Southern California Earthquake Center

Annual Report: Year 3

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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

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 three consecutive phases, SCEC2 (1 Feb 2002 to 31 Jan 2007), SCEC3 (1 Feb 2007 to 31 Jan 2012), and SCEC4 (1 Feb 2012 to 31 Jan 2017). This report outlines the accomplishments of the third year of the SCEC4 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 (Figure 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.

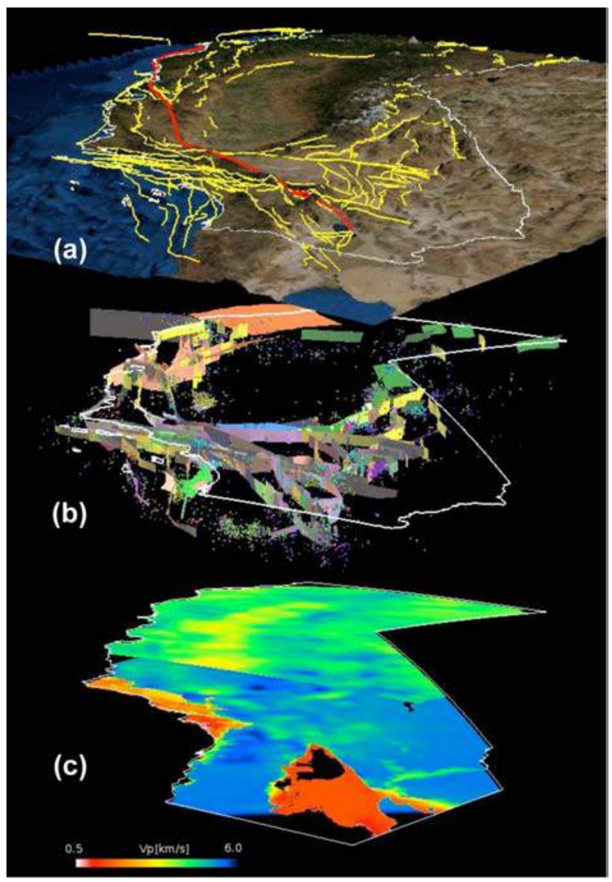


Figure 1.1. Perspective of California, looking northwest and showing elements of the Unified Structural Representation (USR): **(a)** traces of active faults (yellow lines) and the San Andreas master fault (red lines), **(b)** the statewide Community Fault Model (CFM), and **(c)** statewide Community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

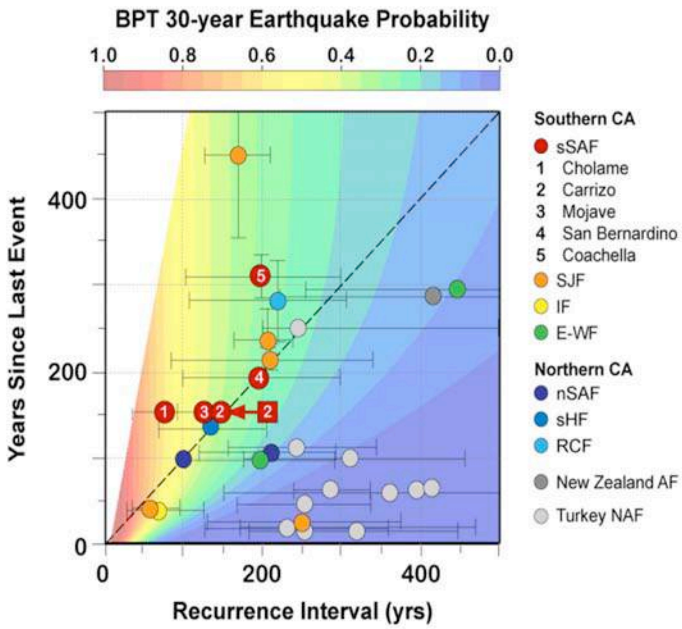


Figure 1.2. A plot of time since the last event vs. mean recurrence interval for sections of the southern San Andreas fault (red points) and other strike-slip faults in California and elsewhere. The arrow indicates the reduction in the mean recurrence interval for the Carrizo section implied by the new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

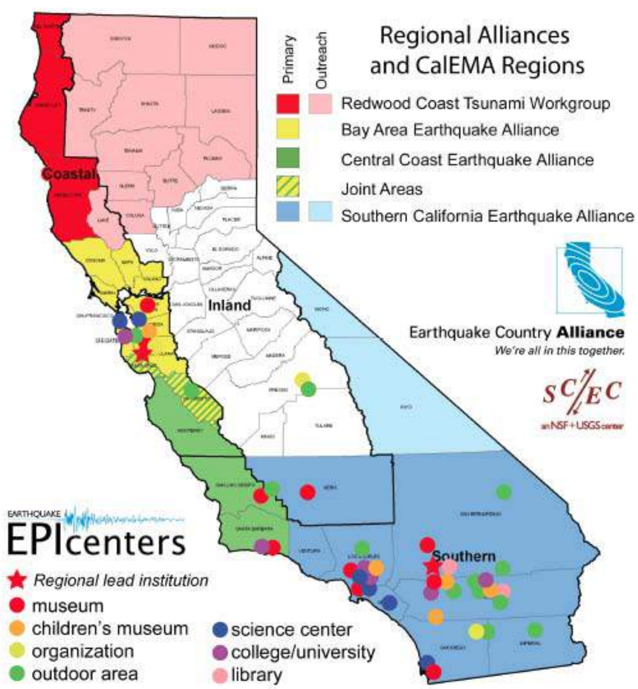


Figure 1.3. Four chapters of the Earthquake Country Alliance (colored areas) and locations of the EPIcenters (colored symbols), two key partnerships developed by the SCEC CEO program.

Carrizo section of the fault has been revised from a previous estimate of over 200 years to 140 years or less [Akciz et al., 2009; Akciz et al., 2010; Zielke et al., 2010; Grant et al., 2010], which compares to the 153-year interval since its last rupture (1857). The urgency of SCEC research has come from a recognition that the entire southern San Andreas may be "locked and loaded" (Figure 1.2).

SCEC research has led to important advances, including a Unified Structural Representation (Figure 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 (Figure 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 (Figure 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 SCEC4, the number of "core institutions" that commit sustained support to SCEC has grown to 17, and the number of "participating institutions" that are self-nominated through participation of their scientists and students in SCEC research is currently 50 (Table 1.1).

The SCEC community now comprises one of the largest formal research collaborations in geoscience. Among the most useful measures of SCEC size are the number of people on the Center's email list (1809 as of November 2014) and the registrants at the SCEC Annual Meeting (573 in 2014). Annual Meeting registrations for SCEC's entire 24-year history and other demographic information are shown in Figure 1.4.

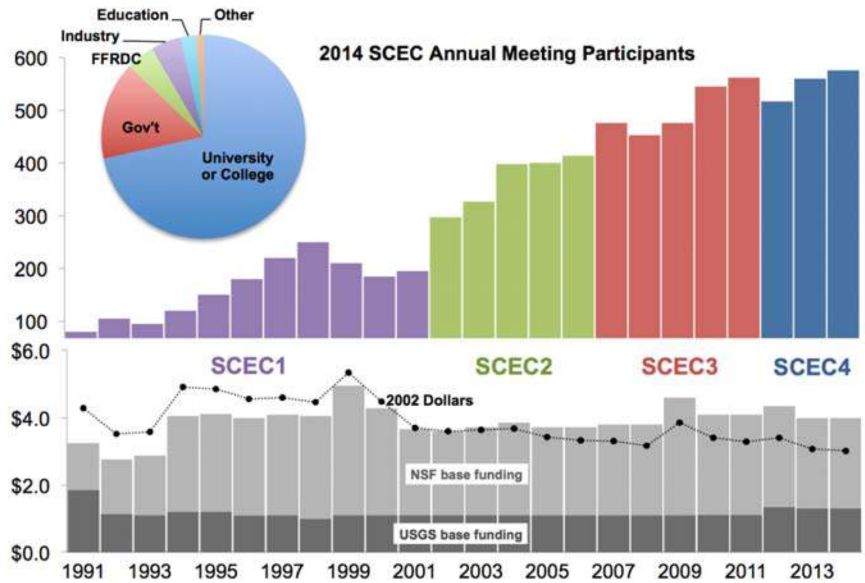


Figure 1.4. Colored bars show registrants at SCEC Annual Meetings, one measure of how the collaboration has grown during its 24-year history, 1991-2014. Pie chart shows the institutional profile for 2014 pre-registrants (573 total). The lower bar chart is the history of SCEC base funding in as-spent 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. SCEC 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. SCEC Member Institutions (November, 2014)

Core Institutions (17)	Participating Institutions (50)
California Geological Survey California Institute of Technology Columbia University Harvard University Massachusetts Institute of Technology San Diego State University Stanford University U.S. Geological Survey, Golden U.S. Geological Survey, Menlo Park U.S. Geological Survey, Pasadena University of California, Los Angeles University of California, Riverside University of California, San Diego University of California, Santa Barbara University of California, Santa Cruz University of Nevada, Reno University of Southern California (lead)	Appalachian State University; Arizona State University; Brown University; Cal-Poly, Pomona; Cal-State, Fullerton; Cal-State, Long Beach; Cal-State, Northridge; Cal-State, San Bernardino; California Geological Survey; Carnegie Mellon University; Colorado School of Mines; CICESE (Mexico); Cornell University; Disaster Prevention Research Institute, Kyoto University (Japan); ETH Zurich (Switzerland); Georgia Tech; Institute of Earth Sciences of Academia Sinica (Taiwan); Earthquake Research Institute, University of Tokyo (Japan); GNS Science (New Zealand); Jet Propulsion Laboratory; Lawrence Livermore National Laboratory; Marquette University; National Central University (Taiwan); National Chung Cheng University (Taiwan); National Taiwan University (Taiwan); Oregon State University; Purdue University; Smith College; SUNY Stony Brook; Texas A&M University; University of Alaska; UC, Berkeley; UC, Davis; UC, Irvine; University of Cincinnati; University of Illinois; University of Kentucky; University of Massachusetts; University of Michigan; University of New Hampshire; University of Kentucky; University of Oregon; University of Texas, Austin; University of Texas, El Paso; University of Utah; University of Wisconsin; URS Corporation; Utah State University; Utah Valley University; Western University (Canada) ;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 SoSAFE, with UNAVCO to transfer 125 stations of the SCIGN array to the PBO in Southern California, and with the Computational Infrastructure for Geodynamics (CIG), the Geosciences Network (GEON), and the Incorporated Research Institutions for Seismology (IRIS) to develop user-friendly software packages, IT tools, and educational products. The SCEC Communication Education and Outreach (CEO) program has steadily grown a diverse network of partnerships. The statewide ECA now comprises of hundreds of 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, non-governmental 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.

