science research, with sociologists and other experts.

a. Earthquake Country Alliance

The ECA is the primary structure within this thrust area, and is described in §II.B. Due to the success of the 2008 ShakeOut, the ECA is now statewide and includes four regional alliances (Fig. 1.3). Prior to and during SCEC4, the relationship of the umbrella group to the four regional groups will be strengthened so that our goals of consistency in messaging and development of shared resources can be achieved. The Great California ShakeOut has been the primary collaborative activity so far, but soon additional short- and long-term goals, timelines, and measurable outcomes will be developed. This planning will build on a California Emergency Management Agency earthquake communications plan developed in 2009 that emphasizes the value of a statewide collaboration.

In addition to specific goals and metrics, the composition of the ECA will develop both in terms of number of participants as well as diversity of the participants and organizations involved. To reach all aspects of society, it is important that the ECA membership include additional community-based organizations (CBOs) and faith-based groups that often are the most effective at serving the needs of underserved communities. New members will also come from the inclusion of tsunami experts and officials. Based on the work of the Redwood Coast Tsunami Workgroup, the other Alliances will expand their tsunami messaging and programming, and all ECA members will receive instructions on implementing and communicating preparedness and mitigation strategies for both earthquakes and tsunamis.

b. ShakeOut Earthquake Drills

SCEC is at work on the third annual *Great California ShakeOut* drill in October 2010 (see www.shakeout.org), and also developing plans with Emergency Management British Columbia for a province-wide ShakeOut drill in January 2011, and with the Central U.S. Earthquake Consortia for an eight-state ShakeOut drill in April 2011. The British Columbia drill will likely be expanded into a Cascadia drill (with Washington and Oregon) in 2012. Furthermore, New Zealand is considering a nationwide ShakeOut drill in 2012, and Utah, Istanbul, and other locations have also expressed interest.

In order to develop and maintain the ShakeOut brand and reduce potential confusion between the different drills, SCEC intends to work with officials in these regions and for many will host the website for their drill, as we did for a regional ShakeOut drill in New Zealand in 2009. This will also serve to standardize earthquake messaging nationally and internationally, and allow groups to share best practices for recruiting participation, such as the use of social networking sites.

Prior to SCEC4, the original California ShakeOut will likely have expanded greatly, from 6.9 million in 2009 to well over 10 million participants annually. New materials and activities for additional communities and in multiple languages will be developed each year. In the future, operational earthquake forecasts should create additional interest for the ShakeOut drills and increase participation and preparedness in general (as well as interest in earthquake science). The ShakeOut drills are also an excellent structure to prepare Californians to respond to earthquake early warnings. For the warnings to be effective, individuals, organizations, and governments must be trained in how to respond appropriately given their situation. Also, the Shakeout drills will continue to be an annual exercise of SCEC's post-earthquake response plan.

SCEC's partnership with several state agencies (Department of Education, Emergency Management, etc.) has been bolstered as a result of the ShakeOut, and each has expressed their commitments to support the ShakeOut indefinitely. A state-sponsored survey of household earthquake preparedness in 2008 will hopefully be repeated regularly so that the ShakeOut effort can be continually improved. A new ECA Evaluation Committee will encourage additional social science research specific to the ShakeOut.

c. Putting Down Roots in Earthquake Country

This print and online publication series remains very popular and likely will be replicated in additional regions prior to and during SCEC4, similar to new versions produced since 2005 (Fig. 2.24). The existing versions will continue to be updated and improved with new science and preparedness information. Research results related to earthquake forecasting are already included in the handbook, and this information will be updated as operational earthquake forecasts and earthquake early warning become a reality in California. Tsunami content will also be added to the Southern California and Bay Area versions of the handbook, based on content created for the 2009 version of *Living on Shaky Ground*. This is a similar publication of the Redwood Coast Tsunami Workgroup that now also includes the SCEC/ECA *Seven Steps to Earthquake Safety.*

Beyond updates focusing on content, new versions or translations of the publication will expand the reach of *Roots* with particular emphasis on underserved communities. This will involve partners that specialize in communicating in multiple languages and via culturally appropriate channels. Additionally, versions for low-literate or visually impaired audiences, and perhaps for children and seniors will be pursued.

While the publication remains popular, ongoing evaluation will be conducted which will include information from those who have replicated Roots in other areas. Having multiple versions with different graphical designs and content allows for testing of what works best (in terms of content, terminology, overall design) by sociologists, risk communication experts, marketing specialists, and others.

d. Earthquake Education and Public Information centers (EPIcenters)

This network of "free-choice" learning institutions within the ECA has grown rapidly, with over 50 participants involved as of March 2010 (Fig 1.3) Many more are expected to join as a result of outreach by SCEC and the participants, including new museums, parks, and other venues in California, but also in other states. National organizations such as the American Museum Association will also be involved.

Members of the EPIcenter network have well-established ties to the communities that they serve and are regarded as providers of reliable information. They share a commitment to demonstrating and encouraging earthquake preparedness, organize ECA activities in their region, and lead presentations and other events in their communities. For example, they could quickly implement programs based on elevated forecasts and will educate visitors about how to respond to earthquake early warnings.

In addition to managing the EPIcenter network, SCEC will continue to maintain its existing exhibits and interpretive trails, and create new venues with EPIcenter partners. For example, SCEC will be consulting with the California Science Center as it updates its earthquake exhibit. We will also update our field trip guides to local faults, and organize them within a *SCEC Seismic Sites* online framework along with video footage of locations. This will be a resource for EPIcenter partners to use for their field trips.

As the EPIcenter network grows, clear agreements for use of materials and participation will be developed. A set of collateral (materials) and memoranda of understanding for their use will be created to outline the costs and benefits of being a partner, along with responsibilities. A rigorous evaluation process will be developed, including surveys that members can conduct of their visitors.

e. Media Relations

SCEC has developed extensive relationships with the news media and is increasingly called upon for interviews by local, national, and international reporters and documentary producers. This is especially true after earthquakes, such as the 2010 Haiti and Chile earthquakes. As a result the demand on SCEC scientists after a large California earthquake will be even greater than in previous earthquakes. In addition, the breadth of SCEC's research, including its information technology programs and the development of time-dependent earthquake forecasting, will also increase the need for expanded media relations. New strategies and technologies will be developed to meet these demands.

One such technology now available to SCEC and the ECA for ShakeOut media relations (and other ECA activities) is media-relations software (purchased by the California Earthquake Authority) that provides current contact information for all reporters and assignment editors, tracks news coverage, distributes news releases, and much more. Because this software can be used to assess how research findings and other messages are being communicated to the public, we will investigate such an investment, as suggested by the SCEC Advisory Council.

Social media capabilities will be expanded in SCEC4, including the use of podcasts, webinars, virtual news conferences, twitter, and other technologies. SCEC and the ECA will increase the availability of multi-lingual resources (materials, news releases, experts, etc.) to more effectively engage all media, including foreign media. Summer and school-year internships for journalism or communications students will be offered to assist CEO staff in developing these technologies and resources.

An important component to our media relations strategy will be media and risk communication training for the SCEC Community. Training will likely be held each year at the SCEC Annual Meeting, and will be coordinated among media relations personnel from SCEC institutions. New content management software for SCEC's web pages will allow members of the community to create online summaries of their research, along with video recordings of presentations, as part of a new experts directory. SCEC will partner with USGS, Caltech, and other partners to offer annual programs that educate the media on how to report earthquake science, including available resources, appropriate experts, etc.

3. K-14 Earthquake Education Initiative

The primary goal of this new Initiative is to educate and prepare California students for living in earthquake country. This includes improved earth science education as well as broadened preparedness training. The science of earthquakes provides the context for understanding why certain preparedness actions are recommended and for making appropriate decisions; however earthquake science and preparedness instructions are usually taught in a manner that lacks this context. For example, earthquake science is mostly taught in the context of plate tectonics and not in terms of local hazards. Large distant earthquakes are something that happened "over there" and local connections are not often made.

SCEC's position is that knowledge of science content and understanding of how to reduce earthquake risk may be best achieved through an event-based (teachable-moment) approach to the topic. In other words, even if most earthquake content remains in California's sixth grade curriculum, earthquake science and preparedness education should be encouraged in all grades when real-world events increase relevance and therefore interest. While we cannot plan when earthquakes will happen, the annual ShakeOut drill provides teachers a new type of teachable moment for teaching earthquake science.

In addition to event-based education opportunities such as the ShakeOut, educational materials must also be improved or supplemented to provide better information about local earthquake hazards and increase relevance for learning about earthquakes (place-based education). SCEC's role as a content provider is its ability to convey current understanding of earthquake science, explain how this understanding is developed, and provide local examples. The SCEC4 focus on time-dependent earthquake forecasting may take many years to appear in textbooks, yet SCEC can develop useful resources for teachers now.

SCEC's approach will be as follows. First, we will facilitate learning experiences and materials for use with real earthquakes and the ShakeOut drill. This will include online resources and activities, appropriate for various subjects (science, math, geography, etc.) for teachers to download immediately after large earthquakes and prior to the ShakeOut. Second, SCEC and our education partners will develop learning materials that complement traditional standards-based instruction with regional and current earthquake information. Teacher workshops will be offered to introduce these resources to educators at all levels, and will include follow-up activities over the long-term to help implement the content. Evaluation will be conducted across all activities, perhaps involving education departments at SCEC institutions.

For these activities to be successful, participation and commitment are essential from groups such as the California Department of Education, producers of educational media and materials (e.g. textbook companies), science educators, providers of teacher education, EPIcenters, and science education advocacy groups such as the California Science Teachers Association. We have developed partnerships with these groups and will bring them together as a new component of the Earthquake Country Alliance.

4. Experiential Learning and Career Advancement

The SCEC Experiential Learning and Career Advancement (ELCA) program seeks to enhance the competency and diversity of the STEM workforce by facilitating career advancement pathways that (1) engage students in research experiences at each stage of their academic careers, and (2) provide exposure and leadership opportunities to students and early career scientists that engage them in the SCEC Community and support them across key transitions (undergraduate to graduate school, etc.).

The ELCA program in SCEC4 will be built on the foundation of our long-established UseIT and SURE internship programs (described in §II.B) that challenge undergraduates with difficult, real-world problems that require collaborative, interdisciplinary solutions. Each summer they will involve more then 60 students (including students at minority-serving colleges and universities and local community colleges). The interns will experience how their skills can be applied to societal issues, and benefit from interactions with practicing professionals in earth science, engineering, computer science, and policy.

In addition to continuing these undergraduate programs, we plan to develop a high school to graduate school career pathway for recruiting the best students, providing them with high-quality research, education, and outreach experiences, and offering career mentoring and networking opportunities.

High school awareness and research opportunities will be closely linked with SCEC's K-14 Earthquake Initiative and based on successful programs that expose high school students to earthquake research, inquiry-based curricula, and visits by SCEC scientists. This may identify students that could participate in UseIT or a SURE project at a local SCEC institution, perhaps even prior to college.

In addition to our undergraduate internships, we will be exploring additional funding for master's level internships that provide unique opportunities. This will include support for cross-disciplinary computer science research by master's students similar to the ACCESS program (which completes in 2010). Students may participate in the UseIT program as mentors, conduct research projects with scientists at other SCEC institutions, and participate in CEO activities such as media relations, curricula development, and program evaluation. If funding from new sources does not become available, we may re-budget some funds to support master's interns.

The ELCA program for graduate students and post-docs will be focused on collaboration, networking, and employment opportunities, as most are supported by their institution, or with SCEC research funding (see section §I.B.3). Social networking will allow interaction across institutions and research projects. Students will be encouraged to interact within the SCEC collaboratory irregardless if they or their advisor has received SCEC research funding.

In addition to research opportunities, mentoring will be offered to help ELCA participants consider career possibilities, and longitudinal tracking of alumni will provide data on how students are progressing. Alumni will also be able to interact via social networking and SCEC meetings.

The final element of the ELCA program is career advancement opportunities for early-career researchers, including post-docs, young faculty, and research staff. In addition to employment opportunities that are shared via SCEC's email list, we have recently begun a SCEC Honorary Lectureship program, providing travel support and stipends for SCEC researchers (including early career researchers) to give presentations about their work at institutions nationwide. Also, SCEC leadership positions, especially the planning committee, provide opportunities for exposure and career advancement.

D. Diversity Plan

The SCEC leadership is committed to the growth of a diverse scientific community and recognizes that the Center must actively pursue this goal. A diversity working group of the Board of Directors formulates policies to increase diversity, and our progress is closely monitored by the SCEC Advisory Council and feedback to the Board through its annual reports. This diversity planning and review process has provided SCEC3 with effective guidance. We propose to continue to advance diversity in SCEC4 through several mechanisms:

- Currently, 16 of the 18 Board members are appointed by the core institutions, which are encouraged to consider diversity in their appointments of Board members. SCEC will continue this dialog and will continue to consider diversity in electing the Board's members-at-large.
- Diversity will continue to be a major criterion in appointments to the Planning Committee. The Planning Committee has significant responsibilities in managing SCEC activities and serves as a crucible for developing leadership.
- Many women and minority students are involved in intern and other undergraduate programs; however, successively smaller numbers participate at the graduate student, post doctoral, junior faculty and senior faculty levels. SCEC has little control in hiring scientists and staff at core and participating institutions or in admitting students—institutional diversity goals can be encouraged but not mandated. However, diversity will be included in the criteria used to evaluate proposals and construct the Annual Collaboration Plan.
- We recognize that the current situation is not unique to SCEC and reflects historical trends in the geoscience and physical science communities. We believe SCEC can be most effective in changing these trends by promoting diversity among its students and early-career scientists; i.e., by focusing on the "pipeline problem". The SCEC internship programs have been an effective mechanism for this purpose (e.g., **Fig. 3.22)**, and we will redouble our efforts to encourage a diverse population of students to pursue careers in earthquake science.

Tangible progress has been made in populating SCEC leadership positions with outstanding women scientists. Four women now serve on the Board of Directors (out of 18), including one as Vice-Chair of the Board. Eight women currently serve as working group leaders or co-leaders (more than twice the number in SCEC2), and they are participating visibly in the SCEC3 Planning Committee process. Women also have key roles in SCEC3 administration and CEO and will be assuming even greater roles in SCEC4 administration. CEO has contracted with women-owned small businesses in its ECA and ShakeOut activities. Some progress has also been made in terms of participation of minorities in SCEC leadership positions; two Board members and one Planning Committee members are Latino. Early-career scientists occupy SCEC3 leadership positions, and they have been active in pushing for increased diversity.

Recognizing that diversity is a long-term issue requiring continuing assessments and constant attention by the Center, the leadership has taken a number of concrete steps to improve its understanding of the composition and evolution of the SCEC community. Annual Meeting participants must register with SCEC, which includes providing demographic information. This allows us to continually assess the demographics of the community and track the career trajectories of students and early-career scientists. Fig. 1.4 shows a snapshot of the diversity of the SCEC Community as a whole. Of the 892 participants in SCEC3, diversity levels generally reflect historical trends in the geosciences, with much greater diversity among students than senior faculty. In terms of gender, women account for 52% of SCEC undergraduates, 34% of graduate students, 30% of technical staff, 18% non-geoscience researchers, and 21% of geoscience researchers. Participation of under-represented minorities is very low (7% overall), again reflecting the Earth Sciences at large.

A bright spot in our diversity efforts are the SCEC intern programs. During SCEC3, 47% of interns have been women, and 28% were under-represented minorities (Figs. 2.25). We believe that the key to increasing the diversity of SCEC participants in the future is to involve, interest, and retain students of diverse backgrounds, encouraging them to continue into research careers. Our recruitment activities now include active participation in regional minority science meetings around the country, and the distribution of recruitment information to historically black colleges and other minority-serving undergraduate institutions nationwide. We also are establishing partnerships with Southern California community colleges, which co-fund students to participate in the SURE and UseIT programs. These recruitment activities have been very successful and will continue in SCEC4.

