Southern California Earthquake Center
Final Report

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Principal Investigator: Thomas H. Jordan
University of Southern California
3651 Trousdale Parkway, ZHS 169
Los Angeles, CA 90089-0742
tjordan@usc.edu | 213-740-5843 | 213-740-0011 fax

Project Outcomes Report for the General Public
Southern California Earthquake Center, 2007-2012 (SCEC3)

T. H. Jordan, Principal Investigator

Earthquakes pose the greatest natural threat to life and property in California. During the past five years, the SCEC consortium has coordinated over 600 earthquake scientists from more than 60 research institutions worldwide in a research program on (a) how tectonic forces evolve within active fault networks over years to millennia to generate sequences of earthquakes, (b) how forces produce slip on time scales of seconds to minutes when faults rupture during earthquakes, and (c) how seismic waves propagate from the rupture region and cause shaking on the surface of a heterogeneous crust. This basic research has pioneered novel methods for data analysis in seismology, earthquake geology, and tectonic geodesy, and the SCEC collaboration has substantially advanced integrative modeling in earthquake system science. The latter has been enabled by a new cyberinfrastructure for physics-based seismic hazard analysis that comprises a complementary and interactive set of high-performance computational platforms. These vertically integrated platforms are now capable of executing the principal computational pathways of earthquake system science on NSF and other national supercomputers at unprecedented resolution, with outer-scale/inner-scale ratios up to 10^{17}.

Through integrated studies of earthquake processes, SCEC has worked with its principal agency partners—the National Science Foundation, the U.S. Geological Survey, and the California Geological Survey—to translate this basic geoscience and computational research into practical products that can reduce seismic risk and improve community resilience to earthquake disasters. A steadily improving series of Uniform California Earthquake Rupture Forecasts (UCERFs) has been developed on the OpenSHA platform by the Working Group on California Earthquake Probabilities (2008, 2012) in response to requests from the California Earthquake Authority and the National Seismic Hazard Mapping Project. The CyberShake ground-motion prediction platform is now capable of running, processing, and archiving the very large suites (~10^6) of earthquake simulations needed for the probabilistic calculations of physics-based seismic hazard analysis. CyberShake has produced the first comprehensive, simulation-based hazard models for the Los Angeles region. These models are being extended statewide, and they are being coupled to structural models of the built environment developed by NSF's earthquake engineer research centers, with the goal of achieving a "rupture-to-rafters" simulation capability that will aid in the design of earthquake-resilient communities.

Meta-organizations fostered and administered by SCEC, such as the statewide Earthquake Country Alliance and the 60-institution EPIcenters program of informal education, have provided entirely new venues for helping the public understand and deal with seismic risks. SCEC has deepened collaborations among earthquake scientists, and it has extended them to mathematicians who study earthquake statistics, computer and computational scientists who design and execute large-scale simulations, physical scientists who study rock behavior in the laboratory, earthquake engineers who understand hazard in the context of risk, social scientists who understand public behavior in the face of risk, and decision-makers who must forge public policies based on the best available science. One transformative activity that binds together this diverse assemblage of expertise is the Great ShakeOut drills. These annual earthquake preparedness exercises, which have been developed by SCEC and its partners since 2008, now involve millions of people across the United States and in other several other countries, including Canada, New Zealand, Italy, and Japan.

Earthquake system science relies on the premise that detailed research on fault systems in different regions can be synthesized into a global, physics-based understanding of earthquake phenomena. SCEC has worked towards this synthesis with a growing set of international partners, comparing well-calibrated regional models in diverse tectonic settings around the world. A successful example is the International Collaboratory for the Study of Earthquake Predictability, founded in 2007, which is evaluating earthquake forecasting models in California, New Zealand, Italy, Japan, and China, as well as on a global scale.

SCEC has fostered interdisciplinary interactions among early-career scientists and provided them with new leadership roles. SCEC intern programs have involved over 250 undergraduates in earthquake research, recruiting a diverse set of students into earthquake studies. As a virtual institute, the Center has introduced early-career scientists to interdisciplinary, multi-institutional earthquake system science. It has equipped them with new scientific tools to mitigate earthquake hazards and given them an appreciation of how deep collaborations and international partnerships can be applied in solving global problems.

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 report outlines the accomplishments of the SCEC3 program.

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.

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 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.

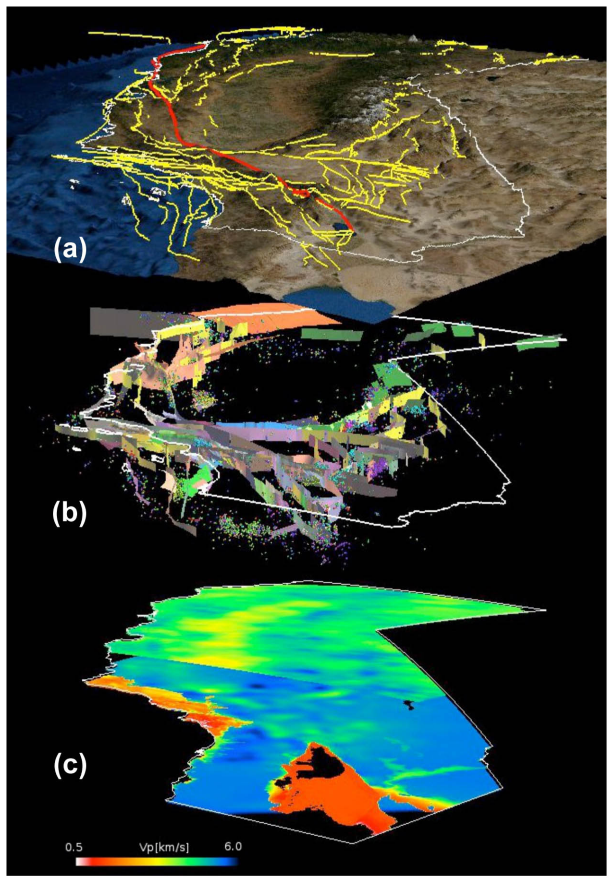


Figure 1.1. Perspective of California, looking northwest and showing elements of the Unified Structural Representation (USR): **(a)** traces of active faults (yellow lines) and the San Andreas master fault (red lines), **(b)** the statewide Community Fault Model (CFM), and (**c**) statewide Community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

Southern California is home to an urbanized population exceeding 20 million, and it comprises the lion's share of the national earthquake risk [FEMA, 2000]. 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% [Field et al., 2009]. Moreover, SCEC3 research under 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 [Hudnut et al., 2010]. 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

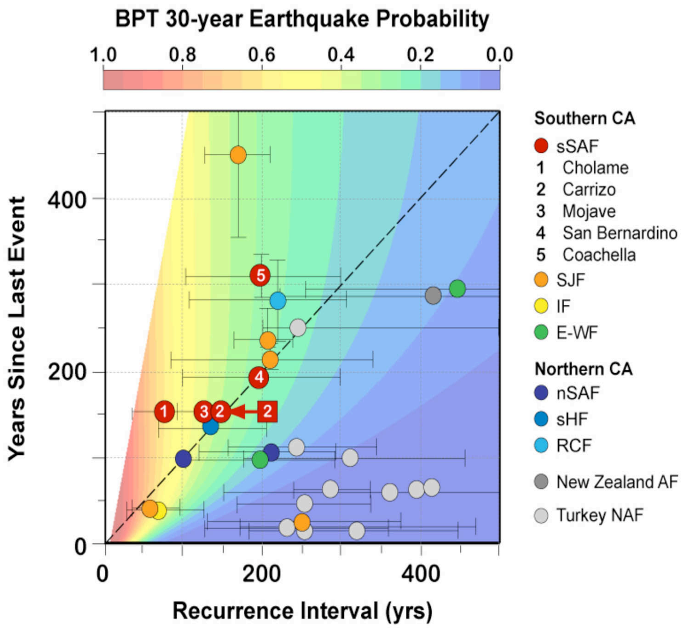


Figure 1.2. A plot of time since the last event vs. mean recurrence interval for sections of the southern San Andreas fault (red points) and other strike-slip faults in California and elsewhere. The arrow indicates the reduction in the mean recurrence interval for the Carrizo section implied by the new 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".

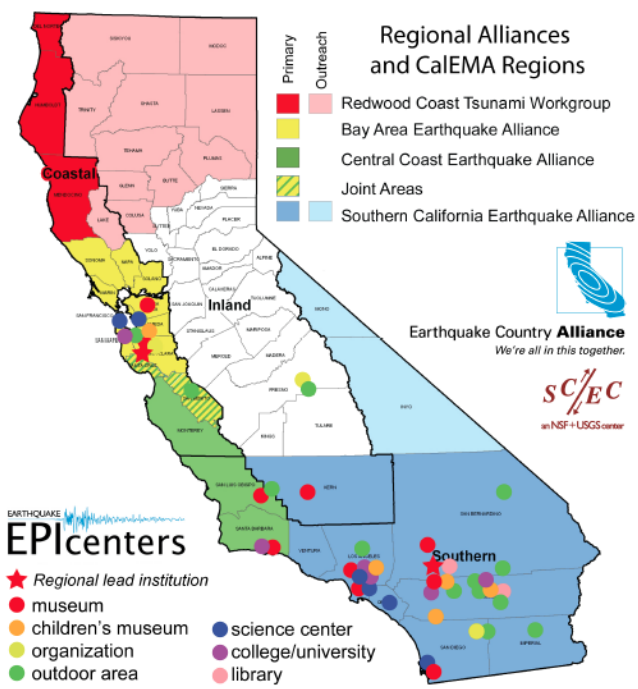


Figure 1.3. Four chapters of the Earthquake Country Alliance (colored areas) and locations of the EPIcenters (colored symbols), two key partnerships developed by the SCEC CEO program.

less [Akciz et al., 2009; Akciz et al., 2011; Zielke et al., 2010; Grant et al., 2010], which compares to the 153-year interval since its last rupture (1857). The urgency of SCEC3 research has come from a recognition that the entire southern San Andreas is "locked and loaded" (**Fig. 1.2**).

SCEC3 research has led to 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 [NSFCC, 2007] and in other NSF reports on virtual organizations (VOs) [Cummings et al., 2008]. Here we describe five important dimensions of SCEC's organizational capabilities.

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. In SCEC3, the number of "core institutions" that commit sustained support to SCEC grew to 16, and the number of "participating institutions" that were self-nominated through participation of their scientists and students in SCEC research grew to 57 (Table 1.1).

The SCEC community now comprises one of the largest formal research collaborations in geoscience. Among the most useful measures of SCEC3 size are the number of people on the Center's email list (1423 on August 17, 2011), active SCEC participants on SCEC projects (1259), and the registrants at the SCEC Annual Meeting (562 in 2011). Annual Meeting registrations for SCEC's entire 21-year history and other demographic information are shown in **Fig. 1.4**.

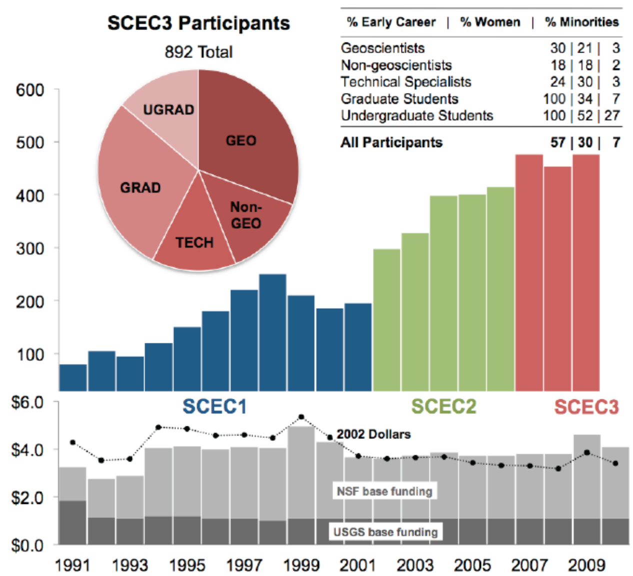


Figure 1.4. Colored bars show total registrants at SCEC Annual Meetings, one measure of how the collaboration has grown during its 20-year history, 1991-2011. Pie chart and table show the demographics of SCEC3. The lower bar chart is the history of SCEC base funding in as-spent dollars; the connected dots are the base-funding totals in 2002 dollars.

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. SCEC3 has developed a number of new computational platforms that apply high-performance computing and communication (HPCC) to large-scale earthquake modeling.

3. SCEC is an ***open community of trust*** that nurtures early-career scientists and shares information and ideas about earthquake system science. 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.

Table 1.1. SCEC3 Member Institutions (June 1, 2011)

Core Institutions (16)	Participation Institutions (58)
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: California Geological Survey Proposed: 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 Alaska; 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

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 So-SAFE, 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*.