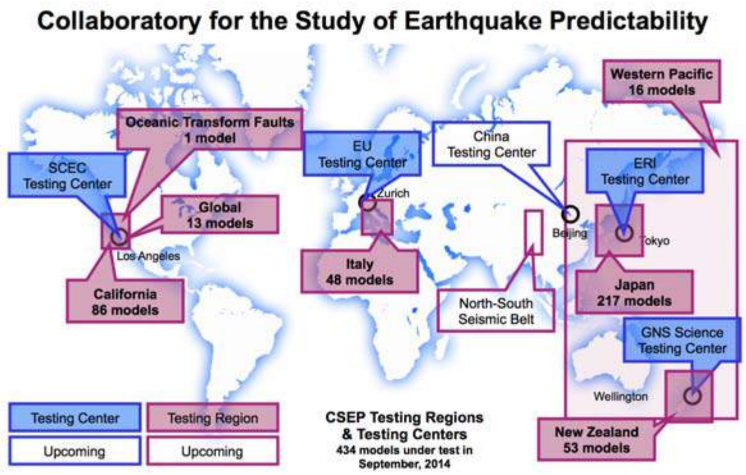


Figure 1.5. Map showing the worldwide distribution of activities developed under the Collaboratory for the Study of Earthquake Predictability (CSEP).

5. SCEC is an ***international leader*** that inspires interdisciplinary collaborations, and it involves many scientists from other countries. Currently, 10 leading foreign universities and research organizations are enrolled as participating institutions (Table 1.1), and others are involved through CSEP (Figure 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.

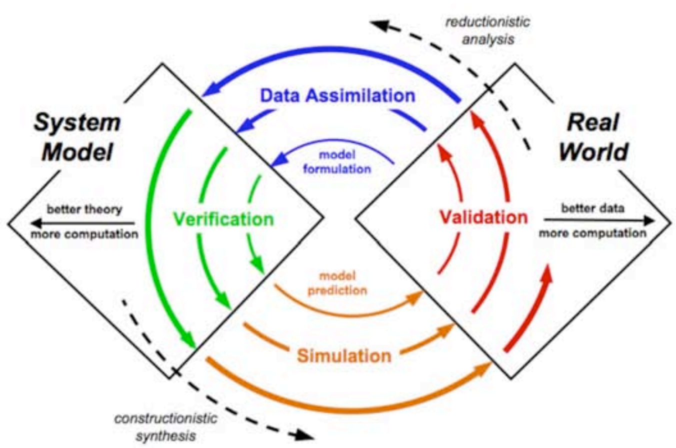


Figure 1.6. The inference spiral for system science, illustrating the improvement of system-level models through an iterated cycle of model formulation (blue), model verification (green), simulation-based prediction (orange), validation against observations (red), and data assimilation (blue). Verification 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 (Figure 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. As of November 2014, the institutional membership stands at 66, comprising 17 core institutions and 50 participating institutions (Table 1.1). SCEC institutions are not limited to universities, nor to U.S. organizations. The California Geological Survey has joined SCEC4 as a core institution, and URS Corporation will continue as a participation institution. We are very pleased that three of the major USGS offices—Menlo Park, Pasadena, and Golden—will remain core institutions represented by liaison (non-voting) members on the SCEC Board. There are currently 10 foreign institutions recognized as partners with SCEC through a growing list of international cooperative agreements. SCEC currently involves more than 600 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 Figure 1.4.

A. Board of Directors

Under the SCEC4 by-laws, each core institution appoints one member to the Board of Directors, and two at-large members were elected by the Board from the participating institutions. The Board is the primary decision-making body of SCEC; it meets 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. The liaison members of the U.S. Geological Survey are non-voting members. The Board is chaired by the Center Director, Tom Jordan, who also serves as the USC representative. Nadia Lapusta of Caltech serves as its Vice-Chair.

We also elect two people from our participating institutions as at-large members of the Board. These positions are currently filled by Judi Chester of Texas A&M and Roland Bürgmann of UC-Berkeley.

B. Administration

The Director, Tom Jordan of USC, acts 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 serves as the chief spokesman for the Center to the non-SCEC earthquake science community and funding agencies, appoints committees to carry out Center business, and oversees all Center activities.

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

The Associate Director for Administration, John McRaney of USC, assists the Center Director in the daily operations of the Center and is 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 is charged with developing an overview of SCEC operations and advising the Director and the Board. Since the inception of SCEC in 1991, the AC has played a major role in maintaining the vitality of the organization and helping its leadership chart new directions. The AC comprises 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 are drawn from academia, government, and the private sector. The Council meets annually to review Center programs and plans and prepare a report for the Center. AC reports are submitted verbatim to the SCEC funding agencies and its membership (Appendix C).

There have been several changes to the AC membership since last year. Gail Atkinson (Western University, Canada) has taken over from Jeff Freymueller (U. Alaska) as the AC chair, and we look forward to her leadership of the Council. Bob Lillie (Oregon State) and Susan Cutter (U. South Carolina) have rotated off the AC, and, at this meeting, we welcome three new members: Norm Abrahamson (PG&E), Warner Marzocchi (INGV, Italy), and Tim Sellnow (U. Kentucky).

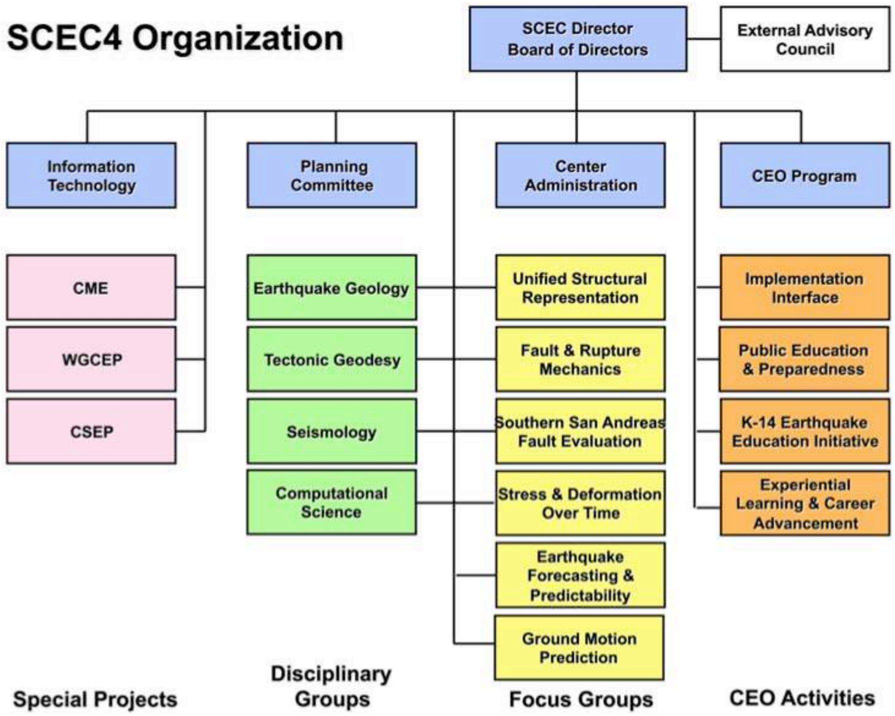


Figure 2.1. The SCEC4 organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects (pink), CEO activities (orange), management offices (blue), and the external advisory council (white).

D. Working Groups

The SCEC organization comprises a number of disciplinary committees, focus groups, special project teams, and technical activity groups (Figure 2.1). The Center supports disciplinary science through standing committees in Seismology, Tectonic Geodesy, and Earthquake Geology (green boxes of Figure 2.1). A new disciplinary committee in Computational Science has been added for SCEC4. They are responsible for disciplinary activities relevant to the SCEC Science Plan, and they make recommendations to the Planning Committee regarding the support of disciplinary research and infrastructure.

SCEC coordinates earthquake system science through interdisciplinary focus groups (yellow boxes). Four of these groups existed in SCEC3: Unified Structural Representation (USR), Fault & Rupture Mechanics (FARM), Earthquake Forecasting & Predictability (EFP), and Ground Motion Prediction (GMP). The Southern San Andreas Fault Evaluation (SoSAFE) project, funded by the USGS Multi-Hazards Demonstration Project for the last four years, has been transformed into a standing interdisciplinary focus group to coordinate research on the San Andreas and the San Jacinto master faults. A new focus group called Stress and Deformation Through Time (SDOT) has merged the activities of two SCEC3 focus groups, Crustal Deformation Modeling and Lithospheric Architecture and Dynamics. Research in seismic hazard and risk analysis is being bolstered through a reconstituted Implementation Interface (an orange box in Figure 2.1) that includes educational as well as research partnerships with practicing engineers, geotechnical consultants, building officials, emergency managers, financial institutions, and insurers. Mike Oskin of UC Davis is replacing Lisa Grant as the leader of the Earthquake Geology Disciplinary Group, and Whitney Behr of the University of Texas will be joining the group as co-leader.

SCEC sponsors Technical Activity Groups (TAGs), which self-organize to develop and test critical methodologies for solving specific problems. TAGs have formed to verify the complex computer calculations needed for wave propagation and dynamic rupture problems, to assess the accuracy and resolving power of source inversions, and to develop geodetic transient detectors and earthquake simulators. TAGs share a *modus operandi:* the posing of well-defined “standard problems”, solution of these problems by different researchers using alternative algorithms or codes, a common cyberspace for comparing solutions, and meetings to discuss discrepancies and potential improvements. There are currently five active TAGs: Ground Motion Simulation Validation (GMSV), Aseismic Transient Detection, Source Inversion Validation (SIV), Dynamic Rupture Code Validation, and Earthquake Simulators. This year we welcome Sanaz Rezaeian as co-leader of the Ground Motion Simulation Validation TAG.

E. Planning Committee

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

F. Communication, Education and Outreach

The Communication, Education, and Outreach (CEO) program is managed by the Associate Director for CEO, Mark Benthien of USC, who supervises a staff of specialists. The Experiential Learning and Career Advancement program and other education programs is managed by Robert deGroot of USC. The Implementation Interface between SCEC and its research engineering partners is managed by Jack Baker of Stanford University, who serves on the Planning Committee. This year we welcome Jason Ballmann, who has joined the CEO staff as Communciation Specialist.

Through its engagement with many external partners, SCEC CEO fosters new research opportunities and ensures the delivery of research and educational products to the Center’s customers, which includes the general public, government offices, businesses, academic institutions, students, research and practicing engineers, and the media. It addresses the third element of SCEC’s mission: *Communicate understanding of earthquake phenomena to the world at large as useful knowledge for reducing earthquake risk and improving community resilience*.