The expanded Experiential Learning and Career Advancement program (§II.C.4) will add attention to diversity into graduate school and beyond, where the numbers of women and under-represented minorities traditionally decline substantially. Through this program, SCEC will mentor students at all levels and encourage trajectories towards STEM careers.

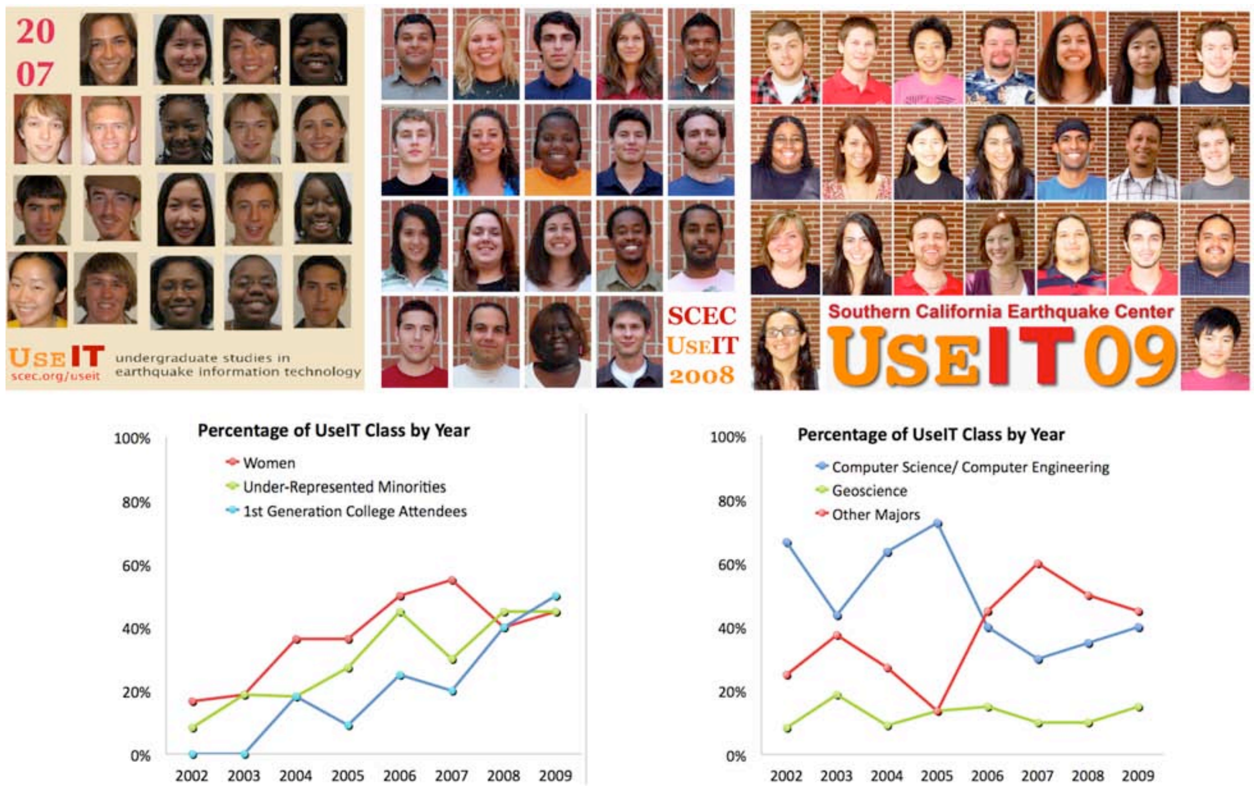


Figure 3.22. Top panels show the UseIT interns for the last three years (2007-2009). Lower graphs, which are taken from the 2009 external CEO review, plot several measures of diversity (left) and disciplinary specialization (right). The correlation indicates that intern diversity can be increased by broadening the participation to include students that have not yet elected to pursue STEM careers.

E. Information Technology Plan

SCEC information technology will support collaboration through communication by leveraging strong facilities and operations support from USC [*319*] with results from NSF-funded efforts to enhance virtual organizations [e.g. *320*]. The Center will continue to introduce, implement, and develop new collaboration tools to create a smarter and greener SCEC. Collaboration tools that support sharing and co-editing of documents, shared desktops, and video-conferencing have been greatly improved [*321*] and are now widely available and inexpensive. SCEC will encourage its research groups to adopt tools that are open-source and based on standard research community practices (e.g. Skype, Drupal, GNU, and Globus). IT support for SCEC administration of contracts, grants, staff, and facilities will be based on USC academic computing services, ensuring that SCEC operates with an up-to-date and inexpensive cyberinfrastructure. IT will support increased use of multimedia within SCEC with audio and video editing tools and media distribution capabilities.

Public interactions with the Center often start at the SCEC website [*322*]. It will communicate an overall view of SCEC earthquake system science and establish how specific SCEC research projects contribute to the larger earthquake system science research program. SCEC's Community Organized

Resource Environment (CORE) will be used to manage digital content for public use, while its Community Information System (CIS) will manage information about the SCEC community. The CIS provides extensive capabilities to connect researcher with proposals, contracts, and supports working group activities; in SCEC4, it will provide new ways for community members to find and work with each other using many new communications services including cell and text messaging, VoIP, and instant messaging.

SCEC faces a flood of file-based digital research artifacts, including papers, posters, presentations, images, animations, data, and software [*323*,*324*]. We will measure, and then manage, this digital flood by developing a SCEC digital inventory using DSpace [*325*], which provides extensive file management and collection management capabilities, and iRods [*326*] to support physical storage of very large collections at NSF and DOE HPC centers. The SCEC digital inventory will manage any artifact accessible through a network address (a physical copy of the file in the inventory is not required).

SCEC digital inventory management will borrow from systems that manage depreciating physical inventories. As new artifacts are added to the inventory, they will receive persistent identifiers and estimates of expected useful lifetime, cost to produce, and cost to reproduce. Extended storage of artifacts will be based on community interest or perceived value. IT will provide new tools to help researchers contribute, find, and use the SCEC digital inventory. Drupal [*327*], an open-source web-based content management system, has been introduced as a way for researchers to contribute artifacts. A Wikipedia-style [*328*] catalog will be introduced as a SCEC digital inventory discovery tool. Individual projects will contribute description and links to their project descriptions and digital artifacts. Community-developed organization of concepts within this system will form the basis for standardized vocabulary within the collaboratory. Routine metadata for digital artifacts will be improved using project-specific, and file-type-specific, metadata templates [*329*] with default values that can be easily associated with files as they are contributed.

CME computational research continues to push scientific and computational limits of seismic hazard research. SCEC's PRAC award [*330*] will provide access to NSF's Track-1 Blue Waters system when it becomes available in late 2011 [*331*]; it indicates SCEC's leadership role in the national HPC community. Based on current performance benchmarks, SCEC AWP-ODC [*332*] dynamic rupture and wave propagation software will be capable of sustained petaflops performance on Blue Waters.

SCEC computational research objectives rely heavily on computer resources provided by national HPC organizations including NSF TeraGrid, NSF Blue Waters, DOE INCITE [*333*] and other resource providers. SCEC's cyberinfrastructure bridges with USC and multiple NSF TeraGrid sites. The CME will increase its modeling and distribution capabilities by establishing two-way programmatic data, computing, and simulation interfaces with organizations around the world [*334*], including DOE INCITE, Open Science Grid [*335*], National Center for Atmospheric Research [*336*], Advanced National Seismic System [*337*], EarthScope [*338*], IRIS [*339*], Global Earthquake Model [*12*], and NEES [*340*], using our experience in vertical integration to advance system science.

CME computational platforms forecast ground motion across the earthquake cascade from rupture initiation [*81*] to very long-term, physics-based, PSHA [*255*] calculations. CME developers will continue to improve the earthquake physics used in models and increase the scale and frequency content of CME simulations. CME research emphasizes repeatability of calculations and verification and validation of models [*341*]. It has helped to establish standard practices for SCEC collaborative research through use of software version control SVN [*342*], software development and issue tracking tools such as Trac [*343*], and automated testing tools, including xUnit [*344*], CruiseControl [*345*], Metronome [*346*], and Pegasus-WMS [*87*] to re-verify functionality [*347*] during development and integration.

The scientific complexity and broad societal impact of short-term earthquake forecasting motivated SCEC's development of CSEP. The SCEC CSEP testing center [*49*] implements prospective testing of short-term earthquakes forecast over time. Automated testing techniques have been integrated into the CSEP testing framework. The CSEP testing framework, which is now being used to evaluate CISN ShakeAlert ground motion forecasts (an EEW prototype), will also be configured to evaluate other broad impact forecast models, such as ShakeMap and operational earthquake forecasts.

CME simulation data management will seek to reduce the consumption of SCEC resources on long term digital archives. The SCEC digital inventory will organize and manage SCEC project files as well as large-scale CME simulation results. The very large-scale CME computational and data resource requirements will be managed through a SCEC-developed tiered qualification process. Small-scale HPC computer and storage resources will be available to all SCEC researchers. Additional computer time, or large and long-term storage, will be available to SCEC projects that can show readiness for community usage through software and data versioning, issue tracking for code, build and test distributions, and setup and results for community-selected reference problems. CME will ask SCEC researchers to participate in data management and platform management TAG's. SCEC TAG's will review CME platform development, platform usage, data management decisions. Simulation results with exceptional long-term value will be prepared for transfer to existing seismological data centers such as SCEDC [*348*] and IRIS DMS [*349*] for long term storage and distribution. CME will collaborate with IRIS and other organizations to define the metadata requirements for long-term storage of simulation results [*350*].

SCEC researchers will be asked to participate in annual HPC allocation planning to ensure CME efforts reflect interests of core SCEC researchers. Computational efficiencies developed on the largest CME projects will be used to increase the scale of routine processing. New program and data distribution tools and techniques, including Kernel-based Virtual Machine [*351*] and academic and commercial cloud computing [*352*], will be used to distribute SCEC's processing systems to USGS, CGS, FEMA, CalEMA and other operational agencies.

Tracking earthquake cascades in real-time presents major IT challenges [*353*]. SCEC cyberinfrastructure will be extended to bridge real-time and near-real-time seismic systems with CME HPC modeling capabilities. Integration of observational seismic systems with HPC modeling will enable new seismic hazard information such as synthetic ShakeMaps [*354*], rapid source mechanism improvements [*355*], and automated Earth model optimization [*28*].

IV. Management Plan

SCEC4 will operate under a lean, flexible management structure similar to the successful structure of SCEC3. The Center will become a "smarter and greener" virtual organization that contributes to sustainability through an increased use of collaboration tools. The management plan will be codified in a set of by-laws at the transition from SCEC3 to SCEC4. In preparing this proposal, the SCEC Board voted unanimously to operate SCEC4 under the same by-laws as SCEC3 with the University of Southern California (USC) continuing as the managing institution, and with T. Jordan, the Principal Investigator on this proposal, continuing as the Center Director.

Our funding request for SCEC4 is $28M for the 5 years ($20.5M from NSF and $7.5M from USGS) from 2012-2017. These funds will support the SCEC core research program, as well as Center administration; the CEO program; the SURE intern program; the SCEC annual meeting and meetings of the Board, PC, and AC; information technology for the Center; and a modest director's reserve fund. An explanation of the budget (with emphasis on the first year of SCEC4) is contained in the Budget Justification section. The funding request is modest for the ambitious program proposed here. When considered in the historical context of SCEC funding since 1991 (see lower graph of Fig. 1.4), the $5.2M in funding requested for the core program in Year 1 (2012) is similar to the Center's highest level of core funding (reached in 1998), not accounting for inflation.

A. Organization of the Center

Institutional Membership and Board of Directors. The Center will remain an institutionally based organization governed by a Board of Directors (Fig. 3.21). It will recognize both core institutions, which make a major, sustained commitment to SCEC objectives, and a larger number of participating institutions, which are self-nominated through the involvement of individual scientists or groups in SCEC activities and confirmed by the Board. The 18 core and 52 participating institutions planned for SCEC4 (as of the proposal submission) are listed in Supplementary Documents. Membership may evolve, however, because SCEC will continue as an open consortium, available to any individuals and institutions seeking to collaborate on earthquake science in Southern California. Two new institutions have requested SCEC4 core status: the California Geological Survey and the California State University Consortium, which includes 6 CalState campuses. UC-Davis is exploring joining SCEC4 as a core institution, which we would welcome.

Each core institution will appoint one member to the Board. The Board will elect two nominees from the participating institutions to serve two-year terms on the Board as members-at-large. The Board will be the primary decision-making body of SCEC; it will meet three times per year (in February, June, and September) to approve the annual science plan, management plan, and budget, and deal with major business items, including the election of an Executive Committee and an Advisory Council. Provisions in the by-laws will allow the Board to conduct business via email. The Center Director will act as Chair of the Board. Based on the institutional membership listed in Table 1.1, the Board will comprise 20 voting members (18 core institutions plus two at-large members). Non-voting members will include the Deputy Director; the Associate Director for Administration (serving as Executive Secretary); the Associate Director for Communication, Education, and Outreach; and the Associate Director for Information Technology.

The Executive Committee will handle daily decision-making responsibilities, mainly through email. It will have five voting members, the Center Director, who will act as Chair, and four members elected for three-year terms from amongst the Board, as well as two non-voting members, the Deputy Director and the Associate Director for Administration, who will serve as Executive Secretary.

Administration. The Center Director will be the Chief Executive Officer and will bear ultimate responsibility for the Center's programs and budget. The Director will (a) act as PI on all proposals submitted by the Center, retaining final authority to make and implement decisions on Center grants and contracts, and ensuring that funds are properly allocated for various Center activities; (b) serve as the chief spokesman for the Center to the non-SCEC earthquake science community and funding agencies; (c) serve as Chair of the Board of Directors, presiding at Board meetings and overseeing that decisions and votes of the Board are executed, insofar as resources permit; (d) devise a fair and effective process for the development of the annual science plan, based on proposals or work plans submitted to the Center, and oversee its implementation; (e) oversee the development and execution of a plan to communicate and transfer center research knowledge to a broad user community, including academia and K-12 schools, governments at all levels, business, and the public; (f) ensure a broadly diverse SCEC community; (g) appoint committees to carry out Center business; and (h) oversee the preparation of technical reports.

A Vice-Chair (elected from the Board) will call and conduct Board meetings in the absence of the Chair, and will perform duties and exercise powers as assigned by the Center Director and Board.

The Deputy Director will be (a) chair of the Planning Committee, (b) liaison to SCEC science partners, and (c) chair of the annual meeting. The DD will oversee the development of the annual RFP, and recommend an annual collaboration to the Board based on the review process. G. Beroza has agreed to continue as Deputy Director in SCEC4.

The Associate Director for Administration will assist the Center Director in the daily operations of the Center and be responsible for managing the budget as approved by the Board, filing reports as required by the Board and funding agencies, and keeping the Board, funding agencies, and Center participants current on all Center activities. J. McRaney of USC has agreed to continue to serve in this capacity through SCEC4.

Advisory Council. An elected external Advisory Council (AC) will serve as an experienced advisory body to the Center. The Council will report to the Center through its Chair. The AC will comprise a diverse membership representing all aspects of Center activities, including basic and applied earthquake research and related technical disciplines (e.g., earthquake engineering, risk management, and information technology), formal and informal education, and public outreach. Members of the AC will be drawn from academia, government, and the private sector; they will be elected by the Board for three-year terms and may be re-elected. The Council will meet annually to review Center programs and plans and prepare a report for the Center. The AC Chair will be apprised on all major actions of the Center. Council members will be informed of Center activities and invited to participate in all appropriate Center functions. Council reports will be made available to NSF, the USGS, and other funding agencies.