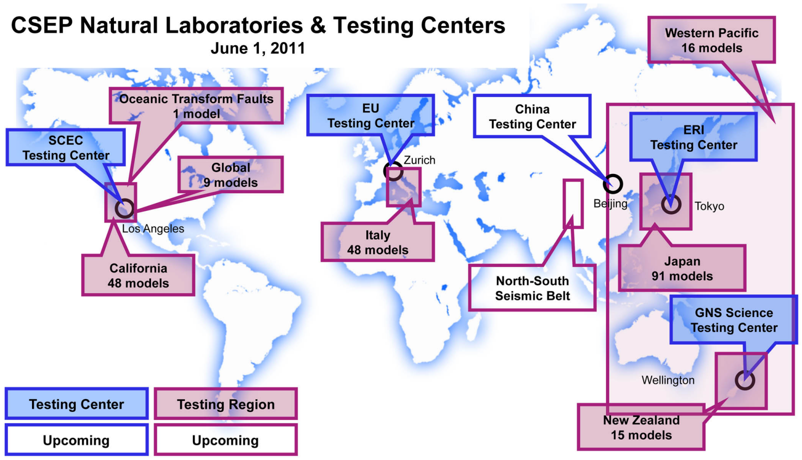


Figure 1.5. Map showing the worldwide distribution of activities developed under the Collaboratory for the Study of Earthquake Predictability (CSEP).

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. The SCEC program is heavily leveraged by contributions by the foreign participants who are supported through their own institutions.

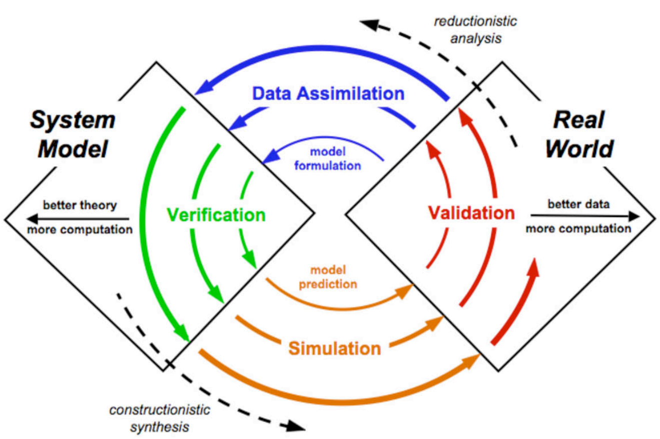


Figure 1.6. The inference spiral for system science, illustrating the improvement of system-level models through an iterated cycle of model formulation (blue), model verification (green), simulation-based prediction (orange), validation against observations (red), and data assimilation (blue). Verification 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.

C. Earthquake System Science

The SCEC3 research program attacked the three main problems of earthquake system science: (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. These problems are coupled through the complex and nonlinear processes of brittle and ductile deformation.

Progress in solving these problems has depended 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.

II. Organization and Management

SCEC is an institution-based center, governed by a Board of Directors, who represent its members. At the end of SCEC3, the membership stood at 17 core institutions and 58 participating institutions (Table 1.1). SCEC currently involves more than 800 scientists and other experts in active SCEC projects. Registrants at our Annual Meetings, a key measure of the size of the SCEC community, is shown for the entire history of the Center in Fig. 1.4. By this measure, participation in SCEC has grown by one-third during the five years of SCEC3.

A. Board of Directors

Under the SCEC3 by-laws, each core institution appointed one member to the Board of Directors, and two at-large members were elected by the Board from the participating institutions. The Board was the primary decision-making body of SCEC3; it met 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. Provisions in the by-laws allowed the Board to conduct business via email. The Board was chaired by the Center Director, Tom Jordan, who also serves as the USC representative. A Vice-Chair, Lisa Grant of UCI, was elected by members.

B. Administration

The Director acted 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. He served as the chief spokesman for the Center to the non-SCEC earthquake science community and funding agencies, appointed committees to carry out Center business, and oversaw all Center activities.

The Deputy Director (DD), Greg Beroza of Stanford, was chair of the Planning Committee, liaison to SCEC science partners, and chair of the annual meeting. The DD oversaw the development of the annual RFP, and recommended an annual collaboration plan to the Board based on the review process.

The Associate Director for Administration, John McRaney of USC, assisted the Center Director in the daily operations of the Center and was 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.

C. External Advisory Council

An external Advisory Council (AC) elected by the Board was charged with developing an overview of SCEC operations and advising the Director and the Board. Since the inception of SCEC in 1991, the AC has played a major role in maintaining the vitality of the organization and helping its leadership chart new directions. The AC comprised 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 were drawn from academia, government, and the private sector. The Council met annually to review Center programs and plans and prepare a report for the Center. AC reports were submitted verbatim to the SCEC funding agencies and its membership.

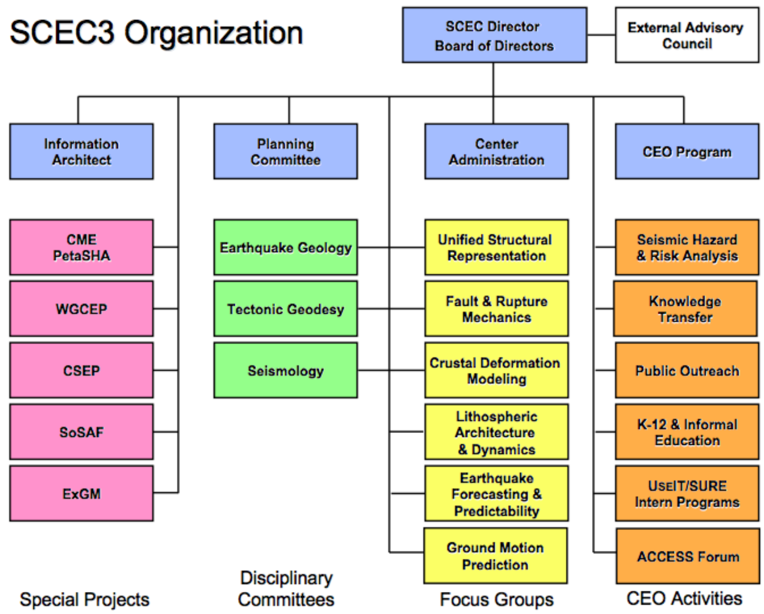


Figure 2.1. The SCEC3 organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects (pink), CEO activities (orange), management offices (blue), and the external advisory council (white).

D. Working Groups

The SCEC3 organization comprised a number of disciplinary committees, focus groups, and special project teams (**Fig. 2.1**). The Center supported disciplinary science through three standing committees in Seismology, Tectonic Geodesy, and Earthquake Geology (green boxes of Fig. 2.1). They were responsible for disciplinary activities relevant to the SCEC Science Plan, and they made recommendations to the Planning Committee regarding the support of disciplinary research and infrastructure.

SCEC3 coordinated earthquake system science through five interdisciplinary focus groups (yellow boxes): Unified Structural Representation (USR), Fault & Rupture Mechanics (FARM), Crustal Deformation Modeling (CDM), Lithospheric Architecture & Dynamics (LAD), Earthquake Forecasting & Predictability (EFP), and Ground Motion Prediction (GMP).

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

SCEC3 initiated a new type of structure, Technical Activity Groups (TAGs), which self-organized to develop and test critical methodologies for solving specific problems. TAGs were formed to verify the complex computer calculations needed for wave propagation and dynamic rupture problems, to assess the accuracy and resolving power of source inversions, and to develop geodetic transient detectors and earthquake simulators. TAGs shared a *modus operandi:* the posing of well-defined "standard problems", solution of these problems by different researchers using alternative algorithms or codes, a common cyberspace for comparing solutions, and meetings to discuss discrepancies and potential improvements.

E. Planning Committee

The SCEC Planning Committee (PC) was chaired by the SCEC Deputy Director and comprised the leaders of the SCEC science working groups—disciplinary committees, focus groups, and special project groups—who together with their co-leaders guide SCEC's research program. The PC had the responsibility for formulating the Center's science plan, conducting proposal reviews, and recommending projects to the Board for SCEC support. Its members will play key roles in formulating the SCEC proposals.

F. Communication, Education and Outreach

The Communication, Education, and Outreach (CEO) program was managed by the Associate Director for CEO, Mark Benthien of USC, who supervise a staff of specialists. The Experiential Learning and Career Advancement program and other education programs wee managed by R. deGroot of USC. The Implementation Interface between SCEC and its research engineering partners was managed by P. Somerville of URS, who served on the Planning Committee.

Through its engagement with many external partners, SCEC3 CEO fostered new research opportunities and ensured the delivery of research and educational products to the Center's customers, which included the general public, government offices, businesses, academic institutions, students, research and practicing engineers, and the media. It addressed 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 provided an expanded capacity for accomplishing this mission.

The CEO program evolved and expanded considerably during SCEC3 within four interconnected thrust areas. The *Implementation Interface* connected 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 promoted the education people of all ages about earthquakes, and motivated them to become prepared. The *K-14 Earthquake Education Initiative* sought to improve earth science education and school earthquake safety. Finally, the *Experiential Learning and Career Advancement* program provided research opportunities, networking, and more to encourage and sustain careers in science and engineering.

G. Participation and Demographics

The demographics of SCEC3 participation is shown in the following table:

Table 2.1. Center database of SCEC participants in 2009-2011.

	Administration or Technical	Faculty Researcher	Non-Faculty Researcher	Graduate Student	Undergraduate Student
RACE					
Asian	7	15	22	9	15
Black	1	0	2	0	4
Hispanic or Latin	0	0	1	0	0
White	29	101	122	26	53
Native American	1	2	0	1	2
No info / Withheld	50	81	133	168	32
ETHNICITY					
Latino	6	7	5	8	25
Not Latino	38	122	141	61	55
No info / Withheld	44	70	134	135	23
GENDER					
Female	27	38	67	83	55
Male	61	161	213	121	53
No info / Withheld	0	0	0	0	0
CITIZENSHIP					
US Citizen	44	115	122	54	87
US Resident	3	17	13	4	4
Other	5	19	79	23	4
No info / Withheld	36	53	31	124	14

DISABILITY STATUS					
None	24	98	126	29	66
Hearing	0	1	1	0	0
Visual	1	0	2	0	0
Mobility	0	0	1	0	0
Other	0	1	0	0	0
No info / Withheld	63	99	151	175	42

H. International Collaborations

1) SCEC Advisory Council. We have one international member, Gail Atkinson of the University of Western Ontario.
2) ERI/Tokyo and DPRI/Kyoto. SCEC has long term MOU's with the Earthquake Research Institute in Tokyo and the Disaster Prevention Research Institute in Kyoto. A two-day workshop with these groups was held at Stanford in December 2011 following the AGU meeting. The agenda focused on the Tohoku earthquake research studies.
3) ACES (APEC Cooperative for Earthquake Simulation). SCEC and JPL are the U.S. organizations participating in ACES. Information on ACES can be found http://www.quakes.uq.edu.au/ACES/. Andrea Donnellan of SCEC/JPL is the U.S. delegate the ACES International Science Board and John McRaney of SCEC is the secretary general. The ACES group held a workshop in Maui in May 2011. There will be a biennial ACES workshop in Maui in October, 2012. SCEC will be the host institution.
4) ETH/Zurich. Stefan Wiemar and Jeremy Zechar are participants in the SCEC/CSEP projects. Daniel Roten participates in the source inversion validation project. Luis Dalguer works in the rupture validation project.
5) KAUST. Martin Mai participates in the source inversion validation project.
6) IGNS/New Zealand. Mark Stirling, David Rhoades, and Matt Gerstenberger of the Institute for Geological Nuclear Sciences of New Zealand are involved in the CSEP program. Charles Williams participates in the ground motion modeling program.
7) Canterbury University/New Zealand. Brendon Bradley participates in the SCEC ground motion simulation program.
8) GFZ/Potsdam. Danijel Schorlemmer (also at USC) is involved in CSEP. Olaf Zielke participates in the simulators project.
9) UNAM/Mexico. Victor Cruz-Atienza works in the ruture validation project.
10) GSJ/Japan. Yuko Kase works in the rupture validation program.
11) CISCSE/Mexico. John Fletcher and Jose Gonzalez-Garcia collaborated with SCEC scientists in post earthquake studies of the El Mayor-Cucupah earthquake and its aftershocks.
12) University of British Columbia/Canada. Elizabeth Hearn of UBC is funded through the SCEC core program.
13) SCEC Annual Meeting. The SCEC annual meeting continues to attract international participants each year. There were participants in the 2011 annual meeting from Australia, China, Japan, India, Mexico, Canada, France, Switzerland, Germany, Russia, Italy, Taiwan, Turkey, and New Zealand.
14) International Participating Institutions. ETH/Zurich, CICESE/Mexico, University of Western Ontario, University of British Columbia, and Institute for Geological and Nuclear Sciences/New Zealand; and 4 institutions from Taiwan (Academia Sinica; National Central University; National Chung Cheng University; National Taiwan University) are participating institutions in SCEC.
15) International Travel by PI and SCEC Scientists. The PI and other SCEC scientists participated in many international meetings and workshops during the report year. They include:1) the ACES workshop in Maui in May 2011, 2) GEM Testing Meeting in London in February 2011, 3) the PGP conference in Norway in May 2011 4) the StatSeis7 meeting in Santorini, Greece in May 2011 5) IUGG conference in Melbourne, Australia in July 2011, 6) the REAKT kickoff meeting in Naples, Italy in September 2011, and 7) the CSEP workshop in Zurich in October 2011.