The theme of the SCEC4 CEO program is *Creating an Earthquake and Tsunami Resilient California*. CEO will continue to manage and expand a suite of successful activities along with new initiatives, within four CEO 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. SCEC Participants and Diversity Plan

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

- Currently, 17 of the 19 Board members are appointed by the core institutions, which are encouraged to consider diversity in their appointments of Board members. SCEC will continue this dialog and will continue to consider diversity in electing the Board’s members-at-large.

- Diversity will continue to be a major criterion in appointments to the Planning Committee. The Planning Committee has significant responsibilities in managing SCEC activities and serves as a crucible for developing leadership.
- Many women and minority students are involved in intern and other undergraduate programs; however, successively smaller numbers participate at the graduate student, post doctoral, junior faculty and senior faculty levels. SCEC has little control in hiring scientists and staff at core and participating institutions or in admitting students—institutional diversity goals can be encouraged but not mandated. However, diversity will be included in the criteria used to evaluate proposals and construct the Annual Collaboration Plan.
- We recognize that the current situation is not unique to SCEC and reflects historical trends in the geoscience and physical science communities. We believe SCEC can be most effective in changing these trends by promoting diversity among its students and early-career scientists; i.e., by focusing on the "pipeline problem". The SCEC internship programs have been an effective mechanism for this purpose (e.g., Table 4 of Appendix B**)**, and we will redouble our efforts to encourage a diverse population of students to pursue careers in earthquake science.

Tangible progress has been made in populating SCEC leadership positions with outstanding women scientists. Five women now serve on the Board of Directors (out of 19), including one as Vice-Chair of the Board. Four women currently serve as working group leaders or co-leaders, and they are participating visibly in the SCEC Planning Committee process. Women also have key roles in SCEC administration and CEO. CEO has contracted with women-owned small businesses in its ECA and ShakeOut activities. Some progress has also been made in terms of participation of minorities in SCEC leadership positions; two Board members and one Planning Committee members are Latino. Early-career scientists occupy SCEC leadership positions, and they have been active in pushing for increased diversity.

Recognizing that diversity is a long-term issue requiring continuing assessments and constant attention by the Center, the leadership has taken a number of concrete steps to improve its understanding of the composition and evolution of the SCEC community. Annual Meeting participants must register with SCEC, which includes providing demographic information. This allows us to continually assess the demographics of the community and track the career trajectories of students and early-career scientists. Table 2.1 shows a snapshot of the diversity of the SCEC Community as a whole. Diversity levels generally reflect historical trends in the geosciences, with much greater diversity among students than senior faculty. Participation of under-represented minorities is very low, again reflecting the Earth Sciences at large.

Table 2.1. Center database of SCEC participants in 2014.

	Race						**Ethnicity**		
	Native	Asian	Black	Pacific	White	NA	Latino	Not	NA
Faculty (Tenure-Track)	0	17	0	0	95	42	8	113	31
Faculty (Non-Tenure-Track)	1	1	0	0	4	1	1	3	2
Research Faculty (Tenure-Track)	0	5	0	0	11	5	0	14	7
Research Faculty (Non-Tenure-Track)	0	3	0	0	7	5	0	9	6
Postdoctoral Scholar or Fellow	0	9	0	0	20	15	3	24	17
Staff Scientist (Doctoral Level)	0	15	1	0	57	19	3	64	25
Staff (Research)	0	3	0	0	17	9	0	16	12
Staff (Management/Administration)	0	3	0	0	19	9	2	20	9
Staff (Communications/Outreach/PR)	0	1	0	0	5	0	0	7	0
Technician	0	0	0	0	1	0	0	1	0
Professional Geologist	0	2	0	0	6	7	2	5	8
Professional Engineer (Civil/Environmental)	0	1	0	0	5	1	0	5	2
Professional Engineer (Other)	0	0	0	0	2	1	0	2	1
Consultant (Engineering)	0	0	0	0	1	1	0	1	1
Consultant (Information Technology)	0	0	0	0	2	1	1	1	1
Consultant (Other)	0	0	0	0	2	2	0	2	2
Self-Employed	0	0	0	0	1	0	0	1	0
Emergency Manager	0	0	0	0	0	1	0	0	1
Teacher (K-12)	0	2	0	0	6	2	1	6	3
Student (Graduate)	0	30	0	0	89	37	7	104	45

Student (Undergraduate)	3	8	4	0	29	13	17	32	4
Student (High School)	0	0	0	0	0	1	1	1	0
Retired	0	0	0	0	2	0	0	2	0
Unemployed	0	0	0	0	1	1	0	0	1

	Gender			**Citizenship**		
	Male	Female	NA	US	Other	NA
Faculty (Tenure-Track)	126	25	1	95	25	34
Faculty (Non-Tenure-Track)	5	1	0	3	2	1
Research Faculty (Tenure-Track)	19	2	0	10	2	3
Research Faculty (Non-Tenure-Track)	12	3	0	10	3	3
Postdoctoral Scholar or Fellow	29	13	2	17	17	10
Staff Scientist (Doctoral Level)	71	20	1	55	20	17
Staff (Research)	18	8	2	16	3	9
Staff (Management/Administration)	23	8	0	23	6	2
Staff (Communications/Outreach/PR)	4	3	0	7	0	0
Technician	0	1	0	1	0	1
Professional Geologist	9	4	2	8	1	4
Professional Engineer (Civil/Environmental)	6	1	0	7	0	0
Professional Engineer (Other)	2	1	0	2	0	1
Consultant (Engineering)	2	0	0	1	0	1
Consultant (Information Technology)	2	1	0	3	0	0
Consultant (Other)	0	4	0	2	0	2
Self-Employed	1	0	0	1	0	0
Emergency Manager	0	1	0	1	0	0
Teacher (K-12)	4	6	0	8	1	0
Student (Graduate)	92	63	1	85	51	21
Student (Undergraduate)	26	27	0	47	3	3
Student (High School)	1	0	0	1	0	0
Retired	2	0	0	2	8	0
Unemployed	1	1	0	1	0	1

	Disability						
	None	Hearing	Visual	Mobility	Learning	Speech	NA
Faculty (Tenure-Track)	100	1	1	0	0	0	50
Faculty (Non-Tenure-Track)	5	0	0	0	0	0	1
Research Faculty (Tenure-Track)	9	0	0	0	0	0	12
Research Faculty (Non-Tenure-Track)	9	0	0	0	0	0	6
Postdoctoral Scholar or Fellow	23	0	0	0	0	0	21
Staff Scientist (Doctoral Level)	66	0	0	0	0	0	26
Staff (Research)	15	0	0	1	0	0	12
Staff (Management/Administration)	19	0	1	1	0	0	10
Staff (Communications/Outreach/PR)	6	0	0	0	0	0	1
Technician	1	0	0	0	0	0	0
Professional Geologist	10	0	0	0	0	0	5
Professional Engineer (Civil/Environmental)	6	0	0	0	0	0	1
Professional Engineer (Other)	2	0	0	0	0	0	1
Consultant (Engineering)	1	0	0	0	0	0	1
Consultant (Information Technology)	2	0	0	0	0	0	1
Consultant (Other)	3	0	0	0	0	0	1
Self-Employed	1	0	0	0	0	0	0
Emergency Manager	0	0	0	0	0	0	1
Teacher (K-12)	8	0	0	0	0	0	2
Student (Graduate)	111	0	0	0	1	1	43
Student (Undergraduate)	38	0	1	0	0	0	14
Student (High School)	1	0	0	0	0	0	0
Retired	2	0	0	0	0	0	0
Unemployed	1	0	0	0	0	0	1

H. International Collaborations

- **SCEC Advisory Council**. We have two international members, Chair Gail Atkinson of Western University in London, Ontario, Canada, and Warner Marzocchi of INGV in Rome.
- **CEO/ShakeOut**. SCEC collaborates with 60 countries on ShakeOut activities, including major partners Canada, Mexico, New Zealand, India, Japan, Italy, Afghanistan, Pakistan and the Philippines on holding ShakeOut drills. SCEC hosts the websites for all ShakeOut drills worldwide.
- **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 new partnership between SCEC and these two institutions was funded in 2012 by NSF under its Science Across Virtual Institutes (SAVI) initiative. This program established a Virtual Institute for the Study of Earthquake Systems (VISES), which will coordinate SCEC/ERI/DPRI collaborations in earthquake system science. A summer school was held in the United States in October 2014 for students of both countries. 41 students participated, primarily from U.S. and Japan universities. 5 students participated from other countries.
- **CSEP (Collaboratory for the Study of Earthquake Predictability).** SCEC founded CSEP in 2006. CSEP testing centers are now located at USC, ERI/Tokyo, GNS/New Zealand, ETH/Zurich, and CEA/China. Matt Gerstenberger and David Rhoades of the New Zealand testing center visited SCEC in September 2014.
- **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 next ACES meeting is scheduled for September 1-5, 2015 in Chengdu or Beijing, China.
- **ETH Zurich/Switzerland**. Stefan Wiemar and Jeremy Zechar are participants in the SCEC/CSEP projects. Daniel Roten participates in the source inversion validation project. Luis Dalguer and Seok Goo Song participate in the rupture validation project.
- **KAUST/Saudi Arabia**. Martin Mai is the leader in the Source Inversion Validation TAG.
- **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, Caroline Holden, and Susan Ellis participate in the ground motion modeling program.
- **Canterbury University/New Zealand**. Brendon Bradley participates in the SCEC ground motion simulation program.
- **GFZ Potsdam/Germany**. Danijel Schorlemmer (also at USC) is the co-leader of the CSEP special project. Olaf Zielke participates in the simulators project.
- **University of Bristol/UK**. Max Werner is the co-leader of the CSEP special project.
- **UNAM/Mexico**. Victor Cruz-Atienza works in the rupture validation project.
- **INGV Rome/Italy**. Emanuele Casarotti is collaborating with Carl Tape on modeling for the CVM. Warner Marzocchi is a member of the Scientific Review Panel (SRP) for the UCERF3 project.
- **University of Naples/Italy**. Iunio Iervolino participates in the Ground Motion Simulation Validation TAG under support from the European REAKT Project.
- **GSJ/Japan**. Yuko Kase works in the rupture validation program.
- **CICESE/Mexico**. John Fletcher and Jose Gonzalez-Garcia are collaborating with SCEC scientists in post earthquake studies of the El Mayor-Cucupah earthquake and its aftershocks and on modeling for the CGM.
- **Scottish Universities Environmental Research Centre Edinburgh/Scotland**. Dylan Rood collaborates on dating tsunami projects.
- **SCEC Annual Meeting**. The SCEC annual meeting continues to attract international participants each year. There were participants in the 2014 annual meeting from Australia, China, Japan, India, Mexico, Canada, France, Switzerland, Germany, Russia, Italy, Taiwan, Turkey, and New Zealand.