Management of Center Research and CEO Activities. The SCEC4 organization chart shown in Fig. 3.21 reflects the changes in working group structure described in §III.B.2. Standing disciplinary working groups in Earthquake Geology, Tectonic Geodesy, and Seismology will coordinate the principal data-gathering activities (e.g., seismic and geodetic networks, geologic field studies, laboratory work) and the disciplinary infrastructure, as well as communal field equipment and experiments. The new Computational Science disciplinary working group will work with SCEC scientists to take advantage of rapidly changing computer architectures and algorithms. Interdisciplinary research will be organized by focus groups in Unified Structural Representation, Earthquake Source Physics, Lithospheric Architecture & Dynamics, Earthquake Forecasting & Predictability, and Ground Motion Prediction. The Southern San Andreas Fault Evaluation (SoSAFE) special project will become an interdisciplinary focus group, a proposal developed in discussion with USGS scientists, who are interested in long-term, interdisciplinary research focused on the San Andreas fault system.

The focus groups will be project-oriented, with well-defined tasks, timelines, and products. They will be responsible for the development, verification, release, maintenance, and improvement of the SCEC Community Models. The chairs of the disciplinary working groups and focus group leaders will be responsible for annual reports and will participate on the Planning Committee. The leaders of the special project groups, which will tentatively include the Community Modeling Environment (CME), the Working Group on California Earthquake Probabilities (WGCEP), the Collaboratory for the Study of Earthquake Predictability (CSEP), Earthquake Early Warning (EEW) project, and the Extreme Ground Motion (ExGM) project, will coordinate activities in these areas and serve on the Planning Committee.

The overall framework for this data-integration and modeling effort, including the software standards for data structures and model interfaces, will be the responsibility of the SCEC Associate Director for Information. The IT Director will report to the Center Director and will coordinate the SCEC CME and other IT activities. P. Maechling, the current SCEC IT Director, has agreed to serve in this position in SCEC4.

The Communication, Education, and Outreach (CEO) program will be managed by the Associate Director for CEO, who will supervise a staff of specialists. M. Benthien has agreed to continue in this role in SCEC4. The Experiential Learning and Career Advancement program and other education programs will be overseen by R. deGroot, Education Programs Manager. The Implementation Interface between SCEC and its research engineering partners will be actively managed by P. Somerville, who will serve on the Planning Committee. His efforts will be facilitated by a contract with URS, a SCEC participating institution involved in earthquake research and engineering implementation.

Smarter and Greener SCEC. The Center will continue to introduce, implement, and develop new collaboration tools to facilitate rapid information exchange for the SCEC community (see §III.E). Adoption of available, mature collaboration tools will contribute to the sustainability of the organization. The available collaboration tools (e.g. interoperable messaging, virtual desktop sharing, remote conferencing, data and other content management systems) will be accessible by community via a secure SCEC web portal, which can be flexibly configured and adapted to meet the community's evolving needs. These tools will enable (1) rapid information sharing during critical times, such as post-earthquake scientific coordination, (2) delivery of hazard-related products for reducing earthquake risk to end-users, and (3) sharing useful knowledge with the public to improve community resilience. The integration of social networking media into the SCEC portal will enhance the ability of the Center's scientists to communicate their results directly to the public. T. Huynh, SCEC Special Projects Manager, will oversee these tasks.

B. Budgeting Process

Planning Process. The SCEC Planning Committee (PC) will be responsible for annual and long-term research planning. The PC will be chaired by the Deputy Director and comprise representatives from each of the working groups; the Associate Directors for Administration, CEO and IT will serve as non-voting members. The annual budget cycle will begin with the articulation of the research plan by the PC during the summer. The draft plan will be presented to the SCEC community and discussed at the annual meeting in September. Following the meeting, the PC will finalize the science plan and present it to the Board and Director for approval. This plan will form the basis for the Annual Collaboration Solicitation released in early October. SCEC participants will submit proposals in response to this solicitation in November. All proposals will be independently reviewed by the Center Director, the Deputy Director, and the chairs and/or co-chairs of at least 3 relevant working groups. Review assignments will avoid conflicts of interest.

The PC will meet in January to review all proposals and construct an Annual Science Collaboration Plan. The plan's objective will be a coherent science program, consistent with SCEC's basic mission, institutional composition, and budget that can achieve the Center's short-term objectives and long-term goals. The Deputy Director will combine the PC's recommendation and submit the Annual Science Collaboration Plan to the Board of Directors. The annual budget will be approved by the Board, signed by the Center Director, and submitted to the sponsoring agencies for final approval and funding.

Annual Collaboration Plan. In constructing the Annual Collaboration Plan, proposals submitted in response to the RFP will be evaluated based on: (a) scientific merit of the proposed research; (b) competence, diversity, career level, and performance of the investigators; (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 PI and institution to the SCEC mission; (f) value of the proposed research relative to its cost; and (g) the need to achieve a balanced budget while maintaining a reasonable level of scientific continuity given funding limitations. With respect to criterion (b), we note that improving the diversity of the SCEC community and encouraging early-career scientists is a major goal of the Center.

Joint SCEC/USGS Planning Committee. SCEC will maintain a close alignment of the Center's activities with the USGS Earthquake Program through three mechanisms: (a) accountability required by USGS funding of SCEC activities, (b) memberships on the Board of Directors by the three USGS offices now enrolled as SCEC core institutions, and (c) a Joint SCEC/USGS Planning Committee (JPC). The latter combines the SCEC Planning Committee with a group of program leaders designated by the USGS. This coordination mechanism has worked very well in SCEC2 and SCEC3 and will be continued in SCEC4. Members of the USGS JPC will continue to participate in the annual PC meeting that reviews the Annual Collaboration Plan.

C. Operations Following a Major Earthquake

Major Southern California earthquakes—1992 Landers (M7.3), 1994 Northridge (M6.7), 1999 Hector Mine (M7.1), 2003 San Simeon (M6.5), and 2004 Parkfield (M6.0)—have been important events for focusing SCEC research and stimulating collaboration. The Center's management structure, as expressed in its working groups, has been able to respond quickly in coordinating field programs with the USGS and other organizations to capture perishable data and conduct post-earthquake studies.

None of these earthquakes occurred during SCEC3; however, and we recognize the need to be constantly prepared. We held a workshop at the 2007 SCEC annual meeting on what scientists most need to learn when the next earthquake occurs and how we would respond. One conclusion was the need to develop better post-earthquake communication capabilities. Towards this end, scientists at SCEC institutions have obtained satellite phones and practice using them periodically. The institutions having satellite phones are: USC (3), Stanford, USGS (Pasadena, Menlo Park, and Reston), Caltech, UC Davis, and UC Riverside. SCEC has also developed an Earthquake Response Content Management System (CMS) that is hosted at USC and mirrored both at Caltech and Stanford.

The DRUPAL-based CMS has important capabilities including threaded discussions, the ability to host graphics, a monitor of who is currently online, etc. SCEC scientists, particularly the disciplinary group leaders of the PC have populated the CMS with an inventory of instrumentation, such as seismographs and campaign GPS instruments. The information includes contact information for SCEC scientists and resources at universities, agencies, and consortia (UNAVCO and IRIS) detailing what's available, where it is, and how to get it. Given that conference calls are critical in coordinating research we have a dedicated 24/7 conference call line (hosted outside California). We exercised the dedicated line, the Earthquake Response CMS, and the satellite phones as part of the 2008 ShakeOut. The CMS proved useful in responding to the March 24, 2009 Bombay Beach swarm, and we exercised it again in the 2009 ShakeOut exercise.

Overall post-earthquake scientific response will be managed by the USGS in coordination with the State of California. Through its cooperative agreements with the NSF and USGS and its contractual arrangements with core and participating institutions, SCEC will provide a well-organized conduit for the funding of scientific investigations in the critical period immediately following a major event. The SCEC components of this response will be managed by the SCEC Director, Deputy Director, and staff, and plans will be executed through the SCEC working groups and special teams. SCEC geologists will move quickly to resolve the scope of surface rupture, which will require immediate access to necessary equipment, clearance, and transportation, including helicopters and aerial photography. SCEC geodesists will quickly install temporary GPS receivers to track post-earthquake slip and coseismic slip during aftershocks, in addition to processing data from PBO. SCEC seismologists will immediately deploy seismometers from SCEC's Portable Broadband Instrument Center into the epicentral region, and request additional instruments from IRIS, to record aftershocks, resolve the properties of the fault rupture, and help assess the potential for additional large events. All these efforts will require coordination with data center seismologists who will be revising real-time information on source properties and ground motions. As observations are reported from the field, the CEO office will help coordinate an effective media response with the USGS, State of California, and other organizations.

Post-earthquake activities will require close coordination among earthquake science and engineering organizations. In 2003, the USGS developed a Plan to Coordinate NEHRP Post-Earthquake Investigations to provide guidance to coordinate post-earthquake investigations supported by the National Earthquake Hazards Reduction Program (NEHRP) [*356*]. The USGS plan addresses coordination of the NEHRP agencies—Federal Emergency Management Agency (FEMA), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), the U.S. Geological Survey (USGS)—and their partners such as SCEC. Part of the plan is devoted to operations of a post-earthquake clearinghouse and recognizes that the State of California has “formalized the process for establishing a clearinghouse.” SCEC is a leader in the California Post Earthquake Information Clearinghouse with USGS, CGS, OES, EERI, and many others.

V. References

1 U.S. Geological Survey (2007), *Facing Tomorrow's Challenges—U.S. Geological Survey Science in the Decade 2007–2017*, U.S. Geological Survey Circular 1309, 70 pp.

2 National Science and Technology Council Committee on Environment and Natural Resources (2005), *Grand Challenges for Disaster Reduction*, Report of the Subcommittee on Disaster Reduction, June, 2005, 21 pp.

3 NSF Advisory Committee for Geosciences (2009), *Geovision Report: Unraveling Earth's Complexities through the Geosciences*, National Science Foundation, October, 2009, 39 pp.

4 Lay, T., ed. (2009). *Seismological Grand Challenges in Understanding Earth's Dynamic Systems*, Report to the National Science Foundation, IRIS Consortium, 76 pp.

5 Federal Emergency Management Agency (2000), *Estimated Annualized Earthquake Losses for the United States*, FEMA Report 366, Washington, D.C., September, 32 pp.

6 Field, E.H., T.E. Dawson, K.R. Felzer, A.D. Frankel, V. Gupta, T.H. Jordan, T. Parsons, M.D. Petersen, R.S. Stein, R.J. Weldon II & C.J. Wills (2009), Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2), *Bull. Seismol. Soc. Am.*, **99**, 2053-2107, doi:10.1785/0120080049. (Originally released as USGS Open File Report 2007-1437.)

7 Hudnut, K., T. Rockwell & K. Scharer (2010), Southern San Andreas Fault Evaluation (SoSAFE) Project: Summary of Results, 2007 to 2009, submitted to the USGS, February 10, 2010, 11 pp.

8 Akciz, S. O., L. Grant Ludwig & J. R. Arrowsmith (2009), Revised dates of large earthquakes along the Carrizo section of the San Andreas fault, California, since A.D. 1310 ± 30, *Journal of Geophysical Research*, **114**, B01313; Akciz, S. O., L. Grant Ludwig, J. R. Arrowsmith & O. Zielke (in review), Century-long average time intervals between ruptures of the San Andreas fault in the Carrizo Plain, *Geology*.

9 Zielke, O., J. R. Arrowsmith, L. Grant Ludwig & S. O. Akciz (2010), Slip in the 1857 and earlier large earthquakes along the Carrizo Plain, San Andreas fault, *Science*, doi:10.1126/science.1182781; Grant Ludwig, L., S. O. Akciz, G. R. Noriega, O. Zielke & J. R. Arrowsmith (2010). Climate-modulated channel incision and rupture history of the San Andreas fault in the Carrizo Plain, *Science*, doi:10.1126/science.1182837.

10 NSF Cyberinfrastructure Council, *Cyberinfrastructure Vision for 21st Century Discovery*, National Science Foundation Report 07-28, Washington DC, March 2007, 57 pp.

11 Cummings, J., Finholdt, T., Foster, I., Kesselman, & Lawrence, K.A. (2008), *Beyond Being There: A Blueprint for Advancing the Design, Development, and Evaluation of Virtual Organizations*, Final Report from Workshops on Building Effective Virtual Organizations, National Science Foundation, May 2008, 58 pp.

12 Global Earthquake Modeling (GEM) Project: *http://www.globalquakemodel.org*

13 Center for Dark Energy Biosphere Interactions (C-DEBI): *http://www.darkenergybiosphere.org/resources/archive.html*

14 National Science Foundation. (2007). *Merit Review Broader Impacts Criterion: Representative Activities*. Arlington, VA: National Science Foundation. Online at: *http://www.nsf.gov/pubs/gpg/broaderimpacts.pdf*.

15 Graves, R., S. Callaghan, E. Deelman, E. Field, N. Gupta, T. H. Jordan, G. Juve,, C. Kesselman, P. Maechling, G. Mehta, D. Meyers, D. Okaya & K. Vahi (2008). Physics-based probabilistic seismic hazard calculations for Southern California, *Proc. 14th World Conference on Earthquake Engineering*, Beijing, China, 8 pp., October, 2008; Graves, R., S. Callaghan, E. Deelman, E. Field, T. H. Jordan, G. Juve, C. Kesselman, P. Maechling, G. Mehta, K. Milner, D. Okaya, P. Small & K. Vahi (2010), CyberShake: Full waveform physics-based probabilistic seismic hazard calculations for Southern California, *Pure and Applied Geophysics*, in press.

16 Power, M., B. Chiou, N, Abrahamson, Y. Bozorgnia, T. Shantz, and C. Roblee (2008). An Overview of the NGA Project, *Earthquake Spectra*, **24**, 3-21.

17 Day, S. M., R. Graves, J. Bielak, D. Dreger, S. Larsen, K. B. Olsen, A. Pitarka & L. Ramirez-Guzman (2008), Model for Basin Effects on Long-Period Response Spectra in Southern California, *Earthquake Spectra*, **24**, 257-277.