III. SCEC3 Accomplishments

A. Research Accomplishments

The SCEC3 program was guided by the 19 research objectives (**Box 1**). They are organized under four priority 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; (13) predict broadband ground motions for a comprehensive set of large scenario earthquakes; and (19) prepare post-earthquake response strategies. We use this framework to describe SCEC3 accomplishments. Objectives (3)-(12) are subsidiary to (2), the main Earthquake Rupture Forecast (ERF) objective, and (14)-(18) are subsidiary to (13), the main Ground Motion Prediction (GMP) objective.

Box 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.**

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, improvement, and extension 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 related to the USR in SCEC3 include development of waveform tomography and incorporation of results from it 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 new formal benchmarking and release protocol for CVM; the extension of the Community Fault Model to encompass the entire state of California, and improvements to the CFM through precise earthquake location, targeted paleoseismological studies, and shallow structural imaging.

Tomography to Improve CVM-H. SCEC has developed two crust and upper mantle velocity models: CVM-S [*Kohler et al., 2003*] and CVM-H [Süss and Shaw, 2003]. 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 [Hauksson, 2000] that extend to 35 km depth and a new upper mantle tomographic model that extends to 300 km depth.

SCEC took 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. [2007] 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. [*2009*] 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. 3.1**). 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 [Chen et al., 2009]. The model perturbation reveals a 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.

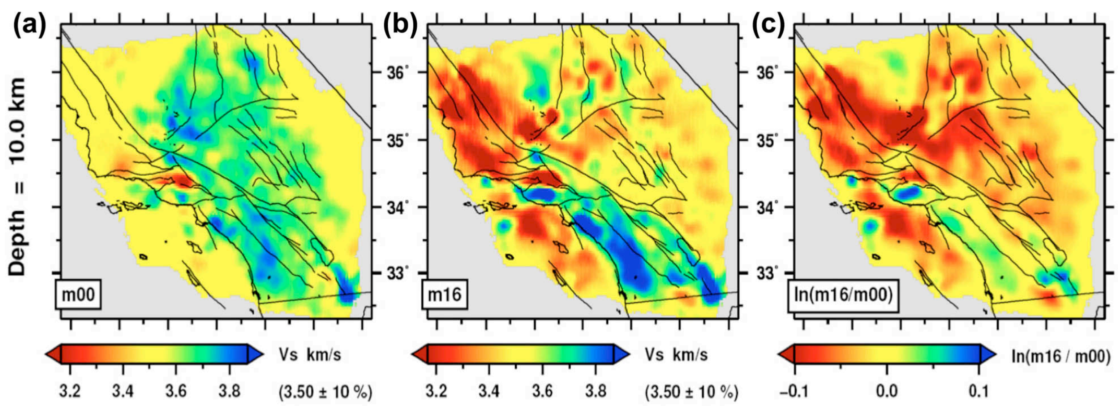


Figure 3.1. Horizontal sections of Vs adjoint tomographic model: (a) starting model CVM-H, (b) adjoint model after 16 iterations, (c) model differences. [Tape et al., 2009]

Additional Improvements to CVM-H. Additional improvements include a revised Moho (**Fig. 3.2**) [Yan and Clayton, 2007; Chulick et al, 2002]. An important improvement for strong ground motion prediction is the implementation of a new bedrock geotechnical layer [Plesch et al., 2007] based on the depth-velocity relations [Boore and Joyner, 1997]. Because of their affect on strong ground motion, sedimentary basins are a particularly particularly important component of the Community Velocity Model. As data on the structure of sedimentary basins improves, it is systematically incorporated into updated releases of the CVM (**Fig. 3.3**). The cumulative effect of these changes is a dramatically improved CVM-H (**Fig. 3.4**).

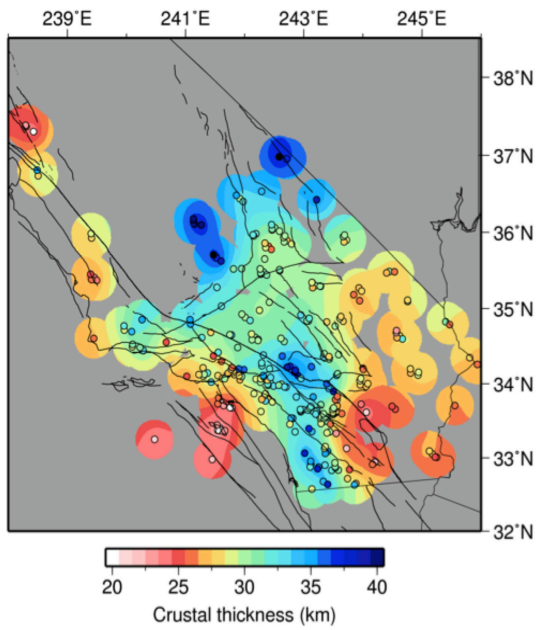


Figure 3.2. CVM-H was updated to include Moho depth from receiver functions. [Yan and Clayton, 2007]

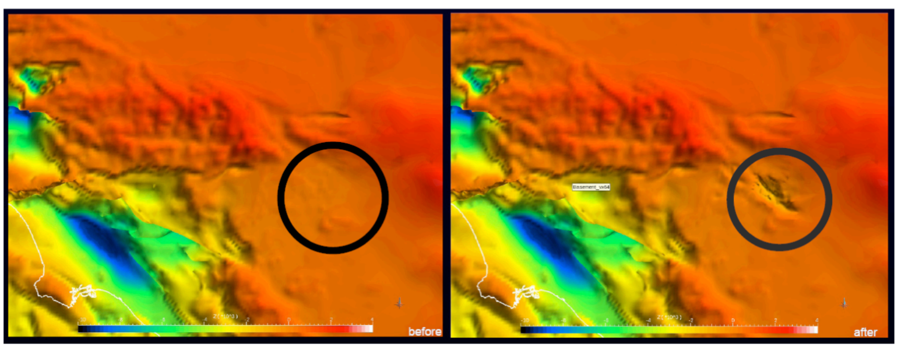


Figure 3.3. CVM-H basement surface before (left) and after (right) definition of the San Bernardino Basin (circled).

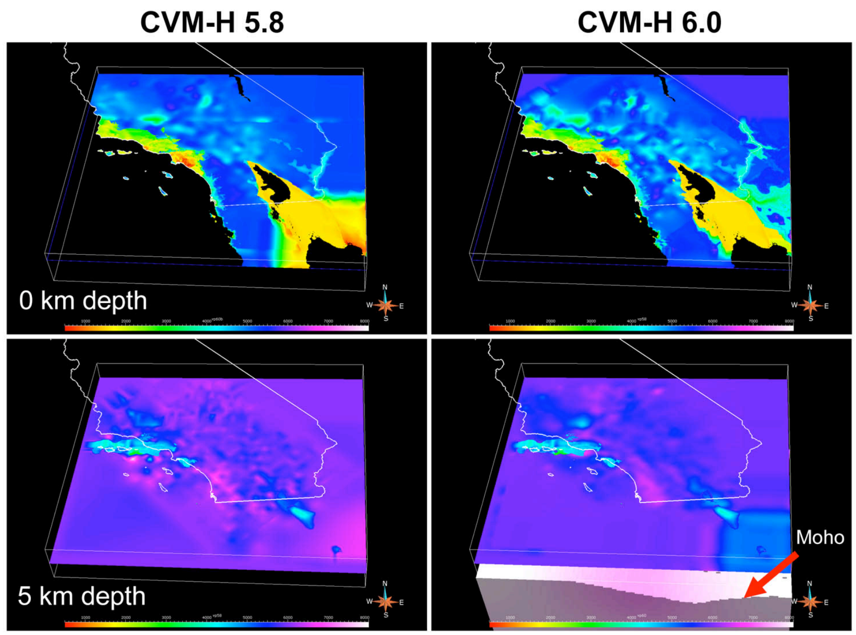


Figure 3.4. SCEC Community Velocity Model, CVM-H 6.0, and later revisions include basin structures embedded in the 3D waveform inversion model, and an explicit representation of the Moho.

Further improvements in the CVM should come rapidly now that waveform tomography is operational and a pathway into the velocity models is established. Ambient-seismic-field Green's functions [Prieto and Beroza, 2008; Ma et al., 2008] will provide new constraints on the elastic [Chen et al., 2009] and anelastic [Prieto et al., 2009] structure. A strength of the ambient-noise approach to CVM development is that it provides constraints in areas are important for seismic hazard analysis that currently lack recordings of earthquakes with which to validate 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.

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 [Olsen and Mayhew, 2010] 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 correlation coefficient, energy flux, 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.

A Statewide Community Fault Model. The community fault model improved rapidly during SCEC3, and 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 [Plesch et al., 2007] and new representations of faults in northern California (**Fig. 3.5**). 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 re-located earthquake catalogs [Hauksson and Shearer, 2005; Shearer et al., 2005; Lin et al., 2007; Waldhauser et al., 2008], which provide significantly improved resolution of many faults, particularly in areas of complex fault junctions [Nicholson et al., 2008]. The Uniform California Earthquake Rupture Forecast (UCERF3) project is critically dependent on the statewide CFM.

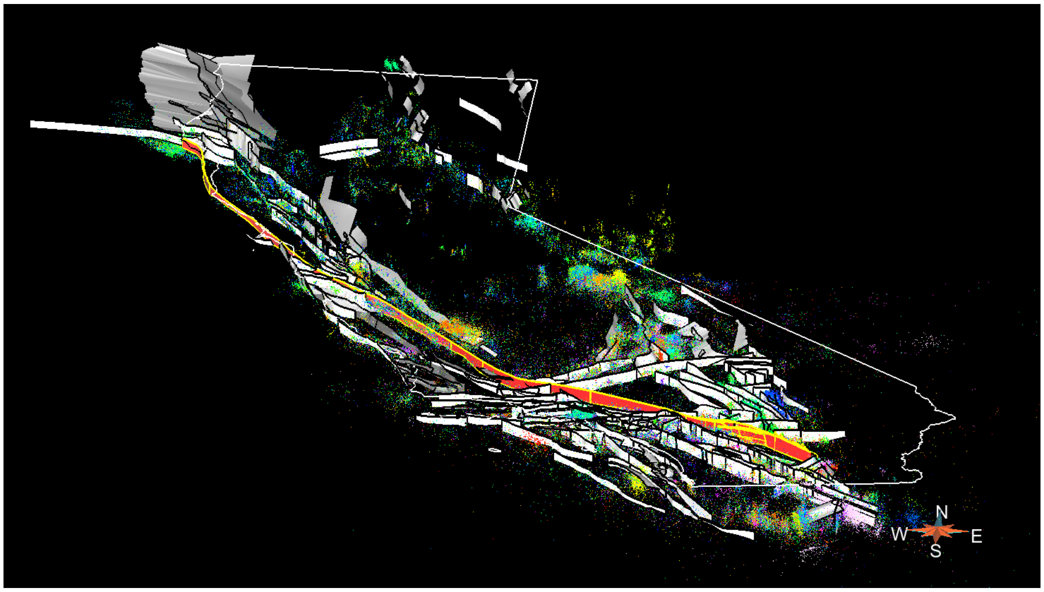


Figure 3.5. Perspective view of statewide Community Fault Model with precisely relocated seismicity. San Andreas Fault is highlighted in red.

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. 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; improved understanding of earthquake potential from compressional structures at and near the Southern California Coast, 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.

More Frequent Large Earthquakes on the South-Central San Andreas Fault. 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 received 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 led to a dramatically different view of the earthquake potential of the San Andreas Fault.