- **International Participating Institutions**. ETH/Zurich, CICESE/Mexico, University of Western Ontario, 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.
- **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 PI visited INGV in Rome in March and December for CSEP and OEF collaborations, 2) the PI attended the John Woodhouse symposium at Oxford in March, 3) the EGU assembly in Vienna, Austria in April, 4) the IUGG Committee on Mathematical Geophysics in Merida, Mexico in June, 5) the Varenna, Italy workshop on “Operational Earthquake Forecasting” in June, 6) the UJNR workshop in Sendai, Japan in October, 7) the REAKT workshop in Naples, Italy in December, and 8) the Hokudan Symposium in Awaji Island, Japan in January.

III. SCEC Accomplishments

A. Research Accomplishments

The fundamental research goal of SCEC4 is understanding how seismic hazards change across all time scales of scientific and societal interest, from millennia to seconds. The SCEC4 science plan was developed by the Center's Board of Directors and Planning Committee with broad input from the SCEC community in support of this goal. Through that process we identified six fundamental problems in earthquake physics:

Table 3.1 Fundamental Problems of Earthquake Physics

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

These six fundamental problems define the focus of the SCEC4 research program. They are interrelated and require an interdisciplinary, multi-institutional approach. During the transition to SCEC4, we developed four interdisciplinary research initiatives and reformulated our working group structure in accordance with the overall research plan. We have also formalized Technical Activity Groups (TAGs) in which groups of investigators develop and test critical methods for solving specific forward and inverse problems.

1. Seismology

The Seismology Group gathers data on the range of seismic phenomena observed in southern California and integrates these data into seismotectonic interpretations as well as physics-based models of fault slip. This past year's accomplishments include: Archival and distribution of seismic waveforms through the Southern California Earthquake Data Center; Refinement and updating of catalogs of earthquake locations and focal mechanisms and application of refined catalogs to the Community Fault Model; Analysis of foreshocks, aftershocks, and triggered events to examine changes in focal mechanism scatter, seismicity rates, and stress drops; Application of new tremor detection techniques and analysis of crustal structure in regions where tremor is observed; Development of new techniques to investigate scattering, site response, and attenuation using very dense array data.

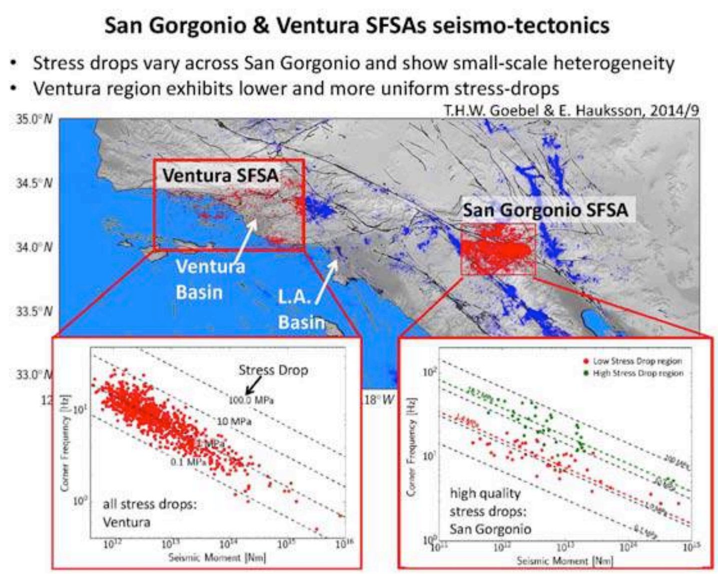


Figure 3.1. Stress drop comparison for Ventura basin region and selected areas in San Gorgonio Pass (from Goebel et al., in review, 2014).

a. Earthquake Locations, Focal Mechanisms, and Fault Representation Refinements: Revised earthquake location catalogs and focal mechanisms are now available for the period 1981-2013. Archived seismic waveforms, improved catalog, and focal mechanisms are routinely used by SCEC researchers to investigate earthquakes and fault processes. Refined catalogs were used in the updated, revised 3D faults in the Community Fault Model, including within the San Gorgonio Pass and Ventura Area Special Fault Study Areas. Revised 3D fault representations for the major active, through-going faults have been added. Goebel et al. (2014b) also investigated stress drop and other source properties in the SFSAs (Figure 3.1).

b. Seismic amplification in sedimentary basins from the ambient seismic field: The cities of Tokyo and Los Angeles are both located in sedimentary basins with the potential to trap and amplify seismic waves. Denolle et al. (2014a&b) studied basin amplification for both cities using the ambient seismic field. For Tokyo, they used data from Hi-Net deep-borehole seismometers distributed across central Honshu as virtual sources, and MeSO-Net shallow-borehole seismometers in the basin as receivers to map the basin response. For the Los Angeles study they used data from the Caltech/USGS Southern California Seismic Network as well as from a portable deployment. They found 3D basin effects that could be developed for ground motion prediction equations, but that the strength of basin amplification depends strongly on the direction of illumination by seismic waves. The ambient seismic noise approach is promising because it can be used to estimate expected long-period ground motions even though strong ground motion from earthquakes that would excite that shaking have not yet been recorded instrumentally.

c. Seismicity and Earthquake Physics: Several seismicity studies are underway to improve the catalog. Researchers are examining data from recent moderate earthquakes that occurred in 2014 in the Los Angeles Basin region including the M4.4 Encino and M5.1 La Habra sequences (Figure 3.2). Meng and Peng (2014) analyzed continuous waveforms recorded by SCSN and applied template matching to detect small events. They observed a seismicity increase in southern California following the 2010 Mw7.2 El Mayor Cucapah earthquake. They suggested that dynamic triggering caused seismicity increases over short time scales while static triggering caused increases in seismicity over a longer time scale. In a different study Chen and Shearer (2013) applied the refined southern California earthquake catalog to study earthquake triggering models and how they apply to swarms and foreshock sequences. They suggested that most small earthquake clustering is driven by fluid or slow slip, rather than inter-event stress triggering. In particular, foreshock sequences may be driven by an aseismic processes rather than by static stress triggering. Using a combined laboratory and seismicity catalog analysis, Sammis et al. developed a fully dynamic micromechanical damage model, which they used to simulate earthquake ruptures. Fault zone damage and propagation appear to be highly asymmetric. Their most recent efforts are directed towards generating spontaneous ruptures in very brittle material. Goebel et al. (2014a) also studied off-fault damage under laboratory conditions.

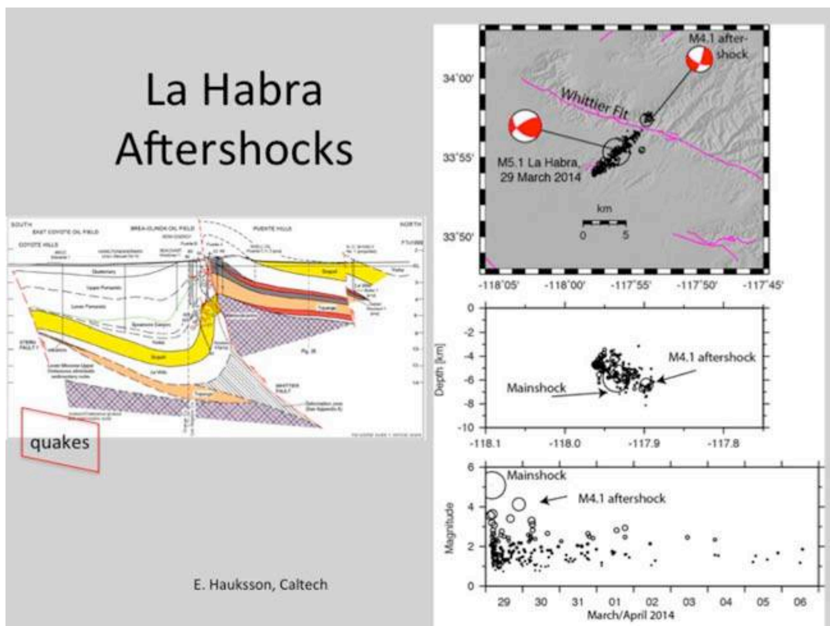


Figure 3.2. Overview of the La Habra earthquake sequence. (Left) Cross-section showing the location of the sequence relative to nearby fault structures. (Right top) Map view of the sequence (circles scaled by magnitude), focal mechanisms for the mainshock and largest aftershock, and major fault structures (pink lines). (Right middle) Cross-sectional view of sequence. (Right bottom) Evolution of the sequence through time. (From Hauksson, unpublished).

2. Tectonic Geodesy

Tectonic Geodesy activities in SCEC4 focus on data collection and analysis that contribute to improved earthquake response and to a better understanding of fault loading and stress transfer, the causes and effects of transient deformation, and the structure and evolution of fault zones and systems. Work by the SCEC community in the area of Tectonic Geodesy this year focused on four areas: development of a Community Geodetic Model (CGM), earthquake early warning, automated transient detection algorithms, and the analysis of high resolution geodetic data.

a. Community Geodetic Model: Densification of GPS arrays as part of Earthscope, rapidly growing volumes of InSAR data, and development of InSAR time series all motivated the development of a Community Geodetic Model (CGM). The CGM should improve geodetic studies of non-secular strain phenomena in Southern California, including post-seismic deformation. It will be distinct from the past SCEC Crustal Motion Map (CMM) because it will be time dependent and incorporate InSAR data to constrain both the vertical deformation field and details of regional deformation. The challenge of the CGM is to exploit the spatially sparse, temporally dense 3D GPS time series and spatially dense, temporally sparse InSAR line-of-site time series consistent with GPS time series in an appropriate projection. The recent launch of two new InSAR satellites will greatly facilitate the development of InSAR time series by providing more accurate and frequent observations from multiple look directions at both C-band and L-band. SCEC funded research in support of the CGM includes data collection to fill gaps in coverage, assessment of appropriate modeling approaches, and exploration of ways to mitigate noise and merge datasets.

California State University San Bernardino and University of Arizona researchers have continued a field program started in 2002 that involves undergraduates and local teachers to collect and interpret GPS data in the San Bernardino mountains and surrounding area where previous coverage was sparse. Researchers at UC Riverside and MIT are combining campaign GPS data from their field surveys with data from continuous networks and archives, to investigate the degree to which the San Jacinto Fault (SJF) slip rate varies along-strike. Continued efforts by MIT scientists to merge PBO and USGS continuous GPS solutions for southern California will prove vital in development of the CGM.