18 Kohler, M., Magistrale, H., and Clayton, R. (2003). Mantle heterogeneities and the SCEC three-

dimensional seismic velocity model version 3, *Bull. Seismol. Soc. Am.,* **93**, 757–774.
19 Süss, M. P., and J. H. (2003), P-wave seismic velocity structure derived from sonic logs and industry reflection data in the Los Angeles basin, California, *J. Geophys. Res.* **108**, 2170, doi: 10.1029/2001JB001628.
20 Hauksson, E. (2000), Crustal Structure and Seismicity Distribution Adjacent to the Pacific and North America Plate Boundary in Southern California, *J. Geophys. Res.*, **105**, 13875-13903
21 Chen, P., L. Zhao and T.H. Jordan (2007), Full 3D Tomography for Crustal Structure of the Los Angeles Region, *Bull. Seismol. Soc. Am.*, **97**, 1094-1120, doi: 10.1785/0120060222.
22 Tape, C., Liu, Q., Maggi, A., and Tromp, J. (2009), Adjoint tomography of the Southern California crust, *Science*, **325**, 988-992.
23 Chen, P., T. H. Jordan, S. Callaghan, P. Maechling (2009), Tera3d: Full-3D Waveform Tomography and Near-Real-Time Seismic Source Inversion in Southern California. SSA Annual Meeting Abstract.
24 Yan, Z., and R. W. Clayton (2007), Regional mapping of the crustal structure in southern California-from receiver functions, *J. Geophys. Res.*, **112**, B05311, doi:10.1029/2006JB004622.
25 Chulick, G. S., and W. D. Mooney (2002), Seismic structure of the crust and uppermost mantle of North America and adjacent oceanic basins: A synthesis, *Bull. Seismol. Soc. Am.*, **92**, 2478–2492.
26 Plesch A., J. H. Shaw, C. Benson, W. A. Bryant, S. Carena, M. Cooke, J. Dolan, G. Fuis, E. Gath, L. Grant, E. Hauksson, T. Jordan, M. Kamerling, M. Legg, S. Lindvall, H. Magistrale, C. Nicholson, N. Niemi, M. Oskin, S. Perry, G. Planansky, T. Rockwell, P. Shearer, C. Sorlien, M. P. SSM., J. Suppe, J. Treiman, R. Yeats (2007), Community Fault Model (CFM) for Southern California, *Bull. Seismol. Soc. Am.*, **97**, 1793-1802.
27 Boore, D. M. and W. B. Joyner (1997). Site amplifications for generic rock sites, *Bull. Seismol. Soc. Am.*, **87**, 327-341.
28 Prieto, G. A. and G. C. Beroza (2008), Earthquake Ground Motion Prediction Using the Ambient Seismic Field, *Geophys. Res. Lett.*, **35**, L14304; Ma, S., G. Prieto, and G. C. Beroza (2008), Testing Community Velocity Models for Southern California Using the Ambient Seismic Field, *Bull. Seismol. Soc. Am.*, **98**, 2694-2714, DOI: 10.1785/0120080947.
29 Prieto, G. A., J. F. Lawrence, and G. C. Beroza (2009), Anelastic Earth Structure from the Coherency of the Ambient Seismic Field, *J. Geophys. Res.*, **114**, B07202, doi:10.1029/2008JB006067.
30 Mayhew, J.E., and K.B. Olsen (2010). Goodness-of-fit Criteria for Broadband Synthetic Seismograms, With Application to the 2008 Mw5.4 Chino Hills, CA, Earthquake, *Seismol. Res. Lett.*, (submitted)
31 Hauksson, E. and P. Shearer (2005), Southern California hypocenter relocation with waveform cross-correlation, Part 1: Results using the double-difference method, *Bull. Seismol. Soc. Am*, **95,** 896, DOI: 10.1785/0120040167; Shearer, P. M., G. A. Prieto, and E. Hauksson (2005), Comprehensive analysis of earthquake source spectra in southern California, *J. Geophys. Res.*, **111**, B06303, doi:10.1029/2005JB003979; Lin, G., P. M. Shearer, and E. Hauksson (2007), Applying a 3D velocity model, waveform cross-correlation, and cluster analysis to locate southern California seismicity from 1981 to 2005, *J. Geophys. Res.*, **112**, doi:10.1029/2007JB004986; Waldhauser, F. and D.P. Schaff (2008), Large-scale relocation of two decades of Northern California seismicity using cross-correlation and double-difference methods, *J. Geophys. Res.*, **113**, B08311, doi:10.1029/2007JB005479.
32 Nicholson, C., E. Hauksson, A. Plesch, G. Lin, and P. Shearer (2008), Resolving 3D fault geometry at depth along active strike-slip faults: simple or complex? 2008 SCEC Annual Meeting, Palm Springs, CA.
33 Sieh, K. (1978), Slip along the San Andreas Fault associated with the great 1857 earthquake, *Bull. Seismol. Soc. Am.,* **68**, 1421-1448.
34 Biasi, G., and Weldon, R. (2009), San Andreas Fault rupture scenarios from multiple paleoseismic records; stringing pearls, *Bull. Seismol. Soc. Am.*, **99**, 471-498.
35 Philibosian, B., T. Fumal, R. Weldon, K. Kendrick, K. Scharer, S. Bemis, R. Burgette, and B. Wisely (2007), Paleoseismology of the San Andreas fault at Coachella, California, 2007 SCEC Annual Meeting Proceedings.
36 Bennett, R. A., A.M. Friedrich, A. M., and K. P. Furlong (2004), Codependent histories of the San Andreas and San Jacinto fault zones from inversion of fault displacement rates, *Geology*, **32**, 961-

964; McGill, S., Weldon, R., and Owen, L. (2008), Preliminary slip rates along the San Bernardino strand of the San Andreas Fault, 2008 SCEC Annual Meeting Proceedings.

37 Onderdonk, N., McGill, S., and Rockwell, T. (2009), New slip-rate, slip-history, and fault structure data from the northern San Jacinto fault zone, 2009 SCEC Annual Meeting Proceedings; Sharp, R. V. (1981), Variable rates of late Quaternary strike slip on the San Jacinto fault zone, southern California, *J. Geophys. Res*, **86**, 1754-1762.10.1029/JB086iB03p01754.

38 T. Rockwell (personal communication)

39 Behr, W.M., Rood, D.H., Fletcher, K.E., Guzman, N., Finkel, R., Hanks, T.C., Hudnut, K.W., Kendrick, K.J., Platt, J.P., Sharp, W.D., Weldon, R.J., Yule, J.D. (2010), Uncertainties in slip rate estimates for the Mission Creek strand of the southern San Andreas fault at Biskra Palms Oasis, *GSA Bulletin*, (in press); Fletcher, K. E., W. D. Sharp, K. J. Kendrick, W. M. Behr, K. W. Hudnut and T. C. Hanks (2009), 230Th/U dating of a late Pleistocene alluvial fan offset along the southern San Andreas fault, *GSA Bulletin*, (submitted).

40 Blisniuk, K., Rockwell, T., Owen, L., Oskin, M., Lippincott, C., Caffee, M., and Dorch, J. (2010), Late Quaternary slip-rate gradient defined using high-resolution topography and 10Be dating of offset landforms on the southern San Jacinto fault, California, *J.Geophys. Res.(*in press); Janecke, S., Dorsey, R., Steely, A., Kirby, S., Lutz, A., Housen, B., Belgarde, B., Langenheim, V., Rittenhour, T., and Forand, D. (2010), High geologic slip rates since early Pleistocene initiation of the San Jacinto and San Felipe fault zones in the San Andreas fault system, southern California, USA, *GSA Bulletin*, (submitted).

41 Rockwell, T., Seitz, G., Dawson, T., Young, J. (2006), The Long Record of San Jacinto fault paleoearthquakes at Hog Lake: Implications for Regional Patterns of Strain Release in the southern San Andreas fault system, *Seismol. Res. Lett*., **77**, 270.

42 Hudnut, K. W., Y. Bock, J. E. Galetzka, F. H. Webb, and W. H. Young (2002). *The Southern California Integrated GPS Network*, Seismotectonics in Convergent Plate Boundaries, ed. Y. Fujinawa and A. Yoshida, 167-189.

43 Loveless, J. P., and B. J. Meade (2010), Stress amplification on the San Andreas Fault due to Interseismic Fault System Interactions, *Nature*, (submitted).

44 Chuang, Y. R., and K. M. Johnson (2009), Are there geologic/geodetic fault slip rate discrepancies in southern California? 2009 SCEC Annual Meeting Proceedings.

45 Fay, N., R. Bennett, J. Spinler, and E. Humphreys (2008), Small-scale upper mantle convection and crustal dynamics in southern California, *Geochem. Geophys. Geosyst.*,**9**, Q08006.

46 Fay, N, & E Humphreys, (2008), Dynamics of the Salton block: Absolute fault strength and crust mantle coupling, *Geology*, **34**, 261-26.

47 Tullis, T. E., H. Noda, H., K. B. Richards-Dinger, N. Lapusta, J. H. Dieterich, Y. Kaneko, and N. M. Beeler (2009), Comparison of earthquake simulators employing rate and state-friction, 2009 SCEC Annual Meeting Proceedings; Ward, S. N. (2009), ALLCALL earthquake simulator - recent progress, 2009 SCEC Annual Meeting Proceedings.

48 Dieterich, J.H. and K.B. Richards-Dinger (2010), Earthquake recurrence in simulated fault systems, *Pure and Applied Geophysics*, **167**, 30.

49 Zechar, J.D., D. Schorlemmer, M. Liukis, J. Yu, F. Euchner, P.J. Maechling, & T.H. Jordan, 2009. The Collaboratory for the Study of Earthquake Predictability perspective on computational earthquake science, Concurrency and Computation: Practice and Experience, doi:10.1002/cpe.1519.

50 Zechar, J., and T. H. Jordan (2008) Testing alarm-based earthquake predictions, *Geophys. J. Int.*, **172**, 715-724, doi 10.111/j.1365-246x.2007.03676.x.

51 Wechsler, N, Allen, E E, Rockwell,T K, Chester,J S, Girty, G H, Ben-Zion, Y (2008), Physical and chemical characterization of pulverized granite from a shallow drill along the San Andreas Fault, Little Rock, CA, *Eos Trans. AGU*, Fall Meet. Suppl., Abstract T51A-1861; Wechsler, N., Allen, E.E., Rockwell, T.K., Chester, J., and Ben-Zion, Y. (2009), Characterization of Pulverized Granite from a Traverse and a Shallow Drill along the San Andreas Fault, Little Rock, CA, Seismological Society of America Annual meeting, *Seismol. Res. Lett.*, **80**, 2, 319.

52 Rockwell, T K, Sisk, M, Stillings, M, Girty, G, Dor, O, Wechsler, N, Ben-Zion, Y (2008), Chemical and Physical Characteristics of Pulverized Granitic Rock Adjacent to the San Andreas, Garlock and San Jacinto Faults: Implications for Earthquake Physics, *Eos Trans. AGU*, Fall Meet. Suppl., **89**, Abstract T53F-02; Dor, O., J.S. Chester, Y. Ben-Zion, J. Brune, T.K. Rockwell (2009), Characteriza-

tion of Damage in Sandstones Along the Mojave Section of the San Andreas Fault: Implications for the Shallow Extent of Damage Generation, *Pure and Applied Geophysics*, **166**, 1747-1773, doi:10.1007/s00024-009-0516-z.

53 Biegel, R. L., H.S. Bhat, C.G. Sammis, A.J. Rosakis, A.J. (2009) The Effect of Asymmetric Damage on Dynamic Shear Rupture Propagation I: No Mismatch in Bulk Elasticity, *J. Geophys. Res*, (submitted); Bhat, H. S., R. L. Biegel, A. J. Rosakis, and C. G. Sammis (2009) The Effect of Asymmetric Dam-age on Dynamic Shear Rupture Propagation II: With Mismatch in Bulk Elasticity, *J. Geophys. Res.* (in press).

54 Andrews, D.J. and T.C. Hanks (2007). Physical limits on ground motion at Yucca Mountain, *Bull. Seismol. Soc. Am.*, **97**, 1771-1792, doi:10.1785/0120070014.

55 Harris, R.A., M. Barall, R. Archuleta, B. Aagaard, J.-P. Ampuero, H. Bhat, V. Cruz-Atienza, L. Dalguer, P. Dawson, S. Day, B. Duan, E. Dunham, G. Ely, Y. Kaneko, Y. Kase, N. Lapusta, Y. Liu, S. Ma, D. Oglesby, K. Olsen, A. Pitarka, S. Song, and E. Templeton (2009), The SCEC/USGS Dynamic Earthquake Rupture Code Verification Exercise, *Seismol. Res. Lett.*, **80**, 119-126, doi:10.1785/gssrl.80.1.119.

56 Dunham, E. M. and J. R. Rice (2008), Earthquake slip between dissimilar poroelastic materials, *J. Geophys. Res.,* **113**, B09304, doi:10.1029/2007JB005405.

57 Noda, H., E. M. Dunham, and J. R. Rice (2009), Earthquake ruptures with thermal weakening and the operation of major faults at low overall stress levels, *J. Geophys. Res.,*, **114**, B07302, doi:10.1029/2008JB006143.

58 Yuan, F., and Prakash, V. (2008) Slip weakening in rocks and analog materials at co-seismic slip rates. *J. Mech. Phys. Sol.*, **56**, 542-560; Yuan, F. and V. Prakash (2008), Use of a Modified Torsional Kolsky Bar to Study Frictional Slip Resistance in Rock-Analog Materials at Coseismic Slip Rates, International Journal of Solids and Structures, Elsevier.

59 Rice, J. R. (2006), Heating and weakening of faults during earthquake slip, *J. Geophys. Res.*,, **111**, B05311, Doi 10.1029/2005jb004006.

60 Beeler, N. M., T. E. Tullis, and D. L. Goldsby (2008), Constitutive relationships and physical basis of fault strength due to flash heating, *J. Geophys. Res.*,, 113, B01401, doi: 10.1029/2007JB004988

61 Tullis, T. and D. Goldsby (2007), Laboratory Experiments on Fault Shear Resistance Relevant to Coseismic Earthquake Slip, SCEC 2007 Final Report.

62 Sagy, A., E.E. Brodsky, and G.J. Axen (2007), Evolution of fault-surface roughness with slip, *Geology,* **35**, doi: 10.1130/G23235A.1, 283-286.

63 Sagy, A., and E. E. Brodsky (2009), Geometric and rheological asperities in an exposed fault zone, *J. Geophys. Res.* **114**, B02301, doi:10.1029/2008JB005701.

64 Kitajima, H., J.S. Chester, F.M. Chester, F.M., T. Shimamoto (2010), High-speed Friction of the Punchbowl Fault Ultracataclasite in Rotary Shear: Characterization of Frictional Heating, Mechanical Behavior, and Microstructural Evolution, *J. Geophys. Res*. (submitted).

65 Bielak, J., R. Graves, K. Olsen, R. Taborda, L. Ramirez-Guzman, S. Day, G. Ely, D. Roten, T. Jordan, P. Maechling, J. Urbanic, Y. Cui, and G. Juve (2010) The ShakeOut earthquake scenario: verification of three simulation sets, *Geophys. J. Int.*, **180**, 375-404.

66 Guatteri, M., P. M. Mai, and G. C. Beroza, (2004) A pseudo-dynamic approximation to dynamic rupture models for strong ground motion prediction, *Bull. Seism. Soc. Amer*., **94**, 2051-2063; Song, S., A. Pitarka, and P. Somerville (2009). Exploring spatial coherence between earthquake source parameters, *Bull. Seism. Soc. Am*. **99**, 564-2,571; Schmedes, J., R. J. Archuleta, & D. Lavallee (2009). Correlation of earthquake source parameters inferred from dynamic rupture simulations, *J. Geophys. Res*., doi:10.1029/2009JB006689, (in press).

67 Andrews, D. J. (1976). Rupture velocity of plane strain shear cracks, *J. Geophys. Res.*, **81**, 5679–5687.

68 Aagaard, B. T., and T. H. Heaton (2004), Near-source ground motions from simulations of sustained intersonic and supersonic fault ruptures, *Bull. Seismol. Soc. Am*., **94**, 2064–2078, doi:10.1785/0120030249; Dunham, E. M. and R. J. Archuleta (2004). Evidence for a Supershear Transient during the 2002 Denali Fault Earthquake, *Bull. Seismol. Soc. Am.,* **94**, S256-S268; Dunham, E. M. and H. S. Bhat (2008), Attenuation of radiated ground motion and stresses from three-dimensional supershear ruptures, *J. Geophys. Res.*, **113**, B08319, doi:10.1029/2007JB005182.

69 Das, S. (2007), The need to study speed, *Science,* **317**, 906-907, doi:10.1126/science.1142143.

70 Bouchon, M. and H. Karabulut (2008). The Aftershock Signature of Supershear Earthquakes, *Science*, **320**, 1323-1325, doi:10.1126/science.1155030.

71 Dunham, E.M., D. Belanger, L. Cong, and Je. E. Kozdon Earthquake Rupture Propagation on Rough Faults (2010), *Bull. Seismol. Soc. Am.* (in preparation).

72 Aagaard, B. T., T. M. Brocher, D. Dolenc, D. Dreger, R. W. Graves, S. Harmsen, S. Hartzell, S. Larsen, M. L. Zoback (2008), Ground-Motion Modeling of the 1906 San Francisco Earthquake, Part I: Validation Using the 1989 Loma Prieta Earthquake, *Bull. Seismol. Soc. Am.*, **98**, 989-1011, doi: 10.1785/0120060409; Aagaard, B. T., T. M. Brocher, D. Dolenc, D. Dreger, R. W. Graves, S. Harmsen, S. Hartzell, S. Larsen, K. McCandless, S. Nilsson, N. A. Petersson, A. Rogers, B. Sjogreen, M. L. Zoback (2008), Ground-Motion Modeling of the 1906 San Francisco Earthquake, Part II: Ground-Motion Estimates for the 1906 Earthquake and Scenario Events, *Bull. Seismol. Soc. Am.,* **98**, 1012-1046, doi: 10.1785/0120060410.