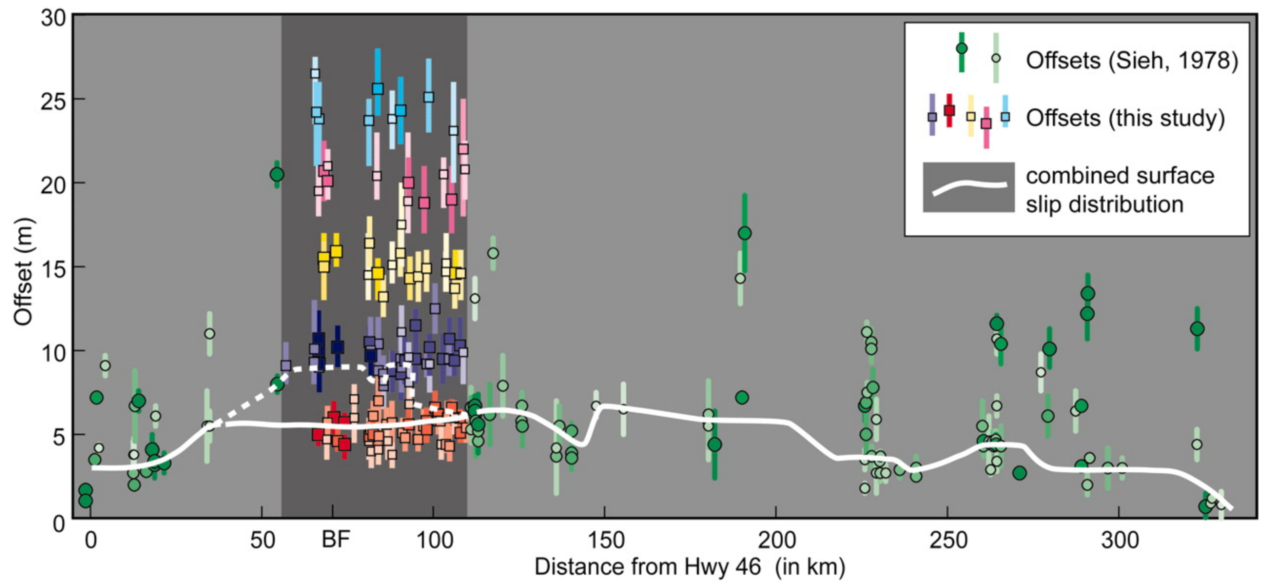


Figure 3.6. Combined surface slip distribution associated with the 1857 earthquake (solid white line). Measurements show quality rating increasing with increasing color intensity. Our measurements along the Carrizo Plain suggest an average slip of 5.3 ± 1.4 m during this event. The previously reported 9.0 ± 2.0 m offsets (dashed white line) represent the cumulative slip of at least two earthquakes. [*Zielke et al.*, 2010]

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. We are just beginning to realize the potential of lidar observations, but an early highlight of this work is the result from Zielke et al. [2010] and Grant Ludwig et al. [2010] demonstrating numerous, subtle 5m offsets along the Carrizo Plain section of the San Andreas Fault (Fig. 6). The youngest offsets cut by half the ~8 m slip attributed to the 1857 Fort Tejon earthquake by Sieh [1978]. This agrees well with new paleoseismic results from the Bidart fan paleoeseismic site, which imply that major events on the south-central San Andreas Fault are about *twice as frequent* as previously believed. In other words, the entire southern San Andreas Fault is “locked and loaded” and could rupture in one, or a series, of large earthquakes at any time.

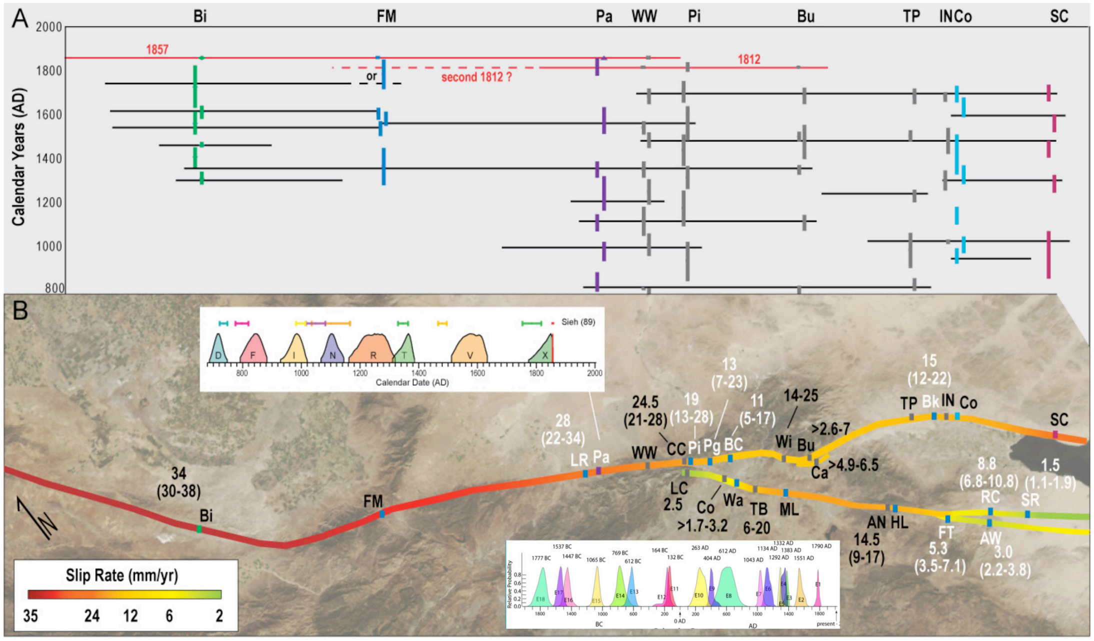


Figure 3.7. San Andreas Fault system data collected during SCEC3. (A) 2σ range for paleoearthquakes on the San Andreas indentified/dated during SCEC3 (in color). Correlations based on age (black) suggest preference for N and S events. Color shows slip rate (mm/yr). Insets show PDFs for Hog Lake (lower) and Pallett Creek (upper).

<u>*Earthquake Recurrence and Slip-Rate Variations.*</u> Several critical paleoseismic data gaps have been filled and important new developments unfolded from synthesis of paleoseismology, slip-rate, and slip-per-event data. New investigations at the Frazier Mountain site are filling 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 [Biasi and Weldon, 2009]. Findings to date 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. 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 [Philibosian et al., 2007]. 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 [Bennett et al., 2004; McGill et al., 2008]. The emerging view is that slip is approximately equally partitioned between the San Andreas and northern San Jacinto Faults (**Fig. 3.7**). The discovery of a new paleoseismic site along the San Jacinto Fault at Mystic Lake [Onderdonk et al., 2009; Sharpe, 1981] 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.

<u>*Quantifying the Threat from Other Faults.*</u> 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 faults that lie closest to urban centers; in particular, the large blind thrust systems directly beneath Los Angeles. Leon et al. [2007] developed evidence for Holocene (M>7) earthquakes on the Puente Hills thrust, under downtown Los Angeles, and Leon et al. [2009] made the case for similar events on the Compton thrust, further to the south, but still under metropolitan 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 [Rockwell, personal communication] indicate 6-7 m of coseismic uplift of the Ventura Anticline in a very large event about 1000 yrs ago.

<u>*Resolving Geologic vs. Geodetic Slip-Rate Discrepancies.*</u> At the end of SCEC2, some geodetic/geologic slip rate discrepancies were substantial and difficult to understand (**Fig. 3.8**). Work at new sites on the

San Jacinto Fault tested for temporal variation of slip rate [Bennett et al., 2004; McGill et al., 2008; Onderdonk et al., 2009]. Geologically based slip-rate studies 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 [Behr et al., 2010; Fletcher et al., 2010], documentation of slip rates showing a gradient in activity on the San Bernardino section north of San Gorgonio Pass [Bennett et al., 2004; McGill et al., 2008], and a multi-site investigation of slip rates on the San Jacinto [Onderdonk et al., 2009; Blisniuk et al., 2010; Janecke et al., 2011]. Evidence for earthquake clustering [Rockwell et al., 2006] and temporal variation in slip rate of the San Jacinto [Blisniuk et al., 2010; Janecke et al., 2011] suggest that its activity may oscillate with the southernmost San Andreas Fault.

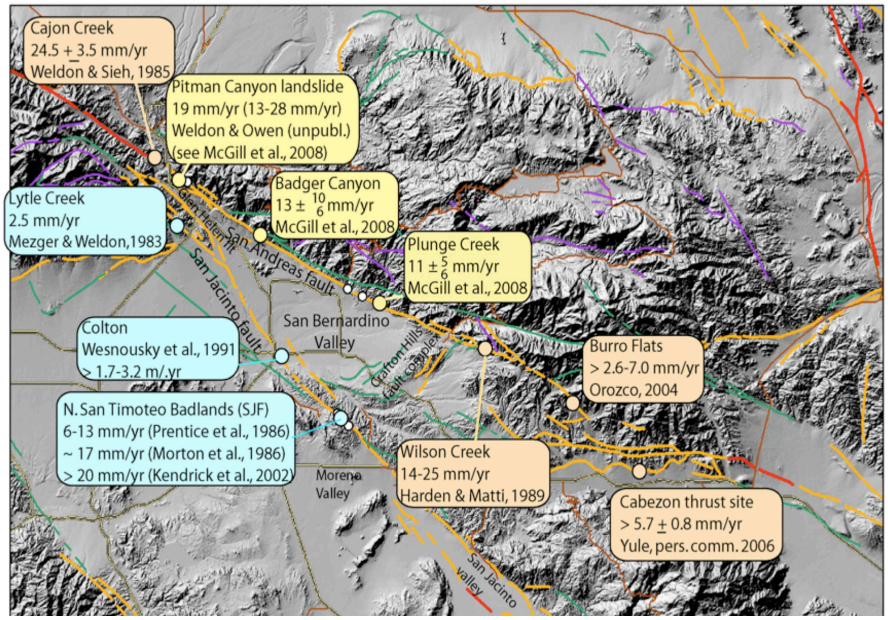


Figure 3.8. Summary of geologic slip rates across the San Andreas and San Jacinto Faults [McGill, Weldon et al.]. All slip rates exceed 5 mm/yr as estimated geodetically [Meade and Hager, 2005].

SCEC played a central role in establishing continuously recording Global Positioning System (GPS) measurements in southern California with the Southern California Integrated GPS Network [Hudnut et al., 2002] (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.

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. 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 in the Eastern California Shear Zone. These discrepancies with geologic measurements [Loveless and Meade, 2011] have been largely resolved by more recent block modeling; 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. 3.9**) 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.

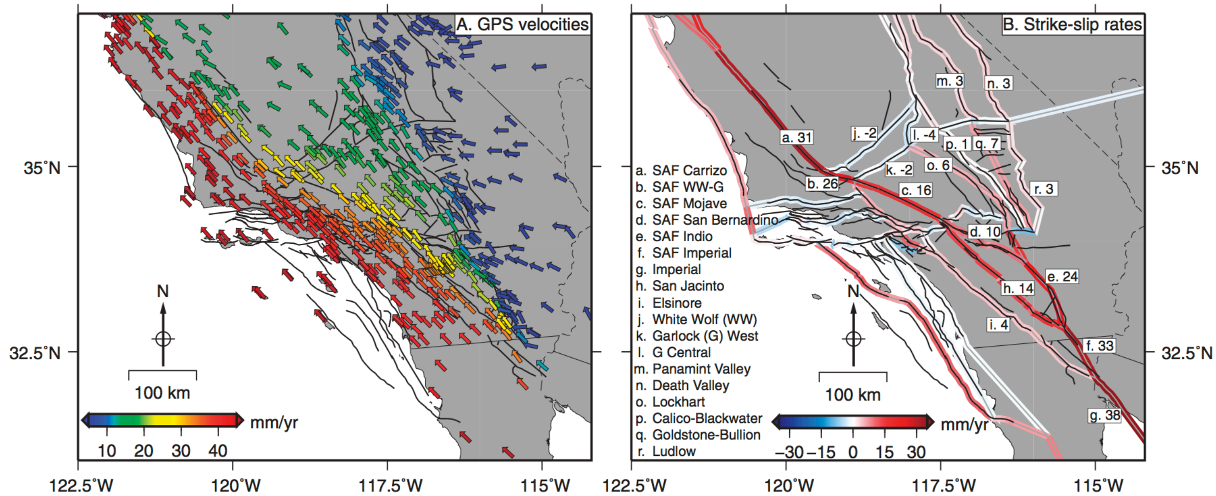


Figure 3.9. Left: Interseismic velocity field based on several GPS networks, relative to stable North America. Speed is denoted by color. Right: Estimated slip rates on block-bounding faults (right lateral is positive). Block geometry constructed from SCEC CFM. SAF—San Andreas Fault. [Loveless and Meade, 2011]

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 [Chuang et al., 2009]. 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, and shows the effect of varying time since the last large earthquake (**Fig. 3.10**).