Ongoing work aims to mitigate decorrelation in InSAR images that have experienced large coseismic offsets. Research at Cornell is focused on integrating InSAR and GPS data into time varying deformation maps by mitigating the effects of atmospheric noise. Scientists at JPL are applying InSAR time series analysis techniques to 18 years of data from southern California to produce line-of-sight velocities showing time-varying deformation (Figure 3.3). Modeling of dense GPS and InSAR velocity transects crossing the Southern San Andreas Fault (SAF) by investigators at SIO and San Diego State University has revealed evidence for along-strike variations in the width and depth of the creeping segment (Figure 3.4).

The 2010 El Mayor Cucapah earthquake has provided opportunities to investigate crust and upper mantle rheology through observations of postseismic deformation. Data collected through a collaboration between Scripps Institution of Oceanography (SIO), UC Riverside, and CISESE resulted in an improved understanding of the afterslip following the El Mayor Cucapah earthquake (Figure 3.5).

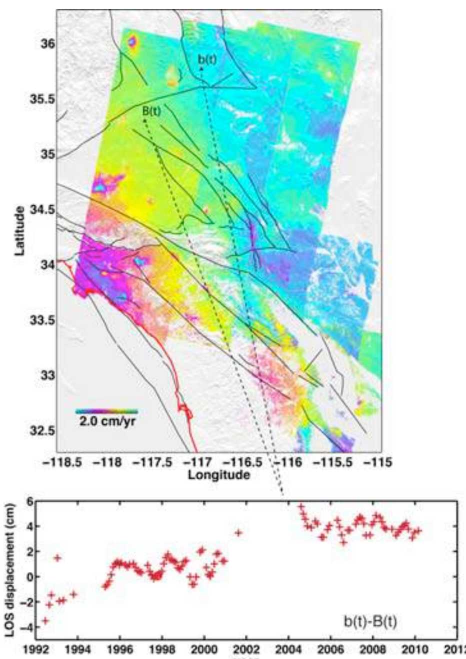


Figure 3.3. InSAR time series. Mosaic view of the mean LOS velocity map of descending tracks 170, 399, 127, 356, and 84 from combining ERS-1/2 and Envisat data. Note that certain tracks are displayed with ERS LOS map only to not show coseismic deformation signals of the Hector Mine earthquake. Differential LOS time series between b(t) and B(t) across East California Shear Zone show long term transient that is likely related to postseismic relaxation of Lander and Hector Mine earthquakes.

Scientists at Appalachian State University, UC Riverside, JPL, and Harvard coordinated efforts to constrain fault slip rates and patterns of interseismic deformation using GPS and InSAR in the western Transverse Ranges with a focus on the Ventura Special Fault Study Area.

Ongoing collaborative activities of the CGM include:

1. First SCEC Community Geodetic Model (CGM) workshop (Menlo Park, CA, May, 2013): This workshop (presentations available at: *http://www.scec.org/workshops/2013/cgm*) addressed major problems and plans for generation of a joint GPS-InSAR 3-D deformation field product. The workshop was summarized in a Meeting report in EOS, Volume 94, Number 35, 2013.
2. Focus Groups: We formed GPS and InSAR focus groups that will assess and validate potential time series generation approaches for the individual data types.
3. InSAR exercise: We initiated an exercise within the InSAR community to process data for a particular frame in Southern California, for the purposes of comparison of the result of different approaches, validation against GPS data and data from overlapping tracks, and assessment of the appropriate errors to use in joint GPS-InSAR efforts.
4. Second SCEC Community Geodetic Model (CGM) workshop – A second GPS/InSAR workshop was held prior to the 2014 SCEC Annual Meeting. See workshop report at *http://www.scec.org/workshops/2014/cgm/index.html*.

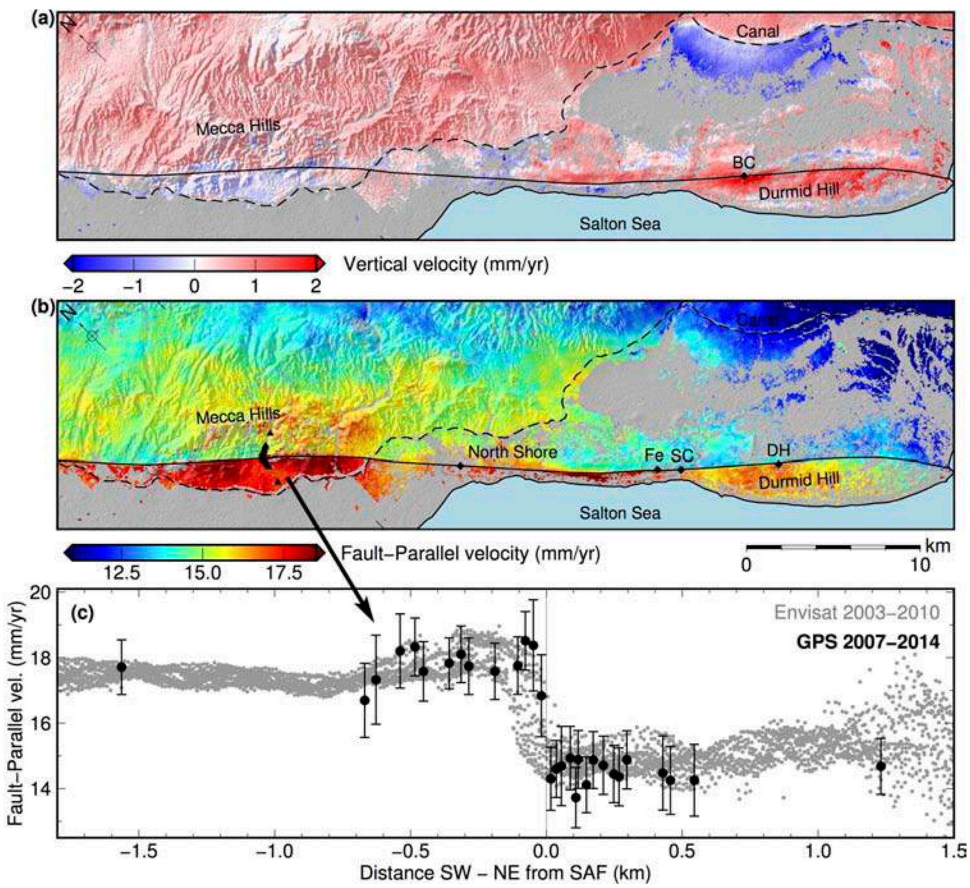


Figure 3.4. Refined near-fault creep measurements. Envisat InSAR and survey-mode GPS observations reveal pattern of uplift and shallow fault creep along the southernmost San Andreas. (a) Vertical ground velocity from Envisat, using a combination of ascending (Track 77) and descending (Track 356) InSAR observations. BC denotes Bat Caves Buttes leveling line, which recorded similar uplift rates [Sylvester et al., 1993]. Note areas of subsidence related to hydrologic processes. (b) Fault-parallel ground velocity from Envisat. Diamonds indicate creepmeters at North shore, Ferrum (Fe), Salt Creek (SC), and Durmid Hill (DH), operated by Univ. Colorado at Boulder. Triangles show locations of GPS monuments at Painted Canyon. (c) Comparison of InSAR velocities with GPS at Painted Canyon. InSAR data are in agreement with ground-based

observations, and reveal that creep occurs along the entire fault segment and is localized on the fault trace only at Durmid Hill and Mecca Hills, where locally the fault strike is transpressive. At Bombay Beach and North Shore, decreased normal stress may lead to distributed yielding; in these areas creep is distributed across a 1-2 km wide zone. (Lindsey et al., J. Geophys. Res., in review).

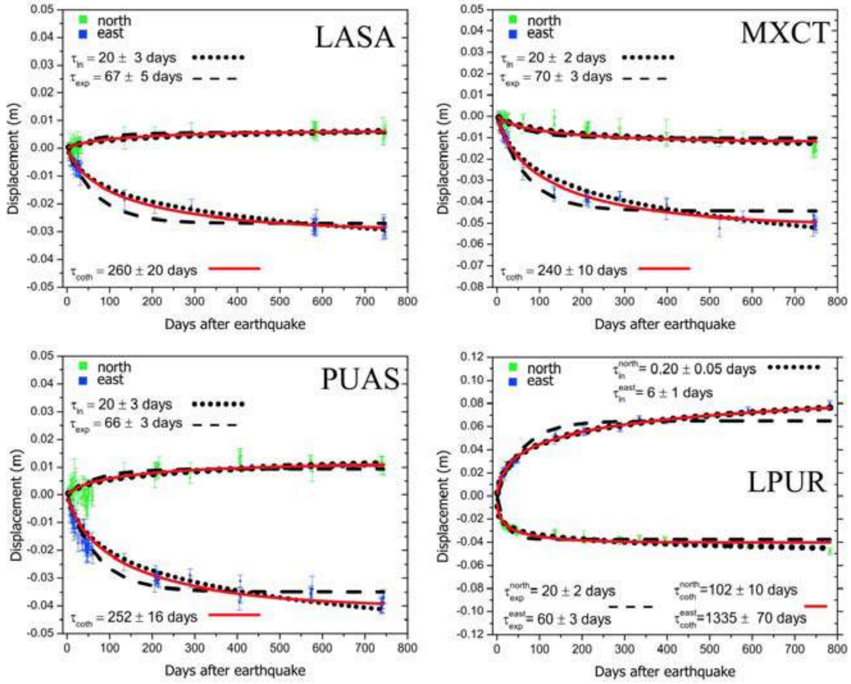


Figure 3.5. Surveys of El Major Cucapah postseismic deformation. Within one day of the rupture scientists from CICESE, UCSD and UCR began campaign surveys in the near field of the rupture zone and continued these measurements for more than 3 years to capture postseismic transients [Gonzales-Ortega et al., 2014]. Daily GPS positions for the four sites closest to the earthquake rupture. North and east components of displacement are denoted by green and blue symbols, respectively. Best-fitting exponential, logarithmic, and hyperbolic cotangent functions are indicated by black dashed, black dotted, and solid red lines, respectively. Also shown are the corresponding relaxation times (τ).

b. Transient Detection and Early Warning: Scientists at UCSD made progress in estimating the magnitude of an emergent earthquake by combining seismometers and GPS sensors to measure the full spectrum of the near-field strong motions. GPS-seismometer units will be deployed at several CRTN stations in southern California during the project period.

Scientists at MIT are refining a transient detection algorithm and have submitted algorithms to the Collaboratory for the Study of Earthquake Predictability (CSEP). They are now running operationally. A transient detection algorithm based on time-dependent displacement gradient fields and statistical analysis of measured strain anomalies was developed at Stony Brook University and is now implemented in the CSEP system. Scientists at Woods Hole Oceanographic institution are studying the 22-year history of aseismic creep transients on the Superstition Hills Fault. They found that models with significant heterogeneity in the shallow frictional properties of the fault are consistent with both the afterslip and interseismic creep events observed on the Superstition Hills Fault.