73 Bozorgnia, Y., K. W. Campbell, N. Luco, J. P.Moehle, F. Naeim, P. Somerville, and T. Y. Yang (2007), Ground motion issues for seismic analysis of tall buildings: a status report, *The Structural Design of Tall Buildings*, **16**, 665-674; Naeim F, and R. W. Graves (2006), The case for seismic superiority of well-engineered tall buildings. *Structural Design of Tall and Special Buildings*, **14**, 401–416; Somerville, P.G., R.W. Graves, S.M. Day, and K.B. Olsen (2007), Ground Motion Environment of the Los Angeles Region', *The Structural Design of Tall and Special Buildings*, **15**, 483-494.

74 Earthquake Country Alliance: *http://www.earthquakecountry.org*; *Putting Down Roots in Earthquake Country*: *http://www.earthquakecountry.org/roots*

75 “Con Los Pies en la Tierra” (With Feet on the Ground) campaign: *http://www.conlospiesenlatierra.gov.co*

76 Dare to Prepare campaign: *http://www.daretoprepare.org*; in Spanish: *http://www.terremotos.org*

77 Jones, L., M., R. Bernknopf, D. Cox, J. Goltz, K. Hudnut, D. Mileti, S. Perry, D. Ponti, K. Porter, M. Reichle, H. Seligson, K. Shoaf, J. Treiman, and A. Wein (2008), The ShakeOut Scenario: *U.S. Geological Survey Open-File Report 2008-1150. http://pubs.usgs.gov/of/2008/1150/*

78 Graves, R., B. Aagaard, K. Hudnut, L. Star, J. Stewart & T. H. Jordan (2008). Broadband simulations for Mw 7.8 southern San Andreas earthquakes: Ground motion sensitivity to rupture speed, *Geophys. Res. Lett.*, **35**, L22302, doi: 10.1029/2008GL035750.

79 Drupal Website: *http://www.drupal.org*

80 Jordan, T. H. & P. Maechling (2003), The SCEC community modeling environment; An information infrastructure for system-level earthquake science, *Seismol. Res. Lett.*, **74**, 324-328.

81 Olsen, K. B., S. Day, J. B. Minster, Y. Cui, A. Chourasia, M. Faerman, R. Moore, P. Maechling, & T. H. Jordan (2006), Strong Shaking in Los Angeles Expected From Southern San Andreas Earthquake, *Geophys. Res. Lett.*, **33**, L07305, doi:10.1029/2005GL025472; Olsen, K.B., S.M. Day, J.B. Minster, Y. Cui, A. Chourasia, D. Okaya, P. Maechling, T.H. Jordan (2008). TeraShake2: Simulation of Mw7.7 earthquakes on the southern San Andreas fault with spontaneous rupture description, *Bull. Seism. Soc. Am.,* **98***,* 1162-1185, doi: 10.1785/0120070148.

82 Olsen, K.B., S.M. Day, L.A. Dalguer, J. Mayhew, Y. Cui, J. Zhu, V.M. Cruz-Atienza, D. Roten, P. Maechling, T.H. Jordan, D. Okaya & A. Chourasia (2009), ShakeOut-D: Ground motion estimates using an ensemble of large earthquakes on the southern San Andreas fault with spontaneous rupture propagation, *Geophys. Res. Lett.*, **36**, L04303, doi:10.1029/2008GL036832.

83 Olsen, K. B. (1994). Simulation of Three-Dimensional Wave Propagation in the Salt Lake Basin, Ph.D. Thesis, University of Utah, Salt Lake City, Utah, 157 pp.; Olsen, K.B., R. Madariaga & R. Archuleta (1997), Three dimensional dynamic simulation of the 1992 Landers earthquake, *Science*, 278, pp. 834-838.

84 Akcelik, V., J. Bielak, G. Biros, I. Epanomeritakis, A. Fernandez, O. Ghattas, E. J. Kim, J. Lopez, D. O'Hallaron, T. Tu & J. Urbanic (2003), High resolution forward and inverse earthquake modeling on terascale computers, Proceedings of the ACM/IEEE Supercomputing SC'2003 conference, published on CD-ROM and at www.sc-conference.org/sc2003; Tromp, J., C. Tape & Q. Liu (2005), Seismic tomography, adjoint methods, time reversal, and banana-donut kernels, *Geophys. J. Int.*, **160**, 195-216.

85 Foster, I., and C. Kesselman (1996), Globus: A Metacomputing Infrastructure Toolkit, *International Journal of Supercomputer Applications*, **11**, 115–128

86 Thain, D., T. Tannenbaum, & M. Livny (2005), Distributed Computing in Practice: The Condor Ex-

perience, *Concurrency and Computation: Practice and Experience*, **17**, 2-4.

87 Deelman, E., G. Singh, M.-H. Su, J. Blythe, Y. Gil, C. Kesselman, G. Mehta, K. Vahi, G.B. Berriman, J. Good, A. Laity, J. Jacob, D. Katz (2005), Pegasus: a Framework for Mapping Complex Scientific Workflows onto Distributed Systems", *Scientific Programming Journal*, **13**, 219-237.

88 Callaghan, S., P. Maechling, E. Deelman, K. Vahi, G. Mehta, G. Juve, K. Milner, R. Graves, E. Field, D. Okaya, D. Gunter, K. Beattie, and T. Jordan (2008), 'Reducing Time-to-Solution Using Distributed High-Throughput Mega-Workflows – Experiences from SCEC CyberShake', Fourth IEEE International Conference on eScience, IEEE, Indianapolis, IN.

89 Deelman, E., G. Mehta, R. Graves, L. Zhao, N. Gupta, P. Maechling, T. Jordan (2006), Managing Large-Scale Workflow Execution from Resource Provisioning to Provenance tracking: The CyberShake Example", IEEE e-Science and Grid Computing 2006, Amsterdam, Netherlands, December 2006 – Best Paper award.

90 Catlett, C. et al. "TeraGrid: Analysis of Organization, System Architecture, and Middleware Enabling New Types of Applications," HPC and Grids in Action, Ed. Lucio Grandinetti, IOS Press 'Advances in Parallel Computing' series, Amsterdam, 2007.

91 Proceedings of the Conference on High Performance Computing Networking, Storage and Analysis (2009), ISBN:978-1-60558-744-8, 778pp.

92 Kwangyoon, L. (2009), IO Optimizations of SCEC AWP-Olsen Application for Petascale Earthquake Computing, Poster at SC09, Portland Oregon, November 15-19, 2009; Juve, G., Deelman E., Vahi, K., Mehta, G. (2009) Corral: A Resource Provisioning System for Scientific Workflows on the Grid, Poster at SC09, Portland Oregon, November 15-19, 2009; Gunter, D., S. Callaghan, G. Mehta, G. Juve, K. Beattie, E. Deelman (2008), When Workflow Management Systems and Logging Systems Meet: Analyzing Large-scale Execution Traces, Poster at SC08, Austin Texas, November 15-21, 2008.

93 Field, E. H. & T.H. Jordan & C.A. Cornell (2003), A developing community-modeling environment for seismic hazard analysis, *Seismol. Res. Lett.*, **74**, 406-419.

94 Maechling, P., Ewa Deelman, Yifeng Cui: Implementing Software Acceptance Tests as Scientific Workflows. PDPTA 2009: Proceedings of the International Conference on Parallel and Distributed Processing Techniques and Applications, PDPTA 2009, Las Vegas, Nevada, USA, July 13-17, 2009, 2 Volumes. CSREA Press 2009, ISBN 1-60132-123-6, pp. 317-32

95 Committee on the Economic Benefits of Improved Seismic Monitoring, Committee on Seismology and Geodynamics, National Research Council (2006), *Improved Seismic Monitoring – Improved Decision-Making: Assessing the Value of Reduced Uncertainty*, National Academies of Sciences, 196p.

96 Gerstenberger, M. C., L. M. Jones, and S. Wiemer (2007), Short-term aftershock probabilities: case studies in California, Seismological Research Letters, 78, 66-77; DOI: 10.1785/gssrl.78.1.66; Reasenberg, P. A., and L. M. Jones (1989), Earthquake hazard after a mainshock in California, *Science*, **243**, 1173 - 1176, DOI: 10.1126/science.243.4895.1173; Reasenberg, P. A. and L. M. Jones (1990), California aftershock hazard forecasts, *Science*, **247**, 345–346.

97 Jordan, T. H., et al. (2009). *Operational Earthquake Forecasting: State of Knowledge and Guidelines for Implementation*, Report of the International Commission on Earthquake Forecasting for Civil Protection, Special Publication of Dipartimento della Protezione Civile, Rome, Italy, October, 2009.

98 STEP website: *http://earthquake.usgs.gov/earthquakes/step*

99 Gerstenberger, M. C., S. Wiemer, and L. M. Jones (2004). Real-time fore- casts of tomorrow's earthquakes in California: A New Mapping Tool. USGS Open-File Report 2004-1390, 1–39; Wiemer, S. (2000), Introducing probabilistic aftershock hazard mapping, *Geophys. Res. Lett.*, **27**, 3405-3408.

100 Allen, R.M., P. Gasparini and O. Kamigaichi (eds) (2009), Earthquake Early Warning, Special Issue, *Seismo. Res. Lett.,* **80**, 682-782; Allen, R. M., and H. Kanamori (2003), The potential for earthquake early warning in southern California, *Science*, **300**, 786-789; Bose, M. E. Hauksson, K. Solanki, H. Kanamori, and T. H. Heaton (2009), Real-time testing of the on-site warning algorithm in southern California and its performance during the July 29, 2008 Mw 5.4 Chino Hills earthquake, *Geophys. Res. Lett.,* **36**, L00B03, doi:10.1029/2008GL036366; Nakamura, H., S. Horiuchi, C. Wu, S. Yamamoto, and P. A. Rydelek (2009), Evaluation of the real-time earthquake information system in Japan, *Geophys. Res. Lett.*, **36**, L00B01.

101 ShakeCast website: *http://earthquake.usgs.gov/research/software/shakecast*; Lin, K.W., and Wald, D.J., 2008, ShakeCast manual: U.S. Geological Survey Open-File Report 20081158, 90 p.; Wald, David J, and K. Lin (2007). USGS ShakeCast- Automating, Simplifying, and Improving the Use of ShakeMap for Post-Earthquake Decision Making , U.S. Geological Survey Fact Sheet 2007-3086, 6pp.; PAGER website: *http://earthquake.usgs.gov/earthquakes/pager*; Earle, P.S., Wald, D.J., Jaiswal, J.S., Allen, T.I., Marano, K.D., Hotovec, A.J., Hearne, M.G., and Fee, J.M. (2009). Prompt Assessment of Global Earthquakes for Response (PAGER): A system for rapidly determining the impact of global earthquakes worldwide: U.S. Geological Survey Open File Report 2009-1131

102 Oskin, M., L. Perg, D. Blumentritt, S. Mukhopadhyay, & A. Iriondo (2007), Slip rate of the Calico fault: Implications for geologic versus geodetic rate discrepancy in the Eastern California Shear Zone, *J. Geophys. Res.,* **112**(B3), B03402, doi: 10.1029/2006JB004451.

103 Meade, B. J., & B. H. Hager (2005), Block models of crustal motion in southern California constrained by GPS measurements, *J. Geophys. Res.,* **110**(B3), B03403, doi: 10.1029/2004JB003209.

104 Dixon, T. H., E. Norabuena, & L. Hotaling (2003), Paleoseismology and Global Positioning System: Earthquake-cycle effects and geodetic versus geologic fault slip rates in the Eastern California shear zone, *Geology,* **31(**1), 55-58; Johnson, K. M., G. E. Hilley, & R. Burgmann (2007), Influence of lithosphere viscosity structure on estimates of fault slip rate in the Mojave region of the San Andreas fault system, *J. Geophys. Res.,* **112**(B7), B07408, doi: 10.1029/2006JB004842.

105 Bird, P. (2009), Long-term fault slip rates, distributed deformation rates, and forecast of seismicity in the western United States from joint fitting of community geologic, geodetic, and stress direction data sets, *J. Geophys. Res.,* **114**, B11403, doi: 10.1029/2009JB006317.

106 Dolan, J. F., D. D. Bowman & C. G. Sammis (2007), Long-range and long-term fault interactions in Southern California, *Geology, 35*(9); 855-858; doi: 10.1130/G23789A.1

107 Pollitz, F.F., & D.P. Schwartz (2008), Probabilistic seismic hazard in the San Francisco Bay area based on a simplified viscoelastic cycle model of fault interactions, *J. Geophy. Res.*, **113**, B05409, doi:10.1029/2007JB005227.

108 Freed, A. M., & R Bürgmann (2004), Evidence of power-law flow in the Mojave desert mantle, *Nature,* **430**, 548-551, doi:10.1038/nature02784.

109 Bürgmann, R., & G. Dresen (2008), Rheology of the lower crust and upper mantle: Evidence from rock mechanics, geodesy and field observations, *Ann. Rev. Earth Plan. Sci.,* **36**, 531-567, doi:10.1146/annurev.earth.36.031207.124326.

110 Wells, D. L., and K. J. Coppersmith (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seismol. Soc. Am.*, **84**, 974-1002.

111 Kagan, Y. Y. (2002), Aftershock zone scaling, *Bull. Seismol. Soc. Am.,* **92**(2), 641-655.

112 Tanimoto, T. (2004) The azimuthal dependence of surface wave polarization in a slightly anisotropic medium, *Geophys. J. Int.,* **156**, 73-78.

113 Shelly, D. R., W. L. Ellsworth, T. Ryberg, C. Haberland, G. S. Fuis, J. Murphy, R. M. Nadeau, & R. Bürgmann (2009). Precise location of San Andreas Fault tremors near Cholame, California using seismometer clusters: Slip on the deep extension of the fault?, *Geophys. Res. Lett.,* **36**, L01303, doi:10.1029/2008GL036367.

114 Hill, D. P., et al. (1993), Seismicity Remotely Triggered By The Magnitude 7.3 Landers, California, Earthquake, *Science*, 260(5114), 1617-1623.

115 Gomberg, J., P. Bodin, K. Larson, H. Dragert (2004), The fundamental process of earthquake nucleation by transient deformations revealed by the M7.9 Denali, Alaska earthquake, *Nature*, **427**, 621-624.

116 Felzer, K. R. and E. E. Brodsky (2006), Decay of aftershock density with distance indicates triggering by dynamic stress, *Nature*, **441**, 735-738.

117 Miller, S.A.,Collettini, C., Chiaraluce, L., Cocco, M., Barchi, M. and Kaus, B.J.P. (2004), Aftershocks driven by a high-pressure C02 source at depth, *Nature*, **427**, 724-727.

118 Harris, R. A., and R. W. Simpson (1992), Changes in static stress on southern California faults after the 1992 Landers earthquake, *Nature*, **360**(6401), 251-254.

119 King, G. C. P., R. S. Stein, and J. Lin (1994), Static Stress Changes And The Triggering Of Earthquakes, *Bulletin of the Seismological Society of America*, **84**(3), 935-953.