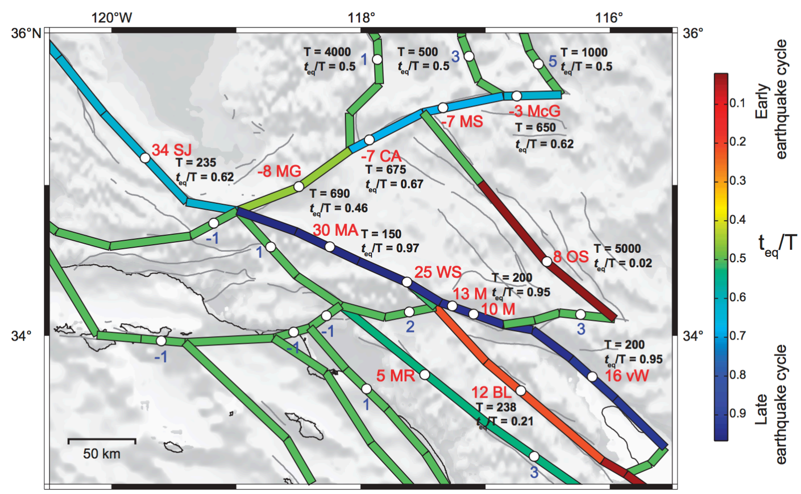


Figure 3.10. Summary of assumed geologic rates, recurrence interval (T), and time since last earthquake (t_{eq}) in Southern California. Blue numbers are expert opinion slip rates from Working Group on California Earthquake Probabilities (2008) and red numbers are from other paleoseismology data. Color of rupture segment represents ratio of time since last earth- quake and recurrence interval. Hot (red) colors show segments are in early earthquake cycle, and cold (blue) colors show late earthquake cycle. [Chuang and Johnson, 2011]

Progress in Modeling Fault Systems. System-level deformation and stress-evolution modeling requires understanding heterogeneities in 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 on 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 loads on the Southern California crust and upper mantle [Fay et al., 2008]. This load is substantial, is consistent with geodetic anomalies (**Fig. 3.11**), and provides an important constraint on absolute stress [Fay and Humphreys, 2008].

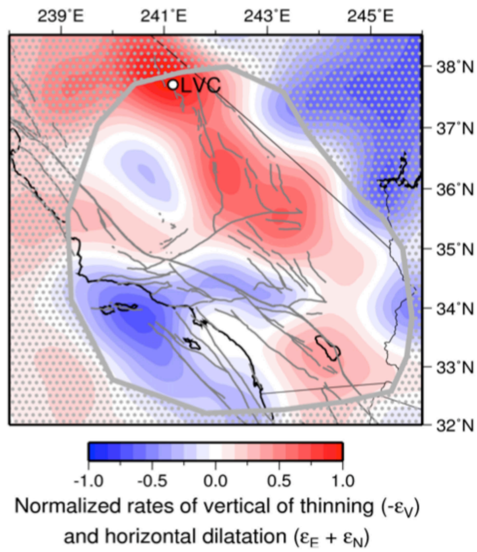


Figure 3.11. Predicted rates of vertical and horizontal strain inferred from seismic tomography of the upper mantle. [Fay et al., 2008]

Development of earthquake simulators, aimed at generating synthetic earthquake catalogs over a range of spatial and temporal scales [Tullis et al, 2009; Dieterich and Richards-Dinger, 2010], emerged as an important activity in SCEC3. Results on a sequence of standardized simulation problems were generated by the participating groups, comparisons 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. 3.12**. The simulator is based a quasi-static boundary-element calculation that employs a Dieterich nucleation model and can handle complex fault geometries [Dieterich and Richards-Dinger, 2010]. The vision for simulator-based seismicity catalogs is that they will provide important input into time-dependent earthquake rupture forecasts by combining short-term triggering with long-term stress renewal.

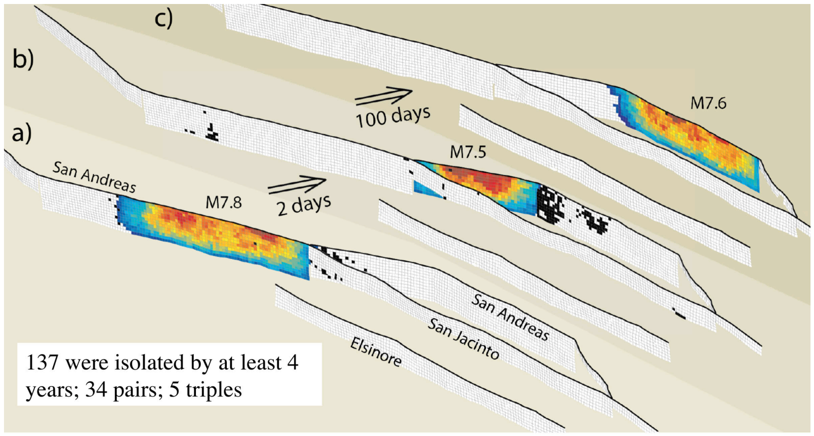


Figure 3.12. Example output from earthquake simulator showing sequence of earthquakes on the San Andreas Fault. There were 72 aftershocks in the 2-day interval between the *M* 7.8 and *M* 7.5 events, and 183 aftershocks in the 100-day interval between that and the *M* 7.6 event. Over the long term, the simulation led to 227 *M*> 7 earthquakes on these faults. [Dieterich and Richards-Dinger, 2010]

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 [Hauksson and Shearer, 2005; Shearer et al., 2005; Lin et al., 2007; Waldhauser et al., 2008], have allowed researchers to discern structures that were previously obscured by location uncertainties (**Fig. 3.13**). 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. Algorithms for improved focal mechanism determination are currently being automated.

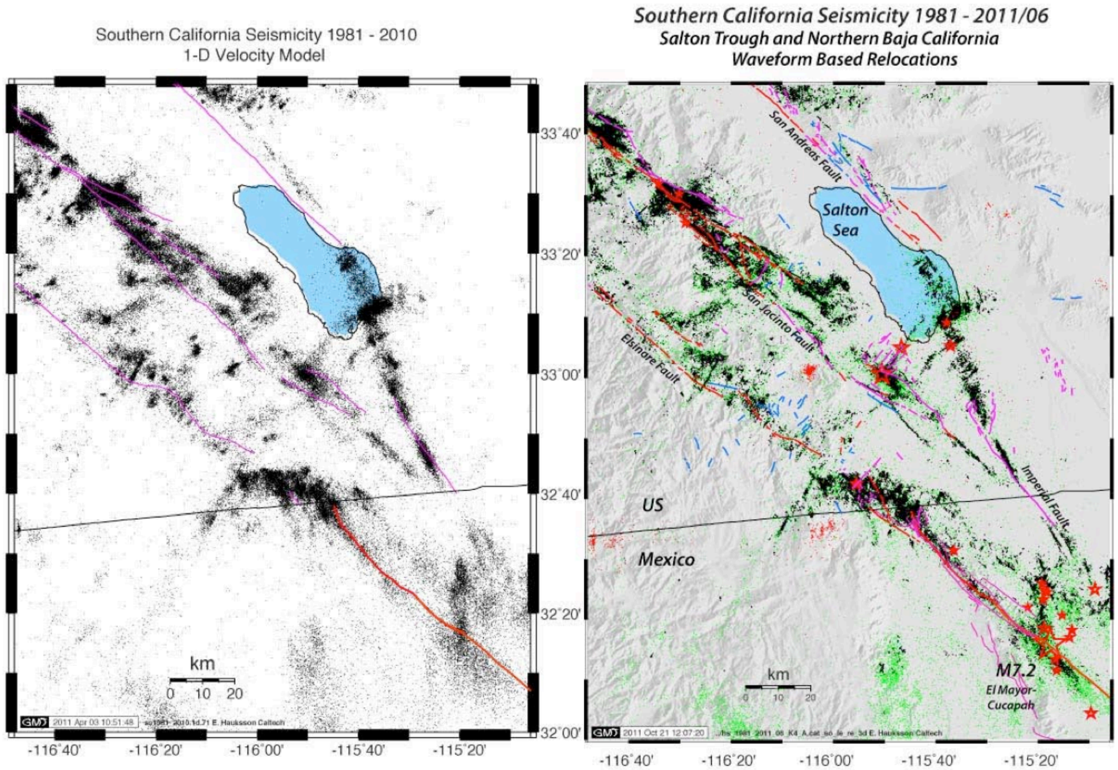


Figure 3.13. Seismicity located with 1-D mode (left) and precisely relocated (right) from 1981 through mid-2011. Similar-event clusters (black) relocated using cross-correlation. Events in SCSN catalog (and uncorrelated events from other catalogs) are shown in color. *M* ≥ 5.5 shown with stars. Late Quarternary faults in red, and early Quaternary in blue. [Hauksson et al., submitted]

<u>*Aseismic Transient Detectors.*</u> A Transient Detection Technical Activity Group was organized in SCEC3 to develop geodetic transient detectors. 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. 3.14**)**.** 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, to make geodetic transient detection an operational capability, was in the process of being realized with a sub-set of the detectors by the end of the SCEC3 project.

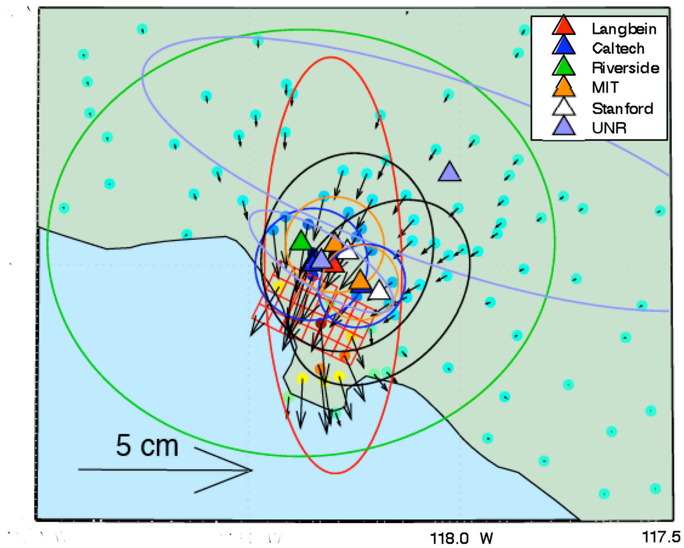


Figure 3.14. Summary of test results from a test dataset used in the Transient Detection Blind Test Exercise. Triangles with ellipses mark centroid location and extent of the transient cumulative displacement detected by each participating group. Cumulative noiseless synthetic displacements that were added to the test data are shown by vectors, and 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 [Zechar et al., 2009]. 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, China; and with testing regions that include: California, Italy, Japan, Northwest Pacific, Southerwest Pacific, New Zealand, and global.

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. 3.15**). 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 [Zechar and Jordan, 2008]. 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.

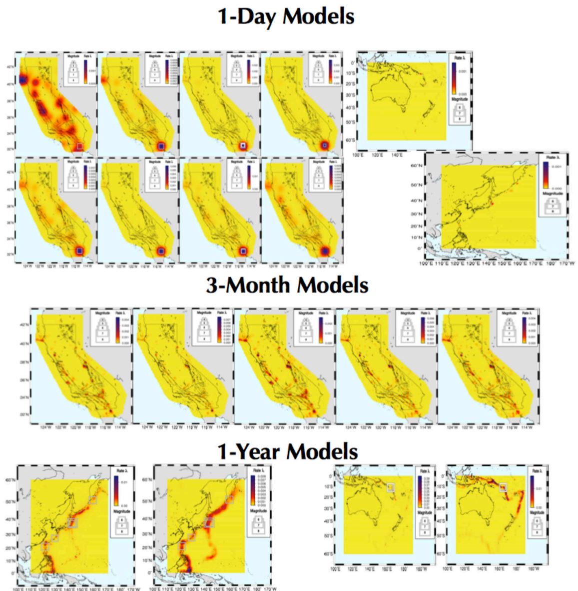


Figure 3.15. Example of earthquake forecast models under evaluation at the CSEP testing center.

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. [2008; 2009] 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 [Rockwell et al., 2008; Dor et al., 2009] 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 [Rockwell et al., 2008; Dor et al., 2009]. The presence of damage has been shown to have a strong effect on dynamic rupture in the laboratory [Biegel et al, 2009; Bhat et al., 2010].

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. 3.16**) 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 [Andrews and Hanks, 2007]. The most recent efforts of the SCEC Rupture Dynamics Code Validation TAG [Harris et al., 2009] 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.

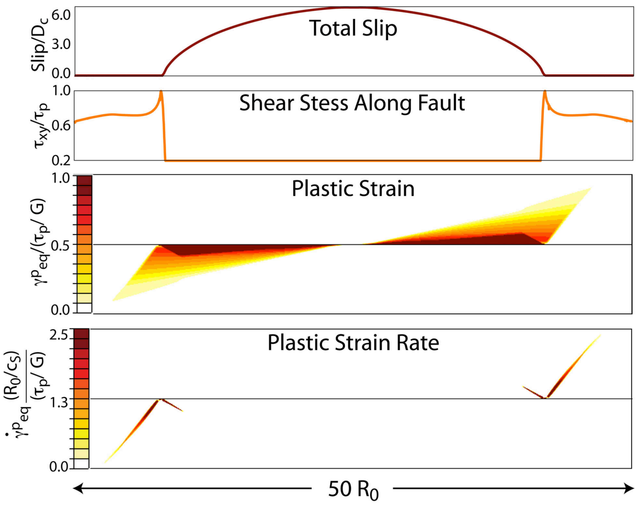


Figure 3.16. Accumulation and evolution of plastic strain during rupture propagation. Plastic strain accumulates in a narrow zone near the crack tip. [*Templeton et al.,* 2009]

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 [2008] and Noda et al. [2009] 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 [Yuan and Prakash, 2008], reflecting the current state of the interface.