Scientists at Stanford University continue to refine their transient detection algorithm through an improved understanding of the network noise processes. They have selected a set of 20 GPS stations over stable North America where the glacial isostatic signal provides a known, large-scale secular signal. A better characterization of the noise in this stable environment will help to refine the network-based transient detection algorithms being deployed in Southern California.

c. High-resolution Geodetic Measurements: PBO borehole strainmeters in the Anza region and laser strainmeters at the Pinon Flat Observatory provide high-resolution observations of transient behavior associated with southern California earthquakes. Triggered aseismic slip on the San Jacinto fault has been inferred from these data to have occurred following the 2005 Anza earthquake and again after the El

Mayor Cucapah earthquake. Transient deformation consistent with aseismic slip during 2010 – 2011 at the location of the 2005 earthquake was also observed. A March 2013 M 4.7 event on the San Jacinto fault near Anza triggered strain rate changes indicative of fault parallel shear with short duration (1–2 hour) slip accelerations. Further analysis and modeling will be required to investigate causes of observed variability in the occurrence and timing of strain recorded at different locations following these events.

3. Earthquake Geology

The Earthquake Geology Group coordinates diverse field-based investigations of the Southern California natural laboratory. The group contributes to earthquake response efforts and supports field observations related to many other focus groups. Among the goals of Earthquake Geology are the determination of long-term slip rates and long, multi-event paleoseismologic records that have a high impact on seismic hazard assessments. In support of these efforts the Earthquake Geology Group coordinates geochronology infrastructure resources that are shared among SCEC-sponsored projects.

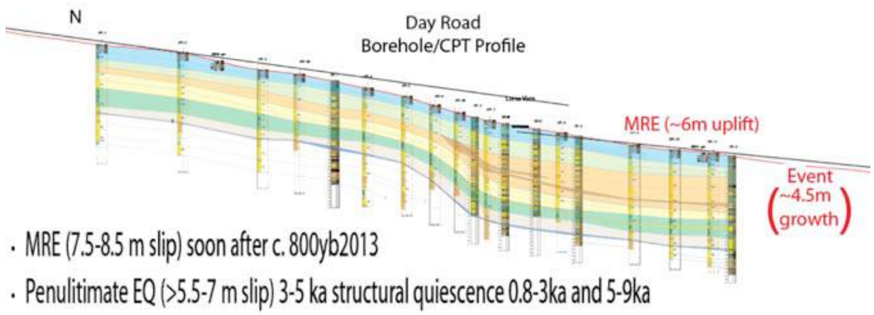


Figure 3.6. Comparison of growth strata above tip of Ventura fault at Day Road and Brookshire Avenue, from Grenader, Dolan et al.

a. Ventura Special Fault Study Area: A self-consistent history of large uplift events is emerging for the Ventura anticline - likely as part of large (>M7.5) reverse-fault ruptures along the northern margin of the Ventura basin. Rockwell et al. identified four Holocene emergent terraces formed in the past 6000 years. Each terrace records uplift of the fold crest by 4 to 6 meters. Grenader, et al. have identified similar magnitudes of coseismic folding above the propagating tip of the Ventura fault (Figure 3.6). Timing of the last event is consistent between sites, circa 800 years ago. However, the penultimate event timing is demonstrably older at the Ventura Day Road site than at Pitas point, which suggests that a hiatus in deposition could obscure an event at the former. New work, in progress along Ventura fault should reveal slip-rate and incremental slip information that will help to resolve this issue.

Coseismic uplifts of the Ventura anticline imply at least 5.5m of slip per event on the underlying Ventura-Pitas Point reverse fault (Figure 3.7). This implies that the Ventura fault ruptured together with adjacent structures. Structural models based on seismic reflection, mapping, and petroleum well data (Hubbard et al., 2014) reveal how structures underlying the Ventura anticline link to a larger, and more continuous reverse fault system bounding the northern margin of the Ventura basin. An earthquake near M 8 is possible on this system. Large events likely involve significant deformation offshore in the Santa Barbara basin as well. Evidence to support this is emerging from paleo-tsunami deposits and sudden submergence of the Carpenteria marsh documented by Simms et al. Tsunamis may also arise from other regional sources or distant earthquakes. New work by Berelson et al. hypothesizes that key terriginous layers in the Santa Barbara basin could represent scour of the shallow shelf and shoreline due to tsunami run-up, and that this basin could preserve a long (ca. 100kyr) record of tsunamis in coastal California.

b. High-Resolution Topography: The SCEC Geology Group continues to advance frontiers in high-resolution topography. The 2013 VISES-SCEC Workshop on High-Resolution Topography held in Tokyo, led to joint analysis of two Japanese dip-slip earthquakes with pre- and post-event airborne lidar scans. Nissen et al. (in press) describes 3-D displacement fields from these events that are smooth within 100m of the surface rupture (Figure 3.7). Structure from Motion (SfM) is a low-cost 3-D imaging technique using photographs of the features taken from multiple distances and orientations (“the motion”). The scene “structure” is computed from the matched features in the images and is the best 3D model explaining their relative positions. The low cost and ease of collection of SfM data will revolutionize post-earthquake geologic studies by digitally preserving ephemeral offset features as 3D models.

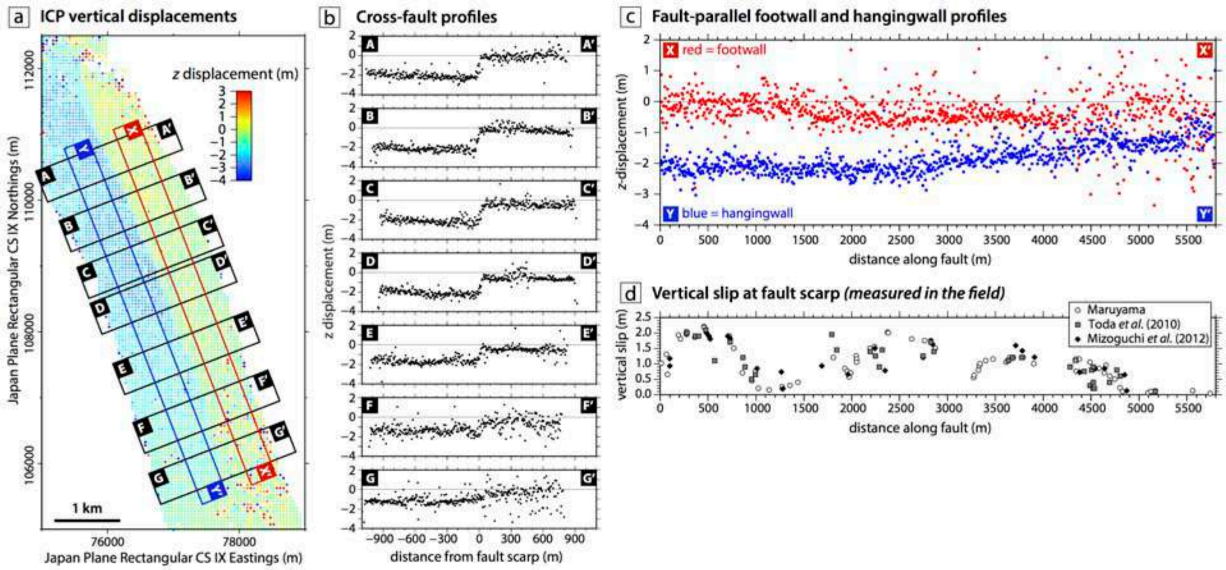


Figure 3.7. Differential lidar results from the 2011 Fukushima (normal-faulting) earthquake, from Nissen et al. in press.

c. Eastern California Fault System: Research in the eastern California shear zone (ECSZ) focuses on the related problems of geologic-geodetic slip-rate discrepancies and temporal variations of strain release across fault systems. Fieldwork by Dolan et al., coupled with advances in OSL dating by Rhodes et al., clearly reveal slip-rate variation via earthquake clustering on the Garlock fault. Similar clustering behavior is inferred for the dextral faults of the ECSZ. An important component of this problem is the discrepancy between geologic and geodetic slip rates in eastern California, which may be in large part due to distributed deformation (e.g. Dolan and Haravitch, 2014). Modeling of the ECSZ by Herbert et al. (2014a) suggests substantial slip is lost to distributed deformation around fault tips within the Mojave block (see also Herbert et al., 2014b). Figure 3.8 shows modeling by Grette and Cooke, using structural data from Selander and Oskin, that shows how newly documented active reverse faulting in the ECSZ contributes to distributed deformation by causing uplift and focusing strain at fault intersections and terminations.

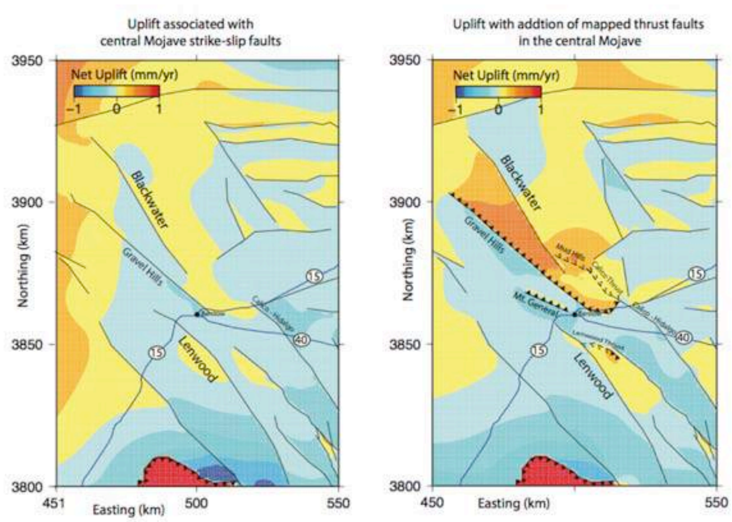


Figure 3.8. (a) Distributed deformation model of the eastern California shear zone predicts zones of uplift and subsidence, from Grette and Cooke. Select Publications.

4. Computational Science

The Computational Science Disciplinary Group promotes the use of advanced numerical modeling techniques and high performance computing (HPC) to address the emerging needs of SCEC users and application community on HPC platforms.

a. Physics of Earthquake Processes: Producing realistic seismograms at high frequencies will require improvements in anelastic wave propagation engines, including the implementation of nonlinear behavior. Nonlinear material behavior has been implemented in both CPU- and GPU-based versions of AWP-ODC. Results on its effect of the 2008 M 7.8 ShakeOut earthquake scenario have shown that nonlinear behavior could reduce ground motion by up to 70% compared to the linear viscoelastic solutions (Figure 3.9).