120 Stein, R.S. (1999), The role of stress transfer in earthquake occurrence, *Nature*, **402**, 605-609.
121 Freed, A. M., R. Burgmann, and T. Herring (2007), Far-reaching transient motions after Mojave earthquakes require broad mantle flow beneath a strong crust, *Geophysical Research Letters*, **34**(19), 5.
122 Peng, Z. G., and P. Zhao (2009), Migration of early aftershocks following the 2004 Parkfield earthquake, *Nature Geoscience*, **2**(12), 877-881.
123 Ogata, Y. (1998), Space-time point-process models for earthquake occurrences, *Annals of the Institute of Statistical Mathematics*, **50**(2), 379-402.
124 Baiesi, M., and M. Paczuski (2004), Scale-free networks of earthquakes and aftershocks, *Physical Review E*, **69**(6), 8.
125 Dieterich, J. H., K. Richards-Dinger & D. E. Smith (2008). Large-scale simulations of fault system seismicity, *Proc. 2008 ACES Meeting* (abstract), *http://www.aces.org.au/ACES08/papers/ACES08_abstract_33944.pdf*.
126 Phillips, W.S., J.T. Rutledge, L.S. House, and M.C. Fehler (2002), Induced microearthquake patterns in hydrocarbon and geothermal reservoirs: Six case studies, *Pure and Applied Geophysics*, **159**, 345-369.
127 Segall, P. and S.D. Fitzgerald (1998), A note on induced stress changes in hydrocarbon and geothermal reservoirs, *Tectonophysics*, **289**, 117-128.
128 Glowacka, E. and F.A. Nava, 1996, Major Earthquakes in Mexicali Valley, Mexico and Fluid Extraction at Cerro Prieto Geothermal Field, *Bull. Seism. Soc. Am.,* **86**, 93-105.
129 Cypser, D.A. and S.D. Davis (1998), Induced seismicity and the potential for liability under U.S. law *Tectonophysics*, **289**, 239–255.
130 Domenico, G. (2009) Geothermal quake risks must be faced, *Nature*, **462**,848-849.
131 Harris, R.A. (2004), Numerical simulations of large earthquakes: Dynamic rupture propagation on heterogeneous faults, *Pure and Applied Geophysics*, **161**, 2171–2181, DOI 10.1007/s00024-004-2556-8.
132 Tullis, T. E (2007), *Friction of rock at earthquake slip rates*, In Treatise on Geophysics, vol. 4, ed. H. Kanamori, 131–152, Amsterdam & Boston: Elsevier.
133 Ampuero, J.-P. and Y. Ben-Zion (2008), Cracks, pulses and macroscopic asymmetry of dynamic rupture on a bimaterial interface with velocity-weakening friction, *Geophys. J. Int.*, **173**, 674-692, doi:10.1111/j.1365-246X.2008.03736.
134 Noda, H., and N. Lapusta (2009), 3D simulations of seismic and aseismic fault slip with evolving temperature and pore pressure: Interaction of two fault segments and low interseismic shear stress, Eos Trans. AGU, 90(52), Fall Meet. Suppl., Abstract T51E-02.
135 Brune, J.N., Henyey, T.L., and Roy, R.F. (1969), Heat flow, stress, and rate of slip along the San Andreas fault, California, *J. Geophys. Res.*, **74**, 3821–3827.
136 Lachenbruch, A.H., and Sass, J.H. (1980), Heat flow and energetics of the San Andreas fault zone, *J. Geophys. Res.,* **85**, 6185–6223.
137 Kano, Y., J. Mori, R. Fujio, H. Ito, T. Yanagidani, S. Nakao, and K. F. Ma (2006), Heat signature on the Chelungpu fault associated with the 1999 Chi-Chi, Taiwan earthquake, *Geophys. Res. Lett.*, **33**, L14306, doi:10.1029/2006GL026733.
138 Tanaka, H., W. M. Chen, C. Y. Wang, K. F. Ma, N. Urata, J. Mori, and M. Ando (2006), Frictional heat from faulting of the 1999 Chi-Chi, Taiwan earthquake, *Geophys. Res. Lett.*, **33**, L16316, doi:10.1029/2006GL026673.
139 Hardebeck, J., and E. Hauksson (2001), Crustal stress field in southern California and its implications for fault mechanics, *J. Geophys. Res.*, **106**, 21859-21882.
140 Townend, J., and M. D. Zoback (2004), Regional tectonic stress near the San Andreas fault in central and southern California, *Geophys. Res. Lett.*, **31**, L15S11, doi:10.1029/203GL018918.
141 Hickman, S., and M. Zoback (2004), Stress orientations and magnitudes in the SAFOD pilot hole, *Geophys. Res. Lett.*, **31**, L15S12, doi:10.1029/2004GL020043.
142 Wesson, R. L., and O. S. Boyd (2007), Stress before and after the 2002 Denali fault earthquake, *Geophys. Res. Lett.,* **34**, L07303, doi:10.1029/2007GL029189.
143 Suppe, J. (2007), Absolute fault and crustal strength from wedge tapers, *Geology*, **35**, doi: 10.1130/G24053A.1, 1127–1130.
144 Dieterich, J.H (2007), Application of rate- and state-dependent friction to models of fault slip and

earthquake occurrence, In Treatise on Geophysics, vol. 4, ed. H. Kanamori, 107–129, Amsterdam & Boston: Elsevier.
145 Sibson, R. H. (1973), Interaction between temperature and pore-fluid pressure during earthquake faulting — A mechanism for partial or total stress relief, *Nature*, **243**, 66–68.
146 Lachenbruch, A. H. (1980), Frictional heating, fluid pressure, and the resistance to fault motion, *J. Geophys. Res.,* **85**, 6097– 6122.
147 Mase, C. W., and L. Smith (1985), Pore – fluid pressures and frictional heating on a fault surface, *Pure and Applied Geophysics*, **122**, 583– 607.
148 Mase, C. W., and L. Smith (1987), Effects of frictional heating on the thermal, hydrologic, and mechanical response of a fault, *J. Geophys. Res.*, **92**, 6249– 6272.
149 Andrews, D. J. (2002), A fault constitutive relation accounting for thermal pressurization of pore fluid, *Journal of Geophysical Research-Solid Earth*, **107**(B12), 2363, Doi 10.1029/2002jb001942.
150 Lim, S. C., and M. F. Ashby (1987), Wear mechanism maps, *Acta Metall*, **35**, 1 – 24.
151 Tsutsumi, A., and T. Shimamoto (1997), High velocity frictional properties of gabbro, *Geophys. Res. Lett.*, **24**, 699–702.
152 Weertman, J. (1980), Unstable slippage across a fault that separates elastic media of different elastic constants, *J. Geophys. Res.*, **85**, 1455–1461.
153 Andrews, D.J., and Y. Ben–Zion (1997), Wrinkle-like slip pulse on a fault between different materials, *J. Geophys. Res.*, **102**, 553–571.
154 Hirose, T., and T. Shimamoto (2005), Growth of a molten zone as a mechanism of slip weakening of simulated faults in gabbro during frictional melting, *J. Geophys. Res.,* **110**, B05202, doi:10.1029/2004JB003207.
155 Brodsky, E.E., and H. Kanamori (2001), Elastohydrodynamic lubrication of faults, *J. Geophys. Res.*, **106**, 16,357–16,374.
156 Di Toro, G., D.L. Golbsby, and T.E. Tullis (2004), Friction falls toward zero in quartz rock as slip velocity approaches seismic rates, *Nature*, **427**, 436–439.
157 Brantut, A. Schubnel, J.-N. Rouzaud, F. Brunet, and T. Shimamoto (2008), High-velocity frictional properties of a clay-bearing fault gouge and implications for earthquake mechanics, *J. Geophys. Res.*, **113**, B10401, doi:10.1029/2007JB005551.
158 Han, R., T. Shimamoto, T. Hirose, J.-H. Ree, and J.-I. Ando (2007), Ultralow friction of carbonate faults caused by thermal decomposition, *Science*, **316**, 878-881, doi: 10.1126/science.1139763.
159 Hirose, T., and M. Bystricky (2007), Extreme dynamic weakening of faults [containing serpentine] during dehydration by coseismic shear heating, *Geophys. Res. Lett.*, **34**, L14311, doi:10.1029/2007GL030049.
160 Segall, P., and J. R. Rice (2006), Does shear heating of pore fluid contribute to earthquake nucleation?, *J. Geophys. Res.*, **111**, B09316, doi:10.1029/2005JB004129.
161 Abercrombie, R. E., and J. R. Rice (2005), Can Observations of Earthquake Scaling Constrain Slip Weakening?, *Geophys. J. Int.*, **162**, no. 2, doi:10.1111/j.1365-246X.2005.02579.
162 Rojas, O., E.M. 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.*, **179**, 1831-1858.
163 Heaton, T. H. (1990), Evidence for and implications of self-healing pulses of slip in earthquake rupture, *Phys. Earth Planet. In.*, **64**, 1–20.
164 Aochi, H., and E. Fukuyama, Three-dimensional nonplanar simulation of the 1992 Landers earthquake, *Journal of Geophysical Research*, **107** (B2), doi: 10.1029/2000JB000061, 2002.
165 Segall, P., and D.D. Pollard (1980), Mechanics of discontinuous faults, *J. Geophys. Res.* **85**, 4337-4350.
166 Sibson, R.H. (1985), Stopping of earthquake ruptures at dilational fault jogs, *Nature* **316**, 248-51
167 King, G., and J. Nabelek (1985). Role of Fault Bends in the Initiation and Termination of Earthquake Rupture, *Science* **228**(4702), 984-987.
168 Wesnousky, S. G. (1988). Seismological and Structural Evolution of Strike-Slip Faults, *Nature* **335**(6188), 340-342.
169 Wesnousky, S.G., Predicting the endpoints of earthquake ruptures (2006), *Nature*, **444**, doi:1038/nature05275.
170 Harris, R.A., and S.M. Day (1999), Dynamic 3D simulations of earthquakes on en echelon faults, *Geophysical Research Letters*, **26**(14), 2089-2092.

171 Shaw, B.E. (2006), Initiation propagation and termination of elastodynamic ruptures associated with segmentation of faults and shaking hazard, *J. Geophys. Res.* **111,** B08302, DOI:10.1029/2005JB004093

172 Shaw, B.E., and J.H. Dieterich (2007), Probabilities for jumping fault segment stepovers, *Geophysical Research Letters*, **34**, L01307, doi:10.1029/2006GL027980, 2007.

173 Black and Jackson (2008), Probability of multifault rupture, *Bull. Seismol. Soc. Am*, **98**, 3017, DOI: 10.1785/0120070271.

174 Harris, R.A., R.J. Archuleta, and S.M. Day (1991), Fault Steps and the Dynamic Rupture Process - 2-D Numerical Simulations of a Spontaneously Propagating Shear Fracture, *Geophysical Research Letters*, **18** (5), 893-896.

175 Kase, Y., and K. Kuge (1998), Numerical simulation of spontaneous rupture processes on two non-coplanar faults: the effect of geometry on fault interaction, *Geophysical Journal International*, **135** (3), 911-922.

176 Duan, B., and D.D. Oglesby (2006), Heterogeneous fault stresses from previous earthquakes and the effect on dynamics of parallel strike-slip faults, *Journal of Geophysical Research*, **111** (B05309), doi:10.1029/2006JB004138.

177 Oglesby, D.D. (2008), Rupture termination and jump on parallel offset faults, *Bulletin of the Seismological Society of America*, **98** (1), 440-447.

178 Aochi, H., E. Fukuyama, and M. Matsu'ura (2000), Selectivity of spontaneous rupture propagation on a branched fault, *Geophysical Research Letters*, **27** (22), 3635-3638.

179 Anderson, G., B. Aagaard, and K. Hudnut (2003), Fault interactions and large complex earthquakes in the Los Angeles Area, *Science*, *302*, 1946-1949.

180 Kame, N., J.R. Rice, and R. Dmowska (2003), Effects of pre-stress state and rupture velocity on dynamic fault branching, *Journal of Geophysical Research*, **108** (B5), 2265, doi: 10.1029/2002JB002189.

181 Oglesby, D.D., S.M. Day, Y.-G. Li, and J.E. Vidale (2003), The 1999 Hector Mine earthquake: the dynamics of a branched fault system, *Bulletin of the Seismological Society of America*, **93** (6), 2459-2476.

182 Bhat, H.S., R. Dmowska, J.R. Rice, and N. Kame (2004), Dynamic slip transfer from the Denali to Totschunda Faults, Alaska: Testing theory for fault branching, *Bulletin of the Seismological Society of America*, **94,** S202-S213.

183 Fliss, S., H.S. Bhat, R. Dmowska, and J.R. Rice (2005), Fault branching and rupture directivity, *Journal of Geophysical Research*, **110**, B06312, doi:10.1029/2004JB003368.

184 Bhat, H.S., M. Olives, R. Dmowska, and J.R. Rice (2007), Role of fault branches in earthquake rupture dynamics, *Journal of Geophysical Research*, **112,** B11309, doi:10.1029/2007JB005027.

185 Duan, B., and D.D. Oglesby (2007), Nonuniform prestress from prior earthquakes and the effect on dynamics of branched fault systems, *Journal of Geophysical Research*, **112**, B05308, doi:10.1029/2006JB004443.

186 Nielsen, S.B., and L. Knopoff (1998), The equivalent strength of geometrical barriers to earthquakes, *Journal of Geophysical Research*, **103** (B5), 9953-9965.

187 Duan, B., and D.D. Oglesby, Multicycle dynamics of nonplanar strike-slip faults (2005), *Journal of Geophysical Research*, **110**, doi:10.1029/2004JB003298.

188 Liu, Y., and J.R. Rice (2007), Spontaneous and triggered aseismic deformation transients in a subduction fault model, *Journal of Geophysical Research*, **112**, B09404, doi:10.1029/2007JB004930.

189 Andrews, D.J. (2004), Rupture models with dynamically determined breakdown displacement, *Bulletin of the Seismological Society of America*, **94**, 769-775.

190 Bowman, D. D., G. C. P. King, and P. Tapponnier, (2003), Slip partitioning by elastoplastic propagation of oblique slip at depth, *Science,* **300**, 1121-1123.

191 King, G., Y. Klinger, D. Bowman and P. Tapponnier (2005), Slip partitioned surface breaks for the 2001 Kokoxilli earthquake (Mw 7.8), *Bull. Seismol. Soc. Am.*, 95, 731–738, doi: 10.1785/0120040101.

192 Power, W. L., and T. E. Tullis (1991). Euclidean and fractal models for the description of rock surface-roughness, *J. Geophys. Res*. **96**(B1), 415 – 424, doi:10.1029/90JB02107.

193 Dunham, E (2009), Rupture dynamics on nonplanar faults with strongly rate-weakening friction and off-fault plasticity, *Eos Trans. AGU*, **90(**52**)**, Fall Meet. Suppl., Abstract T53E-01.