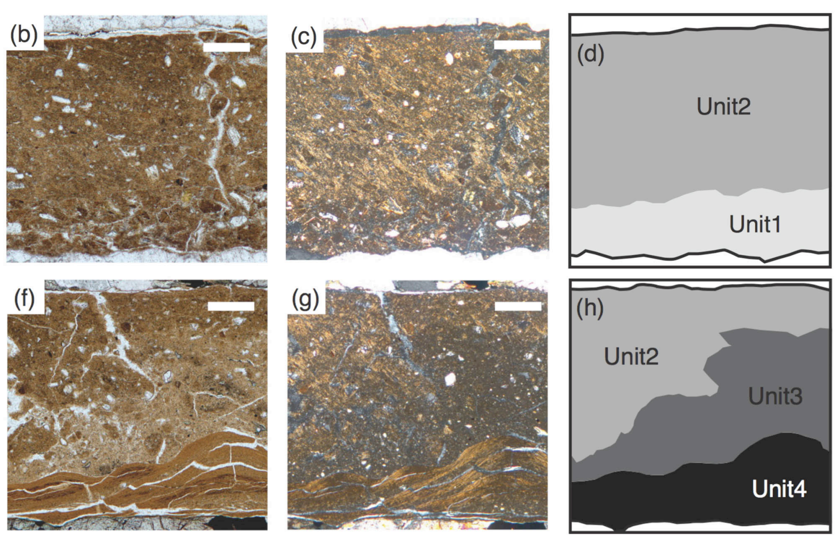


Figure 2.16. Characteristic structure of gouge units showing progressive evolution with slip. Unit 4 has been repeatedly imbricated and stacked [*64*].

Figure 3.17. Characteristic structure of gouge units showing progressive evolution with slip. Unit 4 has been repeatedly imbricated and stacked. [*Kitajima et al.,* 2010].

Theory [Rice, 2006; Beeler et al., 2008] indicates the velocity at the onset of weakening due to flash heating varies inversely with contact size. Tullis and Goldsby [2007] 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. [2007] and Sagy and Brodsky [2009] 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. [2010] 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. 3.17**). These and related findings, have significant implications for improving models of slip on faults that incorporate realistic geological and geometrical complexities.

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.

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.

Verification of Algorithms. Simulating ground motions from complex ruptures in a 3D Earth is a task that absolutely requires high-performance computing (HPC). For that reason, SCEC3 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 [Harris et al., 2009] and ground motion modeling of large scenario earthquakes, such as the ShakeOut scenario [Bielak et al., 2010] (**Fig. 3.18**).

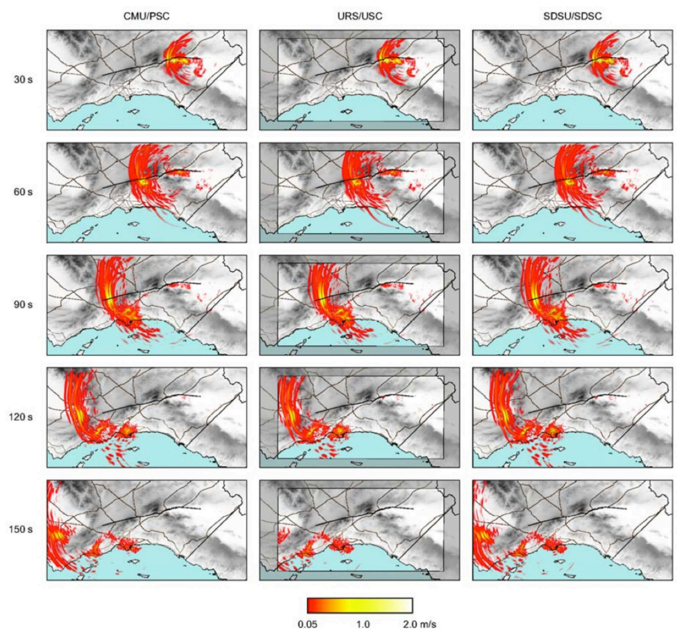


Figure 3.18. Snapshots at 5 different times, of horizontal velocity for 3 ShakeOut simulations. Groups/computer centers are from left to right CMU/PSC, URS/USC, and SDSU/SDSC.

Improved Pseudo-Dynamic Rupture Models. 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 [Guatteri et al., 2004; Song et al., 2009; Schmedes et al., 2010]. Multiple dynamic-rupture variations have been calculated for the ShakeOut scenario earthquake to estimate long-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 3.19**). This suggests that simulation ensemble variances may be substantially reduced through use of sources based on spontaneous rupture simulations.

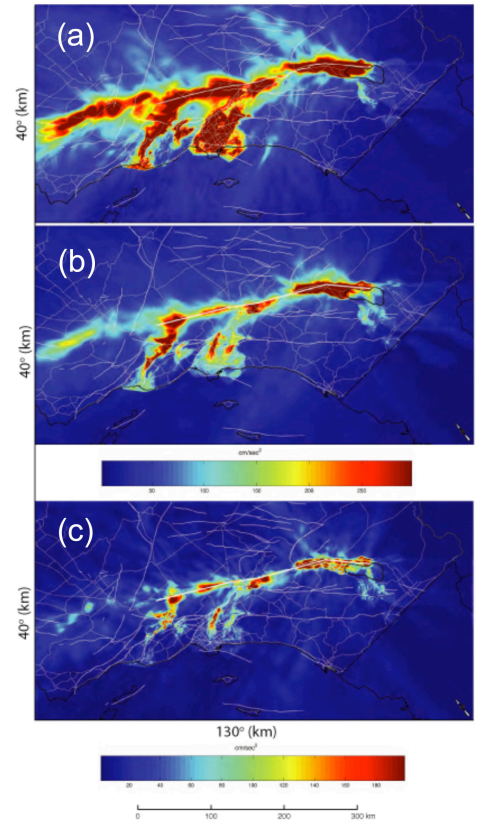


Figure 3.19. 3s Spectral acceleration for (a) kinematic, (b) mean dynamic, and (c) standard deviation of dynamic for ShakeOut scenario earthquake simulations.

Effect of Super-shear Rupture. 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 [Andrews, 1976], but we are still coming to grips with the implications for ground motion prediction because sub- and super-shear ruptures exhibit qualitatively different characteristics [Aagaard and Heaton, 2004; Dunham and Archuleta, 2004; Dunham and Bhat, 2008]. 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. 3.20**). 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 [Das, 2007] and the lack of on-fault seismicity on the San Andreas, here and elsewhere, is also suggestive [Bouchon and Karabulut, 2008]. 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.

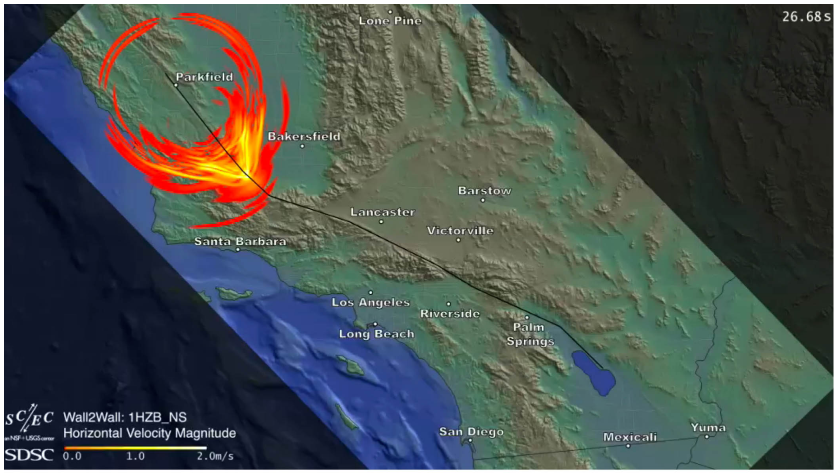


Figure 3.20. Supershear rupture on the Carrizo segment of the San Andreas Fault. In this dynamic simulation of NW-SE rupture, a classic Mach cone - the seismic equivalent of a sonic boom - is formed behind the rupture front.

High-Frequency Excitation. 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. [2011] 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. 3.21).** They include the effects of off-fault plasticity in their simulations. Plasticity enhances the effect due to its role as an energy sink.

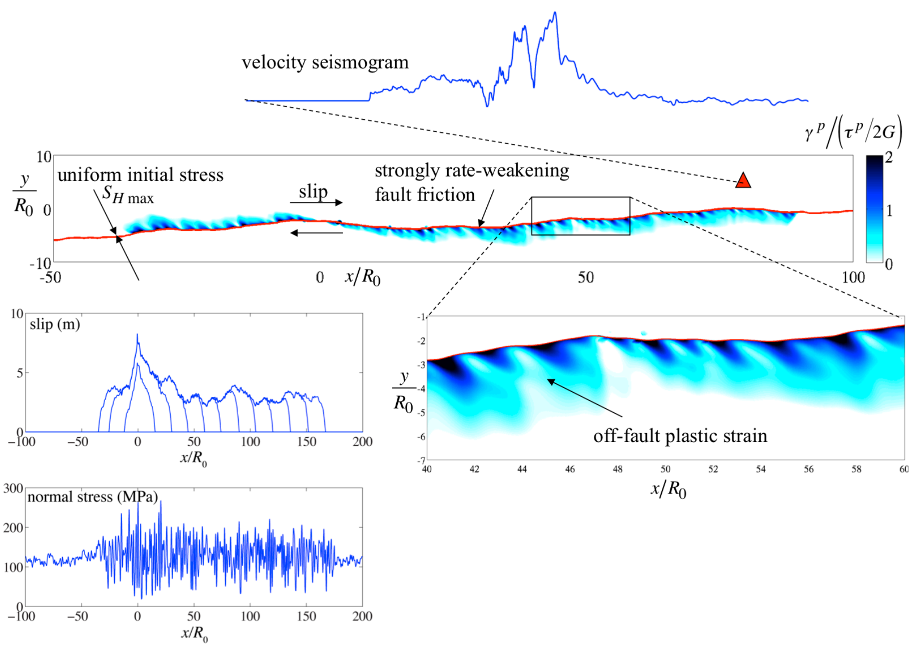


Figure 3.21. Simulation of rupture on fractally rough fault. Material is elastic-plastic. Stress perturbations (lower left) lead to fluctuations in rupture speed and slip (middle left), which are accentuated by plastic yielding (center). The result is production of high frequency ground motion (top).

New Approaches to Validation of Ground Motion Simulations. 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 [Olsen and Mayhew, 2010] demonstrates this approach. This is not possible for many paths of interest, however, owing to the lack of appropriate earthquakes sources. Prieto and Beroza [2008] 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. 3.22** shows that a virtual earthquake developed from data recorded at broadband seismic 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. Corrections for moment tensor and source-depth can be included using the SCEC CVM [Denolle et al., submitted].

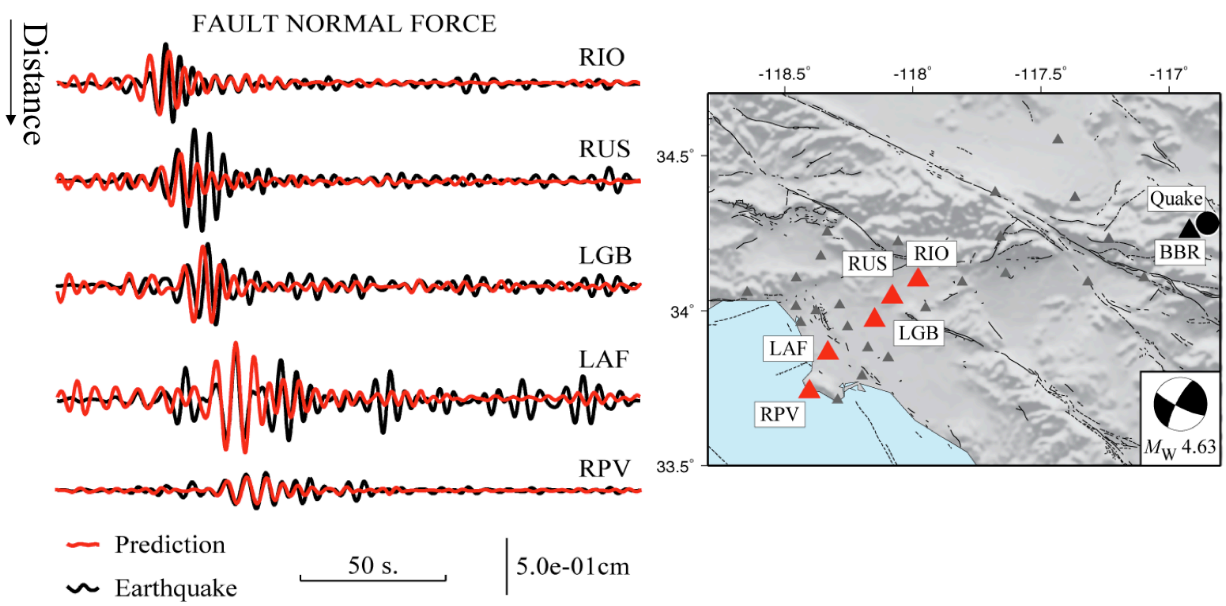


Figure 3.22. Proof of concept for the virtual earthquake approach. The ambient-field Green's functions for station BBR reproduce amplification and duration of the *M* 4.6 Big Bear earthquake shaking as recorded across the Los Angeles Basin. This approach can be used to validate long-period ground motion 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 [Aagaard et al., 2008a; Aagaard et al., 2008b]. 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 (**Fig. 3.23**). PBRs continue to be discovered in strategically important areas, and can provide constraints on PSHA that may otherwise be unobtainable.