Recent earthquake simulations suggest that modeling shorter wavelengths at high frequencies will require significant changes to existing models. There is not sufficient data density to facilitate development of deterministic models at the resolution required for high-frequency simulations. To resolve near-surface small-scale amplification effects, material heterogeneities in the models can be incorporated through stochastic perturbations to velocity models. Withers et al. (2013) show that fine-scale heterogeneities have a significant effect on the ground motion, especially at high frequencies (> 2 Hz), but also at low frequencies. They are currently pursuing various alternatives to incorporate fine-scale irregularities into material models based on statistical characteristics observed in well-log data.

The quality of ground motion simulations at high frequencies depends strongly on the attenuation structure. Measurements of 1/Q in California and elsewhere show that it is roughly constant below ~ 1 Hz, but decreases rapidly at higher frequencies. 1/Q has usually been expressed as a functional of the local *S*- and *P*-wave velocities. The attenuation structure of the upper crust, however, is highly heterogeneous and poorly known. Furthermore, recent investigations (Wang & Jordan, 2014) show that we will need to develop attenuation models that are also depth-dependent.

b. Development of SEISM Framework: High- and mid-level software elements developed by SCEC have been integrated into the SEISM software for physics-based SHA. The components include CyberShake, High-F, F3DT, Broadband platforms, and a community IO library. SEISM supports the use of petascale computers to generate and manage large suites of earthquake simulations for physics-based PSHA, as well as advanced research on rupture dynamics, anelastic wave scattering, and Earth structure. A test version of SEISM-IO has been developed to manage the requirements of petascale simulations. SEISM-IO is built on top of the available high-performance IO libraries consisting of MPI-IO, ADIOS, HDF5 and PnetCDF. The users only need to determine and communicate with API through the abstract data space. Both Fortran and interfaces have been completed and tested using the wave propagation AWP-ODC solver against validated modeling results and observed data on multiple systems, including Blue Waters and XSEDE Stampede systems. SEISM-IO demonstrated a comparable I/O rate to manually optimized I/O performance of AWP-ODC up to 32,768 cores on Blue Waters XE6 nodes (Poyraz et al., 2014).

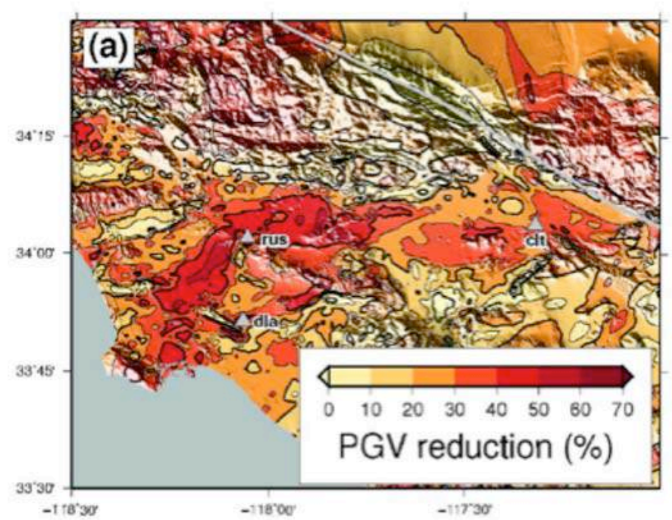


Figure 3.9. Reduction in horizontal peak ground velocities (%) obtained for one nonlinear simulation of the ShakeOut scenario by Roten et al. (2014). The comparison is relative to a linear anelastic solution, which shows reductions up to 70% in peak ground velocity (PGV).

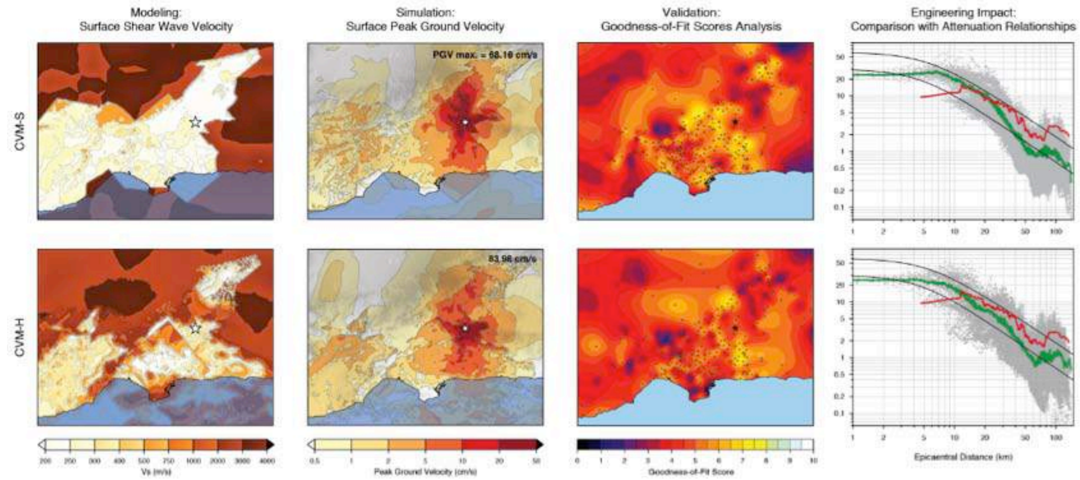


Figure 3.10. Summary results for simulations for the Mw 5.4 2008 Chino Hills earthquake (star) using different velocity models, CVM-S (top row) and CVM-H (bottom row), that connect geoscience modeling to engineering applications. Columns show (1) surface shear wave velocities for each model; (2) peak horizontal ground velocities; (3) goodness-of-fit metrics comparing synthetics with data at >300 recording stations (lighter colors indicate better fit); and (4) comparison with attenuation relationships used by engineers to estimate peak ground velocity. Red line is the average observed value from Chino Hills; two black lines are upper and lower bound of the empirical relationships, and the green line shows the average surface values from the simulation (gray point cloud). Simulations were done using the Hercules code by Taborda and Bielak (2013, 2014).

c. Development of Accelerated HPC Codes: SCEC has developed Hercules-GPU - an octree-based parallel finite element earthquake simulator, using CUDA/MPI. The GPU implementation has been validated against earthquakes that combine Broadband platform, UCVM and High-F platforms. The Hercules GPU was validated against the La Habra earthquake using multiple velocity models including CVM-S4.26 on Titan (Figure 3.10). The largest production problem size tested thus far was a 1 Hz simulation of the 2008 Chino Hills earthquake, with attenuation, using 128 Titan XK7 GPU nodes. This represents a high level of agreement and validates the GPU approach. The acceleration ratio of the GPU implementation with respect to the CPU is of a factor of about 2.5x.

d. Computationally Efficient Boundary Element Solvers for Quasi-Dynamic Earthquake Simulations: Bradley developed open-source software that greatly improves the efficiency of quasi-dynamic simulations. H-matrix compression permits Boundary Element models relating fault slip and traction on N elements in O(N), rather than O(N^2), time. The second package allows the same speed-up with non-uniform meshing, as required with non-uniform friction or fault normal stress, without sacrificing accuracy. Figure 3.11 shows a snapshot in time of a slow slip event propagating bilaterally through a field of randomly distributed circular asperities, providing a possible explanation for tremor that accompanies slow slip events. Each asperity is resolved with about 14 elements along the diameter.

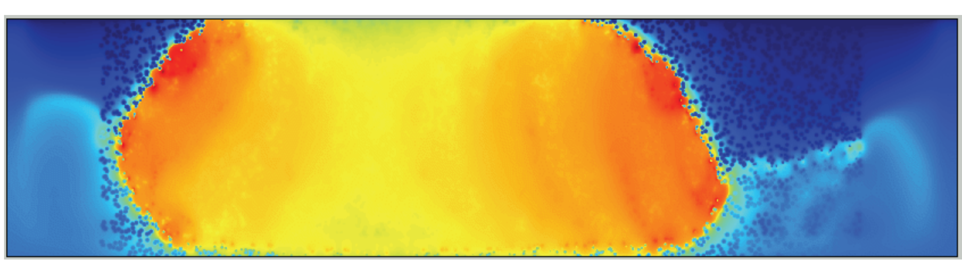


Figure 3.11. Quasi-dynamic simulation of slow slip event, with tremor and low frequency earthquakes occurring as small, randomly distributed asperities rupture. Computational advances permit such simulations, involving ~ 10^6 elements on a single desktop computer. Plot shows $\log_{10}$(slip speed) on fault plane. The asperity failures produce both tremor and back-propagating creep waves (Bradley and Segall).

e. Numerical Methods for Seismic Wave Propagation and Rupture Dynamics in Complex Geometries: Future SCEC activities will require simulation of dynamic ruptures on geometrically complex, branching fault networks in 3D. This can be done most readily using unstructured meshes. Yet within the same simulation framework it is desirable to accurately capture wave propagation to far-field stations; this is best done with structured meshes. To meet both objectives, Kozdon and Wilcox developed a provably stable and high-order-accurate mesh coupling strategy for both finite difference and discontinuous Galerkin methods (Figure 3.12). They are also exploring the use of local time stepping methodologies as well as emerging many-core (GPU) technologies to improve time-to-solution for large rupture simulations.

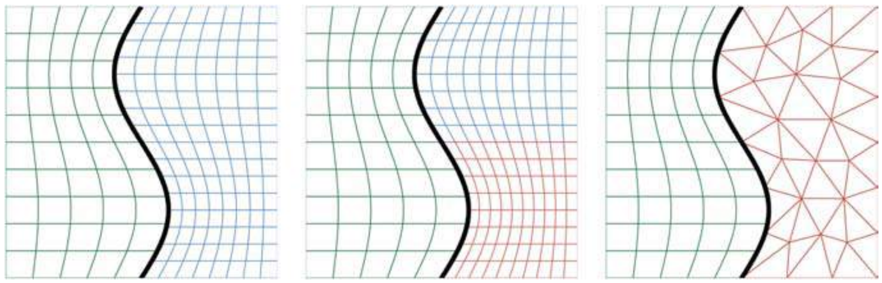


Figure 3.12. Three examples of new mesh couplings supported by a provably stable method developed by Kozdon and Wilcox. (While illustrated here in 2D, the method is implemented in 3D.) In addition to allowing the coupling of arbitrary finite difference meshes, their coupling supports the connection of high-order finite difference methods and unstructured discontinuous Galerkin methods. These developments will help support the dynamic rupture simulation of realistic networks of faults with unstructured grid methods being used around the complex geometry and structured grids being used to propagate waves for long distances.

f. Supercomputing Activities: In 2014 SCEC was granted a record allocation of 500 million core-hours (SUs) on NSF and DOE supercomputers including NCSA Blue Waters, XSEDE and DOE INCITE systems. These allocations support 1) Improved resolution of dynamic rupture simulations by an order of magnitude and investigation of the effects of realistic friction laws, geologic heterogeneity, and near-fault stress states on seismic radiation; 2) Simulations of strong ground motions to 10 Hz for investigating the upper frequency limit of deterministic ground-motion prediction; and 3) Computing and validating PSHA maps.