194 Andrews, D. J. (2005). Rupture dynamics with energy loss outside the slip zone, *J. Geophys. Res.* **110**, B01307, doi:10.1029/2004JB003191.
195 Obara, K. (2002), Nonvolcanic deep tremor associated with subduction in southwest Japan, *Science*, **296**, 1679–1681, doi:10.1126/science.1070378.
196 Miller, M., T. Melbourne, D. Johnson, and William Q. Sumner (2002), Periodic slow earthquakes from the Cascadia subduction zone *Science*, **295**, 2423, 2002.
197 Kao, H., S.-J. Shan, H. Draggert, G. Rogers, J. F. Cassidy, and K. Ramachandran (2005), A wide depth distribution of seismic tremors along the northern Cascadia margin, *Nature*, 436, 841-844.
198 Szeliga, W., Melbourne, T., Santillian, V., Miller, M. (2008), GPS constraints on 34 slow slip events within the Cascadia subduction zone, 1997 - 2005, *Journal of Geophysical Research*, **113**, B04404, doi:10.1029/2007JB004948.
199 Wallace, L. M., and J. Beavan, (2006) A large slow slip event on the central Hikurangi subduction interface beneath the Manawatu region, North Island, New Zealand, *Geophys. Res. Lett.*, **33**, L11301, doi:10.1029/2006GL026009.
200 Larson, K. M., V. Kostoglodov, S. Miyazaki, and J. A. S. Santiago (2007),The 2006 aseismic slow slip event in Guerrero, Mexico: New results from GPS, *Geophys. Res. Lett.*, **34**, L13309, doi:10.1029/2007GL029912.
201 Liu, Y. and J. R. Rice (2005), Aseismic slip transients emerge spontaneously in three-dimensional rate and state modeling of subduction earthquake sequences, *J. Geophys. Res.*, **110**, B08307, doi:10.1029/2004JB003424.
202 Rubin, A. M., (2008), Episodic slow slip events and rate-and-state friction, *J. Geophys. Res.*, 113, B11414, doi:10.1029/2008JB005642.
203 Perfettini, H. and J.-P. Ampuero (2008), Dynamics of a velocity strengthening fault region: Implications for slow earthquakes and postseismic slip, *J. Geophys. Res.*, **113**, B09411, doi:10.1029/2007JB005398.
204 Liu, Y. and J. R. Rice (2009), Slow slip predictions based on granite and gabbro friction data compared to GPS measurements in northern Cascadia, *J. Geophys. Res.*, **114**, B09407, doi:10.1029/2008JB006142.
205 Shelly, D. R., G. C. Beroza, S. Ide & S. Nakamula (2006). Low-frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip, *Nature*, **442**, 188-191.
206 Linde A.T., Gladwin M.T., Johnston M.J.S., Gwyther R.L., and R.B. Bilham (1996), A slow earthquake sequence on the San Andreas fault, *Nature*, **383**, 65-68.
207 Murray, J.R. and P. Segall (2005), Spatiotemporal evolution of a slip-rate increase on the San Andreas fault near Parkfield, CA, *J. Geophys. Res.,* **110***, B09407, doi:10.1029/2005JB003651, 2005.*
208 Lohman, R. B. and J.J. McGuire (2007), Earthquake swarms driven by aseismic creep in the Salton Trough, CA, *J. Geophys. Res.,* **112**.
209 Wei, M., D. Sandwell, and Y. Fialko, A silent 4.7 slip event of October 2006 on the Superstition Hills fault, southern California, *J. Geophys. Res.*, *114*, B07402, doi:10.1029/2008JB006135. 2009.
210 Nadeau, R. M. & Dolenc, D. (2005) Nonvolcanic tremors deep beneath the San Andreas fault. *Science* **307**, 389; doi:10.1126/ science.1107142.
211 Gomberg, J., J.L. Rubinstein, Z. Peng, K.C. Creager, J.E. Vidale and P. Bodin (2008), Widespread Triggering of Nonvolcanic Tremor in California, *Science* **319** (5860), 173.
212 Shelly D. R. (2009), Possible deep fault slip preceding the 2004 Parkfield earthquake, inferred from detailed observations of tectonic tremor, *Geophys. Res. Lett*., **36**, L17318, doi:10.1029/2009GL039589.
213 Shelly, D. R., G. C. Beroza, and S. Ide (2007), Non-Volcanic Tremor and Low Frequency Earthquake Swarms, *Nature*, **446**, 305-307, doi:10.1038/nature05666.
214 Ide, S., D. R. Shelly, and G. C. Beroza (2007). The mechanism of deep low frequency earthquakes: further evidence that deep non-volcanic tremor is generated by shear slip on the plate interface, *Geophys. Res. Lett*., **34**, L03308, doi:10.1029/2006GL028890.
215 Shelly, D. R. (2010), Migrating tremor illuminate deformation beneath the seismogenic San Andreas fault, *Nature*, **463**, 648-652. doi:10.1038/nature0875.
216 Segall, P., and J. R. Rice (1995), Dilatancy, compaction, and slip instability of a fluid-infiltrated fault, *J. Geophys. Res.*, **100**, 22,155–22,171.
217 Boettcher, M., and T. H. Jordan (2004). Earthquake scaling relations for mid-ocean ridge transform

faults, *J. Geophys. Res.*, **109**, doi:10.1029/2004JB003110.

218 Barbot, S., Y. Fialko, and Y. Bock (2009), Postseismic deformation due to the *Mw* 6.0 2004 Parkfield earthquake: Stress-driven creep on a fault with spatially variable rate-and-state friction parameters, *J. Geophys. Res.*, 114, B07405, doi:10.1029/2008JB005748.

219 *http://www.scsn.org/2009bombaybeach.html*

220 Hall, J. F., T. H. Heaton, M. W. Halling, and D. J. Wald (1995). Near-source ground motion and its effects on flexible buildings, *Earthquake Spectra* **11**, 569-605.

221 Krishnan, S., C. Ji, D. Komatitsch, and J. Tromp (2006a). Performance of two 18-story steel moment-frame buildings in southern California during large San Andreas earthquakes, *Earthuake Spectra, Vol* **22***.*

222 Krishnan, S., C. Ji, D. Komatitsch,, and J. Tromp (2006b). Case Studies of Damage to Tall Steel Moment-Frame Buildings in Southern California During Large San Andreas Earthquakes, *Bull. of the Seism. Soc. Am.*, 96, 1523 – 1537.

223 Heaton. T., J. Yang, and J. Hall (2007). Simulated performance of steel moment-resisting frame buildings in the 2003 Tokachi-Oki earthquake, Bull. Earthq. Res. Inst., Univ. Tokyo, 81, 325-329.

224 Muto, M. and S. Krishnan (2009). Hope for the Best, Prepare for the Worst: Response of Tall Steel Buildings to the ShakeOut Scenario Earthquake, in review, *Earthquake Spectra*.

225 Frankel, A., and J. Vidale (1992). A three-dimensional simulation of seismic waves in the Santa Clara Valley, California, from a Loma Prieta aftershock, *Bull. Seism. Soc. Am.* **82,** 2045-2074.

226 Olsen, K.B., R.J. Archuleta, and J.R. Matarese (1995). Three-dimensional simulation of a magnitude 7.75 earthquake on the San Andreas fault, *Science*, **270**, 1628-1632.

227 Graves, R. W. (1998). Three-dimensional finite-difference modeling of the San Andreas fault: source parameterization and ground-motion levels, *Bull. Seism. Soc. Am*. **88**, 881–897.

228 Pitaka, A., K. Irikura, T. Iwata, and H. Sekigushi (1998). Three dimensional simulation of the near fault ground motion for the 1995 Hyogo-ken Nanbu (Kobe), Japan, earthquake, *Bull. Seis. Soc. Am.* **88**, 428-440.

229 Olsen, K.B. (2000). Site amplification in the Los Angeles basin from three-dimensional modeling of ground motion, *Bull. Seis. Soc. Am*. **90**, S77-S94.

230 Komatitsch, D., Q. Liu, J. Tromp, P. Suss, C. Stidham & J.H. Shaw (2004). Simulations of ground motion in the Los Angeles basin based upon the spectral-element method, *Bulletin of the Seismological Society of America* **94**, 187–206.

231 Day, S. M., R. W. Graves, J. Bielak, D. Dreger, S. Larsen, K. B. Olsen, A. Pitarka, and L. Ramirez-Guzman (2008a). Model for basin effect on long-period response spectra, *Earthquake Spectra*, Vol. 24, pp. 257-277.

232 Ma, S., R. J. Archuleta, and M. T. Page (2007), Effects of large-scale surface topography on ground motions, as demonstrated by a study of the San Gabriel Mountains, Los Angeles, California, *Bull. Seismol. Soc. Am*., **97**, 2066–2079, doi: 10.1785/0120070040.

233 Ely, G., S.M. Day, and J-B. Minster (2010). Dynamic rupture models for the southern San Andreas fault, *Bull. Seism. Soc. Am*., **100**,131-150.

234 Ely, G. P., S. M. Day, and J.-B. Minster (2010), Dynamic rupture models for the southern San Andreas fault, BSSA, **100**(1), (in press).

235 Day, S. M. (1982), Three-dimensional finite difference simulation of fault dynamics: Rectangular faults with fixed rupture velocity, *Bull. Seism. Soc. Am.,* **72**, 705–727.

236 Das, S., and Kostrov, B. V. (1983). Breaking of a Single Asperity: Rupture Process and Seismic Radiation*, J. Geophys. Res.*, **88**, 4277-4288.

237 Dunham, E. M. (2005). Dissipative interface waves and the transient response of a three-dimensional sliding interface with Coulomb friction, *J. Mech. Phys. Solids* **53**, 327–357, doi: 10.1016/j.jmps.2004.07.003.

238 Andrews, D. J. (1976), Rupture velocity of plane strain shear cracks, *J. Geophys. Res*., **81**, 5679–5687

239 Das, S., and K. Aki (1977), A numerical study of two-dimensional spontaneous rupture propagation, *Geophys. J. Roy. Astr. Soc.,* **50**, 643–668.

240 Dunham, E. M., P. Favreau, and J. M. Carlson (2003). A supershear transition mechanism for cracks, *Science* **299**, 1557–1559.

241 Dunham, E. M. (2007). Conditions governing the occurrence of supershear ruptures under slip-weakening friction, *J. Geophys. Res.*, **112**, B07302, doi:10.1029/2006JB004717.

242 Day, S. M., S. H. Gonzalez, R. Anooshehpoor, and J. N. Brune (2008b). Scale-model and numerical simulations of near-fault seismic directivity, *Bull. Seism. Soc. Am.*, Vol. 98, doi: 10.1785/0120070190, pp. 1186-1206.

243 Liu, P., R. J. Archuleta and S. H. Hartzell (2006). Prediction of broadband ground motion time histories: Hybrid low/high-frequency method with correlated random source parameters, Bull. Seismol. Soc. Am. 96, 2118-2130, doi: 10.1785/0120060036.

244 Graves, R.W., B. Aagaard, K. Hudnut, L. Star, J. Stewart and T.H. Jordan (2008), Broadband simulations for Mw 7.8 southern San Andreas earthquakes: ground motion sensitivity to Rupture speed, *Geophys. Res. Lett.* **35**, L22302, doi:10.1029/2008GL035750.

245 Imperatori, W., K.B. Olsen, and P.M. Mai (2009). Deterministic simulations and high-frequency scatterograms: validation against the 1994 Northridge earthquake, Proc SCEC Ann Mtg 2009, # 1-034.

246 Magistrale, H., Day, S. M., Clayton, R., and Graves, R. W., 2000. The SCEC southern California reference three-dimensional seismic velocity model version 2, *Bull. Seismol. Soc. Am.* **90**, S65–S76.

247 Thelen, Weston A., Matthew Clark, Christopher T. Lopez, Chris Loughner, Hyunmee Park, James B. Scott, Shane B. Smith, Bob Greschke, and John N. Louie (2006). A transect of 200 shallow shear velocity profiles across the Los Angeles Basin: Bull. Seismol. Soc. Amer., 96, no. 3 (June), 1055-1067, doi:10.1785/0120040093.

248 Zeng, Y., J. G. Anderson, and G. Yu (1994). A composite source model for computing realistic synthetic strong ground motions, *Geophys. Res. Lett.*, **21**, 725-728.

249 Zeng, Y., J. G. Anderson and Feng Su (1995). Subevent rake and scattering effects in realistic strong ground motion simulation, *Geophy. Res. Lett*, **22**, 17-20.

250 Mena, B., P.M. Mai, K.B. Olsen, M.D. Purvance, and J.N. Brune (2010), Hybrid broadband ground motion simulation using scattering Green's functions: application to large magnitude events, Bull. Seis. Soc. Am., (in press).

251 Davis, P. M. and R. Clayton, Application of the telegraph model to coda Q variations in southern California, J. Geophys. Res., 112, B09302, doi:10.1029/2006JB004542, 2007.

252 Sato, H., and M. Fehler, Seismic wave propagation and scattering in the heterogeneous Earth, AIP Press Springer Verlag, New York, 308 pp, 1998.

253 Wennerberg, L., and A. Frankel, On the similarity of theories of anelastic and scattering attenuation, *Bull. Seism. Soc. Amer.*, 79, 4, 1287-1293, 1989.

254 Zeng Y. Su F. Aki K. (1991), Scattered wave energy propagation in a random isotropic scattering medium, J. Geophys. Res. 96, 607-619.

255 Graves, R., S. Callaghan, E. Deelman, E. Field, N. Gupta, T. H. Jordan, G. Juve,, C. Kesselman, P. Maechling, G. Mehta, D. Meyers, D. Okaya & K. Vahi (2008). Physics-based probabilistic seismic hazard calculations for Southern California, *Proc. 14th World Conference on Earthquake Engineering*, Beijing, China, 8 pp., October, 2008.

256 Day, S.M., D. Roten, and K.B. Olsen (2008c). Calculating the Source Sensitivity of Basin Guided Waves by Time-Reversed Simulations, E*os Trans. AGU, 89*(53), Fall Meet. Suppl., Abstract S51D-1797.

257 Andrews, D. J. (1980). A stochastic fault model, **I**, Static case, *J. Geophys. Res*. **85**, 3867– 3877; Andrews, D. J. (1981). A stochastic fault model, **II**, Time-dependent case, *J. Geophys. Res*. **86**, 10,821–10,834.

258 Scholz, C. H., and C. A. Aviles (1986), The fractal geometry of faults and faulting, in *Earthquake Source Mechanics*, edited by Das, S., J. Boatwright, and C. H. Scholz, Geophysical Monograph, Vol 37, p. 147-156, American Geophysical Union, Washington, D.C.

259 Candela, T., F. Renard, M. Bouchon, A. Brouste, D. Marsan, J. Schmittbuhl, and C. Voisin (2009). Characterization of Fault Roughness at Various Scales: Implications of Three-Dimensional High Resolution Topography Measurements, Pure Appl. Geophys., Vol. 166, 1817-1851.

260 Madariaga, R., J.P. Ampuero and M. Adda-Bedia (2006) Seismic radiation from simple models of earthquakes in Radiated Energy and the Physics of Earthquakes, AGU Monograph, A. McGarr, R. Abercrombie, H. Kanamori and G. di Toro, Eds.

261 Duan, B., and S. M. Day (2008), Inelastic strain distribution and seismic radiation from rupture of a fault kink, J. Geophys. Res., 113, B12311, doi:10.1029/2008JB005847.

262 Templeton, E. L., and J. R. Rice (2008), Off-fault plasticity and earthquake rupture dynamics: 1, Dry materials or neglect of fluid pressure changes, *J. Geophy. Res.*, 113, B09306, doi:10.1029/2007JB005529.

263 Bhat, H.S., R. Dmowska, G.C.P. King, Y. Klinger, and J.R. Rice (2007). Off-fault damage patterns due to supershear ruptures with application to the 2001 M_w 8.1 Kokoxili (Kunlun) Tibet earthquake, *J. Geoph. Res*., 112, B06301, doi:10.1029/2006JB004425.

264 Belanger, David (Harvard) and Eric M. Dunham (Harvard), "SCEC/SURE: A Finite Differences Model for Dynamic Ruptures along Rough Faults" (2007 SCEC Annual Meeting).

265 Graves, R.W., B.T. Aagaard and K. Hudnut (2010). The ShakeOut earthquake source and ground motion simulations, submitted to EQ Spectra.

266 Bizzarri, A., and P. Spudich (2008), Effects of supershear rupture speed on the high-frequency content of waves investigated using spontaneous dynamic rupture models and isochrone theory, J. Geophys. Res., 113, B05304, doi:10.1029/2007JB005146.

267 Bizzarri, A., E. M. Dunham, and P. Spudich (2009), Coherence of Mach fronts during heterogeneous supershear earthquake rupture propagation: simulations and comparison with observations, *Journal of Geophysical Research*, submitted 24 July 2009.

268 Marone, C., and C.H. Scholz (1988). The depth of seismic faulting and the upper transition from stable to unstable slip regimes, Geophys. Res. Lett., Vol 15, P. 621-624.

269 Brune, J. N. and Anooshehpoor, A., 1998, A physical model of the effect of a shallow weak layer on strong motion for strike-slip ruptures: Bull. Seism. Soc. Am., **71**, 939-957.

270 Day, S. M. and Ely, G. P., 2002, Effect of a shallow weak zone on fault rupture: numerical simulation of scale-model experiments: Bull. Seism. Soc. Am., **92**, 3022-3041.