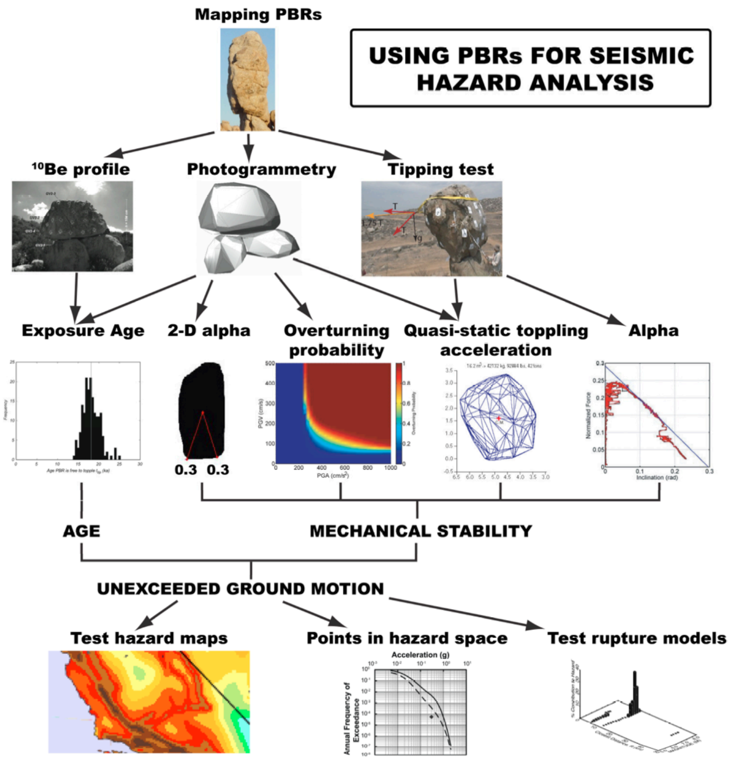


Figure 3.23. Methodology used to address seismic hazards with Precariously Balanced Rocks. Methodologies developed in SCEC3 use these methods to produce ground motion constraints for strategically selected PBRs. [*Grant-Ludwig*, 2012]

Simulation of Extreme Events. 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., Bozorgnia et al., 2007; Naeim and Graves, 2006; Somerville et al., 2007]. A number of buildings and bridges have been designed or evaluated using such records as well.

Contributions to NGA and National Hazard Maps. The Next Generation Attenuation relations 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 and International Building Code. 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. 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.

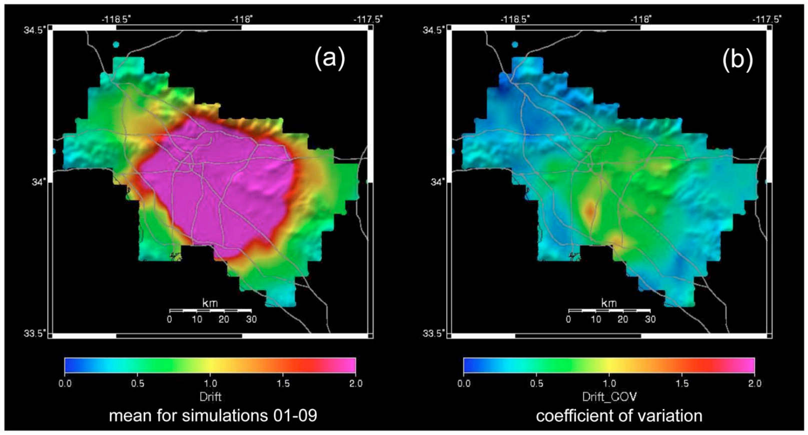


Figure 3.24. Peak inter-story drift (inches) and coefficient of variation throughout the Los Angeles region in a 2-story 1980s-2000s index woodframe house from a *M* 7.1 earthquake on the Puente Hills Blind Thrust. Values in excess of 2 inches (pink areas) would likelycase total loss and potential collapse.

<u>*End-to-End Simulations.*</u> 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. 3.24**. In such calculations, computer models of representative buildings (in the case of Fig. 24, 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.

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.

<u>*ShakeOut Scientific Response Exercises*</u>. 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.

<u>*Earthquake Response Content Management System*</u>. 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 and 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.

In SCEC3, CEO has been very successful in leveraging its base funding with support from the California Earthquake Authority (CEA), FEMA, Cal-EMA, USGS, additional NSF grants, corporate sponsorships, and other sources. For example, for its *Putting Down Roots in Earthquake Country* publication SCEC CEO has leveraged an additional $4.4 million for advertising and printing since 2004. 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.

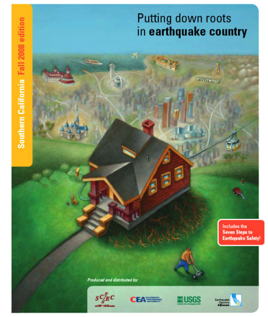
Box 2.2. Summary of Review Panel Findings

- 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 first Spanish version of *Roots* was produced in 2006. The Fall, 2008 version added overviews of the ShakeOut Earthquake Scenario and the Uniform California Earthquake Rupture Forecast study [*Field et al., 2009*].The 2011 version included new tsunami science and preparedness content.

The booklet has spawned the development of region specific versions for the San Francisco Bay Area, California's North Coast, Nevada, Utah, Idaho, and the Central U.S. (totaling an additional 4 million copies, see **Fig 3.25**). 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 [*http://www.earthquakecountry.org*].

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). This partnership resulted from SCEC CEO's involvement in the Earthquakes and Megacities initiative.

Figure 3.25. 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

The ECA is a public-private partnership of people, organizations, and regional alliances, each of which are committed to improving preparedness, mitigation, and resiliency. People, organizations, and regional alliances of the ECA collaborate in many ways: sharing resources; committing funds; and volunteering significant time towards common activities. ECA's mission is to support and coordinate efforts that improve earthquake and tsunami resilience. The Earthquake Country Alliance is now the primary SCEC mechanism for maintaining partnerships and developing new products and services for the general public.

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 [*http://www.earthquakecountry.org*] with similar groups in the Bay Area and North Coast. Participants develop and disseminate common earthquake-related messages for the public, share or promote existing resources, and develop new activities and products. SCEC develops and maintains all ECA websites (*www.earthquakecountry.org*, *www.shakeout.org*, *www.dropcoverholdon.org*, and *www.terremotos.org*), has managed the printing of the "Putting Down Roots" publication series throughout the state, 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 [http://www.daretoprepare.org] 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 [http://www.terremotos.org] 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 [Jones et al., 2008]. It portrays the consequences of a magnitude 7.8 earthquake on the southernmost San Andreas Fault. A SCEC simulation of the scenario earthquake [Graves et al., 2008] 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. SCEC CEO has worked with many other states and several countries to extend the ShakeOut model, and as of April 2012 manages 11 ShakeOut websites (*http://www.shakeout.org*) (See next section).
- *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.

In November 2010, the ECA held a Strategic Planning Workshop to discuss next steps for the organization's expanding programs and to increase engagement in the planning, management, and funding of initiatives. In this Workshop, the five researched solutions presented and discussed included the ECA becoming a 1) 501(c)(3) non-profit; 2) a 501(c)(4) non-profit; 3) a 501(c)(6) non-profit; 4) remaining as the same structure- a loosely organized confederation that cannot accept/administer grant funds directly; or, 5) becoming a program of SCEC under as part of SCEC's USC-based structure. Pros and cons were listed for all options looking at management, funding/budget, legal, governmental requirements, and other implications. The unanimous consensus of ECA leadership was to organize the ECA at USC to be administered by SCEC, under the direction of a statewide Steering Committee made up of regional ECA leaders, with these considerations:

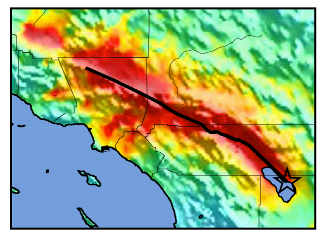
- Recognize the diverse and voluntary nature and size of ECA's component organizations and allow participation by the widest possible net of stakeholders, with an emphasis on regional groupings;

- Acknowledge that although most ECA Associates represent organizations, certain organizations need a role in the management structure;
- Minimize the size and role of the statewide effort in favor of supporting and connecting component organizations and regional alliances;
- Foster information sharing and provide effective and direct means of communication within and among ECA groups.

ECA Associates benefit from their participation by coordinating their programs with larger activities to multiply their impact; being recognized for their commitment to earthquake and tsunami risk reduction; having access to a variety of resources on earthquake and tsunami preparedness; networking with earthquake professionals, emergency managers, government officials, business and community leaders, public educators, and many others; and connecting with ECA sector-based committees to develop customized materials and activities. To participate, visit *www.earthquakecountry.org/alliance/join.html*.

The Earthquake Country Alliance (ECA) has coordinated outreach and recruitment for the California ShakeOut since 2008. Because of the creation and growth of the ShakeOut, and other activities and products, ECA has received national recognition. In 2011 ECA was recognized by FEMA with the "Awareness to Action" award, which resulted in SCEC's Associate Director for CEO Mark Benthien being named a "Champion of Change" by the White House. In April 2012 ECA also received the "Overall National Award in Excellence" at the quadrennial National Earthquake Conference held in Memphis.

Great ShakeOut Earthquake Drills. A major focus of the CEO program since 2008 has been organizing the *Great California ShakeOut* drills and coordinating closely with ShakeOuts in other states and countries. The purpose of the Shakeout is to motivate people to practice how to protect ourselves during earthquakes ("Drop, Cover, and Hold On"), and to get prepared at work, school, and home.



The ShakeOut began in southern California in 2008, to involve the general public in a large-scale emergency management exercise based on an earthquake on the San Andreas fault (the "ShakeOut Scenario"). ShakeOut communicates scientific and preparedness information based on 30 years of research about why people choose to get prepared. SCEC developed advanced simulations of this earthquake used for loss estimation and to visualize shaking throughout the region. In addition, SCEC also hosted the ShakeOut website (*www.ShakeOut.org*) and created a registration system where participants could be counted in the overall total. In 2008 more than 5.4 million Californians participated.

Growth of ShakeOut Drills
2008: 5.4 million
Southern California
2009: 6.9 million
California, New Zealand West Coast
2010: 7.9 million
California, Nevada, Guam
2011: 12.5+ million
CA, NV, GU, OR, ID, BC
130,000 in 5 Central Asia countries
Central US (AL, AR, GA, IN, IL, KY, MI, MO, OK, SC, TN)
2012: 15+ million (projected)
All above plus:
UT, WA, NC, VA, Puerto Rico,
New Zealand (nationwide), Tokyo
2013 and beyond:
AK, HI, American Samoa
Japan (nationwide)
Mexico, other Latin America
India, other Central Asian countries
US military bases/consulates

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

While K-12 and college students and staff comprise the largest number of participants, the ShakeOut has also been successful at recruiting participation of businesses, nonprofit organizations, government offices, neighborhoods, and individuals. Each year participants are encouraged to incorporate additional elements of their emergency plans into their ShakeOut drill. Surveys conducted after each drill are being analyzed and results will be presented in 2012.

7.9 million people participated in the 2010 ShakeOut, up from 6.9 million in 2009. Many participants renew their participation each year, with nearly 5.5 million being staff and students from K-12 schools. The rest are people and organizations that typically do not have earthquake drills. . In addition to registered participants, millions more see or hear about the ShakeOut via the news media. A list of over 300 print and online news stories is available on the ShakeOut web page, which in 2010 included a front-page photo in the New York Times. More than 500 TV and radio news stories across the state and country aired in the days surrouding the drill. A lengthy story on CBS Sunday Morning featured the ShakeOut in 2010.