271 Abercrombie, R. E., Earthquake source scaling relationships from -1 to 5 M_L using seismograms recorded at 2.5km depth, *J. Geophys. Res.,* 100, B12, 24,015-24,036, 1995.

272 Abercrombie, R. E., Near-surface attenuation and site effects from comparison of surface and deep borehole recordings, *Bulletin of the Seismological Society of America*, vol.87, 3, 731-744, 1997.

273 Pasyanos, M. E., G. A. Franz, and A. L. Ramirez (2006), Reconciling a geophysical model to data using a Markov chain Monte Carlo algorithm: An application to the Yellow Sea–Korean Peninsula region, J. Geophys. Res., 111, B03313, doi:10.1029/2005JB003851.

274 Star, L. M., J. P. Stewart and R. W. Graves (2010). Comparison of Ground Motions from Hybrid Simulations to NGA Prediction Equations, submitted to Earthquake Spectra.

275 Baker J.W. and Jayaram N. (2008). Correlation of spectral acceleration values from NGA ground motion models, Earthquake Spectra, 24 (1), 299-317; Jayaram N. and Baker J.W. (2009). Correlation model for spatially-distributed ground-motion intensities, Earthquake Engineering and Structural Dynamics, 38(15), 1687-1708.

276 Yule, D., and Sieh, K., 2003, Complexities of the San Andreas fault near San Gorgonio pass: Implications for large earthquakes: Journal of Geophysical Research, v. 109, no. B11, 2548, doi: 10.1029/2001JB000451.

277 Spotila, J.A., Farley, K.A., Yule, J.D., and Reiners, P.W., 2001, Near-fi eld transpressive deformation along the San Andreas fault zone in southern California, based on exhumation constrained by (U-Th)/He dating: Journal of Geophysical Research, v. 106, no. B12, p. 30,909-30,922, doi: 10.1029/2001JB000348.

278 McGill, S., Weldon, R.J., II, Kendrick, K., and Owen, L., 2006, Late Pleistocene slip rate of the San Bernardino strand of the San Andreas fault in Highland: Possible confirmation of the low rate suggested by geodetic data: Seismological Research Letters, v. 77, no. 2, p. 279.

279 McGill, S., Kendrick, K., Weldon, R.J., II, and Owen, L., 2007, Pleistocene and Holocene slip rate of the San Andreas fault at Badger Canyon, San Bernardino, California: Southern California Earthquake Center Annual Meeting, Proceedings with Abstracts, v. 17.

280 Dair, L., and Cooke, M., 2009, San Andreas fault geometry through San Gorgonio Pass, California, Geology, v. 37, no. 2, p. 119-122., doi: 10.1130/G25101A.1.

281 Hooper, A. and H. Zebker, Phase unwrapping in three dimensions with application to InSAR time

series. *JOSA A*, 24, 9, 2737-2747 doi:10.1364/JOSAA.24.002737, 2007.
282 Ferretti, A., G. Savio, R. Barzaghi, A. Borghi, S. Musazzi, F. Novali, C. Prati, F. Rocca, Integration of InSAR time series analysis and water vapour correction for mapping postseismic deformation after the 2003 Bam (Iran) Earthquake*, IEEE Transactions on Geoscience and Remote Sensing, 45*, 5, 1142 – 1153, dio: 10.1109/TGRS.2007.894440, 2007.
283 Li, Z. E. Fielding, E. and P. Cross, Integration of InSAR time series analysis and water vapour correction for mapping postseismic deformation after the 2003 Bam (Iran) Earthquake*. IEEE Transactions on Geoscience and Remote Sensing, 47* (9). 3220-3230, 2009.
284 Pollitz, F. F., C. Wicks, and W. Thatcher Mantle flow beneath a continental strike-slip fault: Postseismic deformation after the 1999 Hector Mine earthquake, Science, 293, 1814-1818, 2001.
285 Shen, Z.-K., D. C. Agnew, R. W. King, D. Dong, T. A. Herring, M. Wang, H. Johnson, G. Anderson, R. Nikolaidis, M. van Domselaar, K. W. Hudnut, and D. D. Jackson (2003), The Southern California Earthquake Center (SCEC) released the SCEC Crustal Motion Map, Version 3.0, (*http://epicenter.usc.edu/cmm3*).
286 Fialko, Y., D. Sandwell, M. Simons, and P. Rosen, Three-dimensional deformation caused by the Bam, Iran, earthquake and the origin of shallow slip deficit, Nature, 435, doi:10.1038/nature03425, 295-299, 2005.
287 Michael, A.J. (1987), Use of focal mechanisms to determine stress- a control study, *J. Geophys. Res.* **92,** 35**7.**
288 Bokelmann, G.H.R. and G.C. Beroza (2000), Depth-dependent earthquake focal mechanism orientation: Evidence for a weak zone in the lower crust, *J. Geophys. Res.* **115,** 21683.
289 Rivera, L., and H. Kanamori (2002), Spatial heterogeneity of tectonic stress and friction in the crust, *Geophys. Res. Lett.*, *29*, doi:10.1029/2001GL013803.
290 Hardebeck, J. L. (2006), Homogeneity of small-scale earthquake faulting, stress and fault strength, *Bull. Seismol. Soc. Am.*, *96*, 1675–1688.
291 Bailey, I., T. W. Becker, and Y. Ben-Zion (2009), Patterns of co-seismic strain computed from southern California focal mechanisms, *Geophys. J. Int.*, *177*, 1015–1036.
292 Kagan, Y. Y. (2009), On the geometric complexity of earthquake focal zone and fault systems: A statistical study, *Phys. Earth Planet. Inter.*, *173*, 254–268.
293 Crampin, S., and S. Chastin (2003), A review of shear wave splitting in the crack-critical crust, *Geophys. J. Int.*, *155*, 221–240.
294 McKenzie, D. P., and J. Brune (1972), Melting on fault planes during large earthquakes, *Geophys. J. R. Astr. Soc.*, *29*, 65–78.
295 Zoback, M. L. (1992), First- and second-order patterns of stress in the lithosphere: The World Stress Map project, *J. Geophys. Res.*, *97*, 11,703–11,728.
296 Scholz, C. H. (2000), Evidence for a strong San Andreas fault, *Geology*, *28*, 163–166.
297 Heidbach, O., M. Tingay, A. Barth, J. Reinecker, D. Kurfeß, and B. M¨uller (2008), The world stress map database release 2008, doi:10.1594/GFZ.WSM.Rel2008.
298 Meade, B. J., and B. H. Hager (2005), Block models of crustal motion in southern California constrained by GPS measurements, *J. Geophys. Res.*, *110*, doi:10.1029/ 2004JB003209.
299 Smith, B. R., and D. T. Sandwell (2006), A model of the earthquake cycle along the San Andreas Fault System for the past 1000 years, *J. Geophys. Res.*, *111*, doi: 10.1029/2005JB003703.
300 Pollitz, F. F., P. McCrory, J. Svarc, and J. Murray (2008), Dislocation models of interseismic deformation in the western United States, *J. Geophys. Res.*, *113*(B04413), doi:10.1029/2007JB005174.
301 McCaffrey, R. (2005), Block kinematics of the Pacific-North America plate boundary in the southwestern United States from inversion of GPS, seismological, and geologic data, *J. Geophys. Res.*, *110*(B07401), doi:10.1029/2004JB003307.
302 Becker, T. W., J. L. Hardebeck, and G. Anderson (2005), Constraints on fault slip rates of the southern California plate boundary from GPS velocity and stress inversions, *Geophys. J. Int.*, *160*, 634–650.
303 Bird, P. (2008), Fault slip rates in the western U.S. from a joint fit to geologic offsets, GPS velocities, and stress directions (abstract), *EOS Trans. AGU*, *89*(52), T23R–08.
304 Humphreys, E. D., and D. Coblentz (2007), North American dynamics and western U.S. tectonics, *Rev. Geophys.*, *45*(RG3001), doi:10.1029/2005RG000181.
305 Flesch, L. M., W. E. Holt, A. J. Haines, L. Wen, and B. Shen-Tu (2007), The dynamics of western

North America: Stress magnitudes and the relative role of gravitational potential energy, plate interaction at the boundary and basal tractions, *Geophys. J. Int.*, *169*, 866–896.

306 Fay, N., and E. D. Humphreys (2006), Dynamics of the Salton block: Absolute fault strength and crust-mantle coupling, *Geology*, *34*, 261–264.

307 Smith, D.E., and T. Heaton (2008), Models of stochastic, spatially varying stress in the crust compatible with focal mechanism data, Bull. Seism. Soc. Am., submitted.

308 Helmstetter, A., and B. E. Shaw (2006), Relation between stress heterogeneity and aftershock rate in the rate-and-state model, *J. Geophys. Res.*, *111*(B07304), doi: 10.1029/2005JB004077.

309 Marsan, D. (2005), The role of small earthquakes in redistributing crustal elastic stress, *Geophys. J. Int.*, *163*, 141–151.

310 Dieterich, J.H. and D.E. Smith (2009), Nonplanar Faults: Mechanics of Slip and Off-fault Damage, Pageoph, 166, 1799, DOI: 10.1007/s00024-009-0517-y.

311 Harris, R. A., and S. M. Day (1993), Dynamics of fault interaction: Parallel strike-slip faults, J. Geophys. Res., 98, 4461– 4472.

312 Aochi, H., O. Scotti, and C. Berge-Thierry (2005), Dynamic transfer of rupture across differently oriented segments in a complex 3-D fault system, Geophys. Res. Lett., 32, L21304, doi:10.1029/2005GL024158.

313 Ben-Zion, Y., and Z. Shi (2005), Dynamic rupture on a material interface with spontaneous generation of plastic strain in the bulk, Earth Planet. Sci. Lett., 236, 486–496, doi:10.1016/j.epsl.2005.03.025.

314 Viesca, R. C., E. L. Templeton, and J. R. Rice (2008), Off-fault plasticity and earthquake rupture dynamics: 2. Effects of fluid saturation, J. Geophys. Res., 113, B09307, doi:10.1029/2007JB005530.

315 Waldhauser, F. and W.L. Ellsworth (2000), A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California, *Bull. Seismol. Soc. Am*, **90,** 1353.

316 Hardebeck, J. L. & P. M. Shearer (2003). Using S/P amplitude ratios to constrain the focal mechanisms of small earthquakes, *Bull. Seismol. Soc. Am.*, **93**, 2434-2444; *http://www.data.scec.org/ftp/catalogs/hardebeck/socal_focal_JLH/*.

317 Powers, P., and T. H. Jordan, Seismicity distribution across strike-slip faults in California, J. Geophys. Res., in press, Nov. 2009.

318 *http://tinyurl.com/ydq6y4q*

319 University of Southern California Information Technology website: *http://www.usc.edu/its/*

320 Virtual Organizations as Sociotechnical Systems (VOSS), NSF Program Solicitation 10-504

321 Frame, K.F Austen, M Calleja, M.T Dove, T.O.H White, and D.J Wilson New tools to support collaboration and virtual organizations Phil Trans R Soc A 2009 367: 1051-1056.

322 Southern California Earthquake Center website : *http://www.scec.org*

323 Surviving the data deluge, Communications of the ACM, Volume 51 , Issue 12, Dec. 2008 ISSN:0001-0782

324 Carbotte, S., K. Lehnert, S. Tsuboi, W. Weinrebe, and Workshop Participants. 2007. Building a Global Network for Studies of Earth Processes: Report of the International Data Exchange Workshop. May 9-11, 2007, Kiel, Germany, 44 pp.

325 Tansley, R., Smith, M.; Walker, J.H. Source, The DSpace open source digital asset management system: challenges and opportunities, Research and Advanced Technology for Digital Libraries. 9th European Conference, ECDL 2005, Lecture Notes in Computer Science Vol. 3652: 242-53,Cambridge, MA, USA

326 Hedges, Mark and Hasan, Adil and Blanke, Tobias (2007) , Management and preservation of research data with iRODS, CIMS '07: Proceedings of the ACM first workshop on CyberInfrastructure: information management in eScience, 2007, 978-1-59593-831-2, pp. 17—22, Lisbon, Portugal http://doi.acm.org/10.1145/1317353.1317358

327 Drupal website : http://drupal.org/

328 Wikipedia website: http://en.wikipedia.org/

329 Helly , John J., Elvins , T. Todd., Sutton, Don, Martinez, David (1999) A method for interoperable digital libraries and data repositories, Future Generation Computer Systems, v.16 n.1, p.21-28, Nov. 1999 doi:10.1016/S0167-739X(99)00032-1

330 Petascale Computing Resource Allocations (PRAC), NSF Program Solicitation 08-529

---

331 Blue Waters web site: http://www.ncsa.illinois.edu/BlueWaters/

332 Cui, Yifeng, Moore, Reagan, Olsen, Kim, Chourasia, Amit, Maechling, Philip, Minster, Bernard, Day, Steven, Hu, Yuanfang, Zhu, Jing, Majumdar, Amitava, Jordan, Thomas (2007) Enabling Very-Large Scale Earthquake Simulations on Parallel Machine, ICCS '07: Proceedings of the 7th international conference on Computational Science, Part I, ISBN: 978-3-540-72583-1, pp. 46--53,Beijing, China, http://dx.doi.org/10.1007/978-3-540-72584-8_7, Springer-Verlag

333 DOE INCITE web site: hpc.science.doe.gov/

334 Global Ring Network for Advanced Application Development (GLORIAD) http://www.gloriad.org/gloriad/

335 Open Science Grid web site: http://www.opensciencegrid.org/

336 National Center for Atmospheric Research (NCAR) web site: http://www.ncar.ucar.edu/

337 Advanced National Seismic System (ANSS) web site: http://earthquake.usgs.gov/monitoring/anss/

338 Earthscope: An Earth Science Program web site: http://www.earthscope.org

339 Incorporated Research Institutions for Seismology (IRIS) web site: http://www.iris.edu

340 George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) web site: https://www.nees.org/

341 Getting Up to Speed: The Future of Supercomputing (2004), Susan L. Graham, Marc Snir, and Cynthia A. Patterson, Editors, Committee on the Future of Supercomputing, National Research Council

342 Subversion website: http://subversion.tigris.org/

343 Trac Project website: http://trac.edgewall.org/

344 JUnit website: http://www.junit.org/

345 CruiseControl website: http://cruisecontrol.sourceforge.net/

346 NMI Build and Test Lab website: https://nmi.cs.wisc.edu/

347 P. Maechling, 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

348 Southern California Earthquake Data Center website: http://www.data.scec.org/

349 IRIS Data Management Center website: http://www.iris.edu/dms/dmc/

350 R. E. Cohen (Ed.) (2005), High-Performance Computing Requirements for the Computational Solid-Earth Science, Elsevier

351 Kernel-based Virtual Machine (KVM) website: http://www.linux-kvm.org

352 M. Armbrust, A. Fox, R. Griffith, A. D. Joseph, R. H. Katz, A. Konwinski, G. Lee, D. Patterson, A. Rabkin, I. Stoica, M. Zaharia (2009) Above the Clouds: A Berkeley View of Cloud Computing, EECS Department, University of California, Berkeley, Feb 2009, UCB/EECS-2009-28

353 Grand Challenges for Disaster Reduction, National Research Council 2005

354 D. J. Wald, B. C. Worden, V. Quitoriano, and K. L. Pankow (2005). ShakeMap Manual: Users Guide, Technical Manual, and Software Guide, USGS Techniques and Methods 12–A1, 128 pp.

355 Zhao, Li ; Chen, Po; Jordan, Thomas H. Strain Green's tensors, reciprocity, and their applications to seismic source and structure studies BSSA 96, no. 5 (200610): 1753-1763 DOI:10.1785/0120050253

356 USGS, in coordination with FEMA, NSF, NIST: The Plan to Coordinate NEHRP Post-Earthquake Investigations, Circular 1242 (http://geopubs.wr.usgs.gov/circular/c1242/)