The ShakeOut has been so successful that it has spread across the country, and even around the world. In October 2010 Nevada (110,000 participants) and Guam (38,000) joined with California, In January 2011, Oregon (38,000) and British Columbia (470,000) held drills to commemorate the anniversary of the 1700 Cascadia earthquake, and in April 2011 eleven states of the Central and Southern U.S. (Alabama, Arkansas, Georgia, Illinois, Indiana, Kentucky, Mississippi, Missouri, Oklahoma, South Carolina, and Tennessee) commemorated the 1811-1812 New Madrid earthquake bicentennial with a ShakeOut drill that grew to 3 million participations. Idaho held its first ShakeOut in October 2011 and Utah in April 2012. All of these areas are now holding ShakeOut drills annually (see *www.shakeout.org/regions*). SCEC provides consultation and manages the website for each drill. In 2011, 8.6 million Californian's participated along with 4 million additional people participated in *Great ShakeOut* drills worldwide (see chart).

Other areas considering ShakeOut drills include Washington (2012), Alaska (2014), and also Hawaii, Puerto Rico, New Zealand (2012), and Turkey. SCEC is now collaborating with colleagues in Tokyo, to help them coordinate their first ShakeOut on the one-year anniversary of March 2011 devastating earthquake and tsunami. ShakeOut is changing the way people and organizations are approaching the problems of earthquake preparedness.

The ShakeOut's impact has been more than just as a one-day event. Each registered participant receives periodic reminders leading up to the ShakeOut as well as drill instructions, preparedness information and access to a host of resources available on the ShakeOut website. Participants can download a soundtrack to play during their Drop, Cover, and Hold On Drill, ShakeOut posters and flyers, and web banners to place on their own websites encourage others to participate. ShakeOut flyers are available in many versions including custom flyers for schools, individuals and families, businesses, state and local government, retirement communities, museums and libraries and many other participant categories. Information is also available in Spanish, Korean, Vietnamese, and Chinese. The ECA has also created several drill manuals for schools, non-profits, businesses, and government agencies, respectively. Each version of the manual has information specific to the type of institution and has multiple drill levels, from a simple drill, to an advanced emergency simulation drill. These manuals include topics for discussion among the organizations leaders, evacuation procedures, and suggestions for making the simulation more engaging for employees or students. Access to these important earthquake resources is one of the most important benefits of being involved in the ShakeOut.

The ShakeOut has been the focus of significant media attention and has gone a long way to encourage dialogue about earthquake preparedness in California. Through the ShakeOut, the ECA does more than simply inform Californians about their earthquake risk. The ShakeOut teaches people a life-saving response behavior while fostering a sense of community that facilitates further dialogue and preparedness, and as such is an effective structure for advocacy of earthquake preparedness and mitigation.

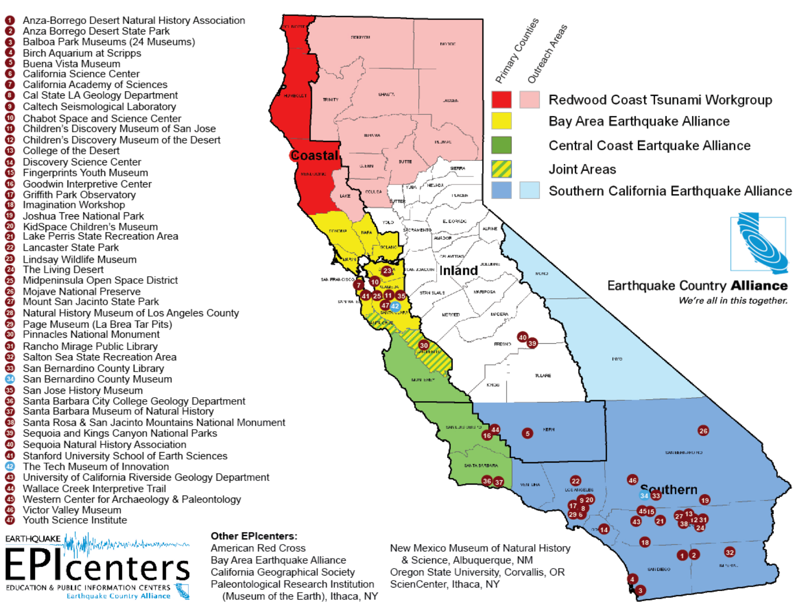
c. Development of the *EPIcenter* informal education network

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 sixty institutional partners, 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. The statewide Network is coordinated by SCEC Education Program Manager Robert de Groot with Kathleen Springer (San Bernardino County Museum) and Candace Brooks (The Tech Museum) coordinating Network activities in Southern and Northern California respectively.

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.



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

The *ShakeZone Earthquake Exhibit* at Fingerprints Youth Museum in Hemet, CA was developed originally in 2001, was redesigned in 2006, and was retired from display in 2011. The redesigned version of the exhibit is based on SCEC's *Putting Down Roots in Earthquake Country* handbook. Major partners involved in the exhibit redesign included Scripps Institution of Oceanography and Birch Aquarium at Scripps. With funding from the United Way and other donors ShakeZone will be expanded in 2010 to include a section on Earthquake Engineering.

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

As a result of the successful collaboration on *Living on the Edge*, SCEC was asked to participate in the development of SBCM's *Hall of Geological Wonders*. To be completed in 2012, the Hall is a major expansion of this important cultural attraction in the Inland Empire. One of the main objectives of the Hall is to teach about the region from a geologic perspective. The museum is devoting a large space to the story of Southern California's landscape, its evolution and dynamic nature. SCEC has played an ongoing advisory role, provided resources for the development of the earthquake sections of the exhibit, and will have an ongoing role in the implementation of educational programming

The most recent debut of an EPIcenter earthquake display is the *Earthquake Information Center* at the Rancho Mirage Public Library in Rancho Mirage, CA. This exhibit, created in partnership with the City of Rancho Mirage, features a computer screen showing recent worldwide and local earthquakes. Located in the computer resource room this exhibit also displays the seven steps to earthquake safety and components of a basic earthquake disaster supply kit. Many hundreds of local residents from the desert communities pass by the exhibit every day on their way to accessing other resources in the library. Recently, the Development of other EPIcenter exhibits and resource areas are occurring at the The California Science Center, Los Angeles, and the Natural History Museum of Los Angeles County.

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 1994, SCEC has provided 457 internships to undergraduate and graduate students (some students participate in multiple years and are counted each time). SCEC currently offers two summer internship programs (SCEC/SURE and SCEC/UseIT) and in 2010 completed a year-round program for both undergraduate and graduate students (ACCESS). These programs are the principal framework for undergraduate student participation in SCEC, and have common goals of increasing diversity and retention. In addition to their research projects, participants come together several times during their internship for orientations, field trips, and to present posters at the SCEC Annual meeting. Students apply for both programs at www.scec.org/internships.

- The *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. 221 internships have been supported since 1994 (150 since 2002).
- SCEC/SURE has supported students working on numerous projects in earthquake science, including the history of earthquakes on faults, risk mitigation, seismic velocity modeling, science education, and earthquake engineering.
- The *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). 167 students have participated since 2002.

- Our UseIT and CME experience identified a “weak link” in cyberinfrastructure (CI)-related career pathways: the transition from discipline-oriented undergraduate degree programs to problem-oriented graduate studies in earthquake system science. We worked to address this educational linkage problem through a CI-TEAM implementation project entitled the *Advancement of Cyberinfrastructure Careers through Earthquake System Science* (ACCESS) which ended in late 2010 with 29 internships having been awarded. The objective of the ACCESS project was to provide a diverse group of students with research experiences in earthquake system science that will advance their careers and encourage their creative participation in cyberinfrastructure development. Its overarching goal was to prepare a diverse, CI-savvy workforce for solving the fundamental problems of system science. Undergraduate (ACCESS-U) internships support CI-related research in the SCEC Collaboratory by undergraduate students working toward senior theses or other research enhancements of the bachelor’s degree. Graduate (ACCESS-G) internships supported up to one year of CI-related research in the SCEC Collaboratory by graduate students working toward a master’s thesis.

Since 2002, over 1100 eligible applications for SCEC internship programs were submitted, with 384 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 54 in 2011). On average 30% of interns were underrepresented minority students, with some years near 50%. A 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 more than 30% by the end of SCEC3.

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.

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

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

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

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

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

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

ShakeOut Curricula. 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, led by SCEC IT Architect Phil Maechling of USC, has supported the 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) 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.

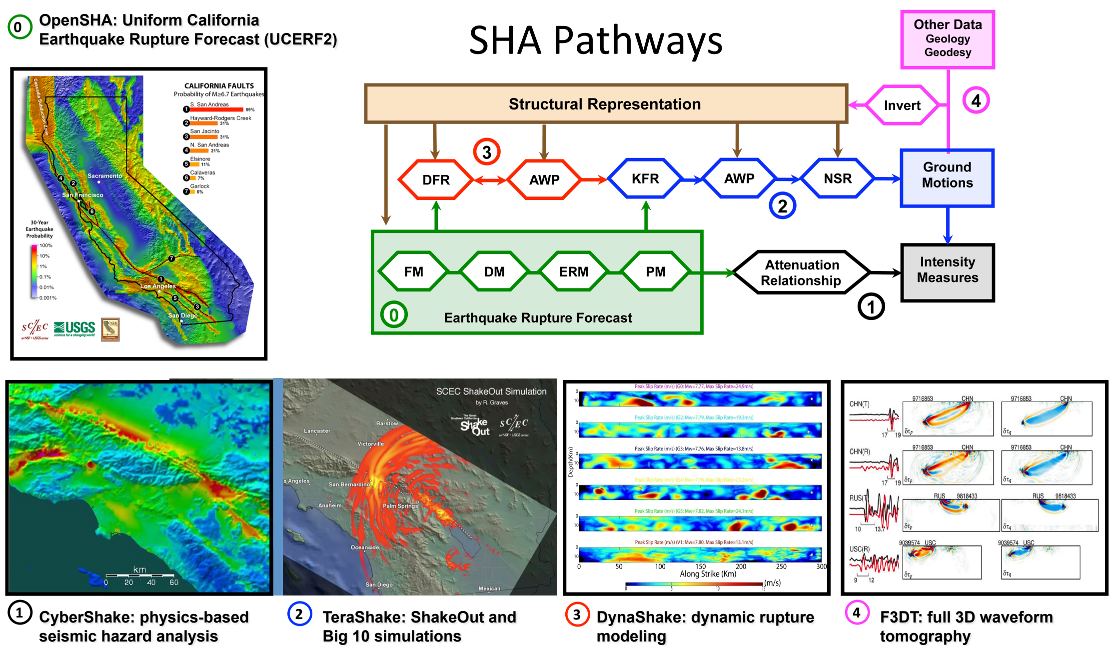


Figure 3.26. Computational pathways for physics-based ground motion prediction in the Community Modeling Environment (CME). (0) UCERF2 empirical earthquake forecast. (1) Cybershake PSHA by ground motion simulation. (2) large earthquake simulation (ShakeOut scenario) using kinematic fault rupture (KFM), 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.

The SCEC Community Modeling Environment (CME) [*Jordan and Maechling, 2003*] provided advanced cyberinfrastructure in support of collaborative earthquake system science research. The interdisciplinary CME collaboration enabled seismic hazard modeling projects that required computational and data resources beyond the capabilities of individual research groups. The SCEC computational pathways served as an organizational framework and a computational blueprint for improving ground motion forecasts on multiple time scales (**Fig. 3.26**). 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 [Olsen et al., 2006; Olsen et al., 2008] at 0.5Hz, ShakeOut [Olsen et al., 2009] at 1.0Hz, and 2009 Chino Hills [Mayhew and Olsen, 2010] at 2.0Hz. SCEC's highly scalable parallel codes include AWP-Olsen [Olsen, 1994; Olsen et al., 1997] and Hercules [Akcelic et al., 2003]. 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 [Foster and Kesselman, 1996] and advanced scientific workflow technology based on CondorDAG Manager [Thain et al., 2005], and Pegasus-WMS [Deelman et al., 2005]. Through collaboration with computer scientists, SCEC's CyberShake 1.0 map calculation [Callaghan et al., 2008] 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 [Deelman et al., 2006]. 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 [Catlett et al., 2007] and SC [SC09, 2009] conferences [Kwangyoon, 2009; Juve et al., 1009; Gunter et al., 2008] as well as at geoscientific conferences.

The CME delivery platforms, including OpenSHA, Broadband, and the Harvard USR webservices, deliver PSHA information to non-CME researchers. OpenSHA [Field et al., 2003] 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 [Field et al., 2009] and will be used in UCERF3 development. It will also be used in Global Earthquake Model (GEM) hazard processing. The SCEC Broadband platform delivers broadband synthetic seismograms to seismologists without HPC training. CME simulations require accurate structural models [Süss and Shaw, 2003], 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 [Maechling et al., 2009b] techniques have been adapted for use in the CSEP forecast modeling testing infrastructure [Zechar et al., 2009] and are being extended for use in SCEC's CISN ShakeAlert EEW testing project.

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V. Publications

The SCEC Publications database was initiated in 1991 for SCEC scientists to report publications relevant to SCEC research. The publications listed below are submitted by the SCEC researchers for the period of SCEC3.

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