A significant accomplishment this year was to enable the CyberShake14.2 calculations on Blue Waters at NCSA. The reduced time of this CyberShake study, from 1467 to 342 hours, was a notable performance enhancement for the calculation of the hazard maps using four models, including the new CVM-S4.26. The CyberShake workflow software stack, including the Pegasus Workflow Management System (Pegasus-WMS, which includes Condor DAGMan), HTCondor, and Globus GRAM, with Pegasus-MPI-Cluster successfully migrated to Blue Waters this year.

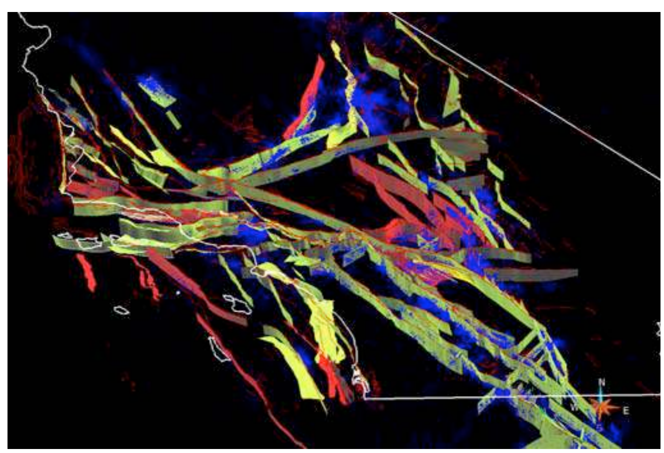


Figure 3.13. New release of CFM (5.0) that includes additional sources and refined versions of faults based on Qfault traces and relocated earthquake and focal mechanism catalogs (e.g., Yang et al., 2012; Hauksson et al., 2012). Faults in red are new representations; others are refined using Qfault traces and seismicity.

5. Unified Structural Representation (USR)

The Unified Structural Representation (USR) Focus Area develops models of crust and upper mantle structure in California for use in a wide range of SCEC science. These efforts include the development of Community Velocity Models (CVM-S, CVM-SI, & CVM-H) and Community Fault Models (CFM, CFM-R, SCFM), which together comprise a USR. In partnership with other working groups in SCEC, the USR group also supports the evaluation and improvement of these models through ground motion simulations, 3D waveform tomography, earthquake relocations, and fault systems modeling.

a. CFM 5.0: SCEC developed a new release of the Community Fault Model (CFM 5.0) for southern California that includes a number of major improvements (Figure 3.13). These include refinement of fault geometries using the USGS Quaternary Fault and Fold Database (Qfault) traces and relocated seismicity (Yang et al., 2012; Hauksson et al., 2012), as well as the addition of new fault representations. CFM 5.0 provides a comprehensive suite of improved fault representations in the Santa Maria and Ventura basins, Santa Barbara Channel, Inner Continental Borderlands, Eastern Transverse Ranges, Peninsular Ranges, San Gorgonio Pass area (Figure 3.14), and the Mojave Desert region. This resulted in fault representations that more precise, and often more segmented than in previous models (Figure 3.15). CFM 5.0 includes the addition of several faults that were not represented in previous models, a revised naming system that is compatible with the USGS Qfault database, and a selection of preferred fault alternatives based on measures such as fit to Qfault traces or earthquake locations as well as structural and tectonic considerations. Scott Marshall and the USR development team have generated a suite of simplified, more regular meshes for CFM faults that are intended to help modelers more readily incorporate these representations into their studies.

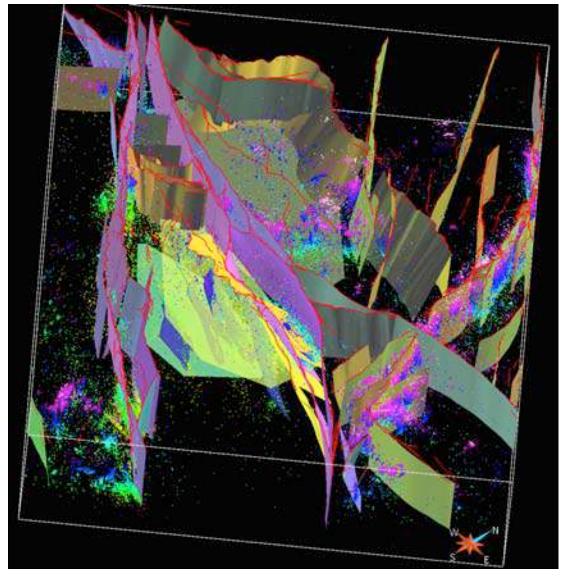


Figure 3.14. USR CFM5.0 San Gorgonio Pass updated fault geometry in CFM5.0 for the San Gorgonio Pass SFSA region.

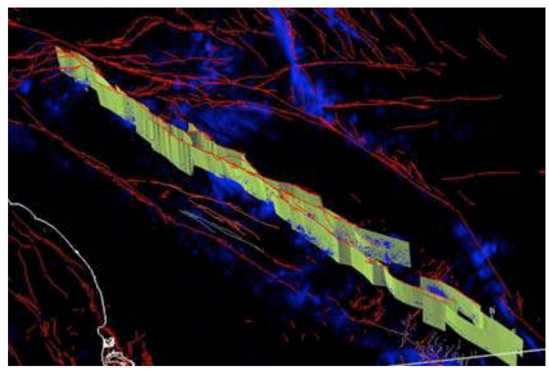


Figure 3.15. USR CFM5.0 San Jacinto Fault Updated San Jacinto in CFM5.0 illustrating refined geometry with more precise segment linkages based on Qfault traces and seismicity.

b. CVMs: SCEC improved the Community Velocity Models - both through 3D tomographic inversions and the development of new basin models. Lee et al., (2014) applied full-3-D tomography (F3DT) based on a combination of the scattering-integral method (SI-F3DT) and the adjoint-wavefield method (AW-F3DT) to CVM version 4.0 (CVM-S4). More than half-a-million misfit measurements made on about 38,000 earthquake seismograms and 12,000 ambient-noise correlagrams were assimilated into the inversion. After 26 F3DT iterations, synthetic seismograms computed using model, CVM-S4.26, show substantially better fit to observed seismograms at frequencies below 0.2 Hz than those computed using the 3-D starting model CVM-S4. CVM-S4.26 also revealed strong crustal heterogeneity throughout Southern California (Figure 3.16) not represented in previous versions. These improvements provide insight into the crustal structure of southern California and will improve earthquake simulations at low frequencies.

A new structural velocity model is now available for the San Joaquin basin that uses tens of thousands of direct velocity measurements from well logs, seismic reflection, and geologic constraints. Carl Tape incorporated this model into SCEC CVM-H 11.9, and generated simulations for San Andreas ruptures that show strong amplification and resonance in the new basin structure. This basin model will be embedded into future versions of the SCEC CVM's, helping to enhance wave propagation simulations.

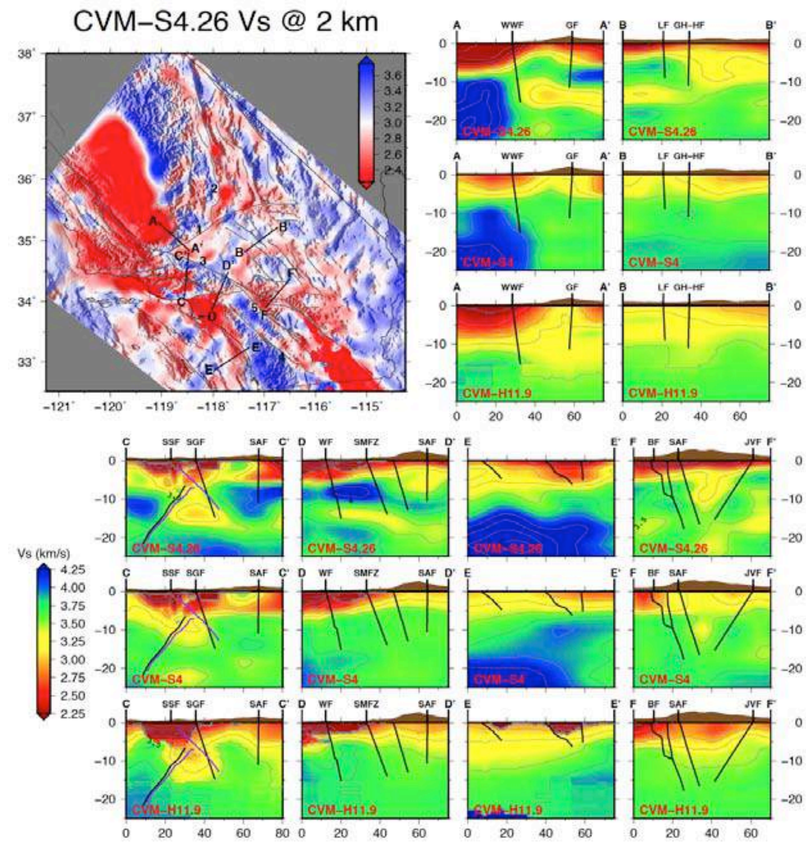


Figure 3.16. USR CVMSI-4.26 Vs at 2 km depth in CVMSI-4.26 and comparison of cross-sections across various faults from CVM-S4, CVM-H11.9, and CVM-SI4.26.

c. ShakeOut Simulations in Alternative CVMs: Robert Graves conducted an analysis of the ground motions for the M7.8 ShakeOut scenario earthquake using three SCEC CVMs (CMV-S4, CVM-SI23, and CVM-H11.9.0). Figure 3.17 shows that along the San Andreas, the pattern is similar for all three models with strong directivity towards the northwest. Other features are present in some models but not all. Both CVM-S4 and CVM-Si23 show strong amplification in San Bernardino, whereas CVM-H11.9.0 shows only modest amplification. On the other hand, both CVM-Si23 and CVM-H11.9.0 show strong amplification in the area north of San Fernando (Santa Clarita-Fillmore basin), but this is not present for CVM-S4. The Los Angeles basin shows very strong amplification for CVM-S4 with PGV exceeding 50 cm/s throughout most of the basin, and reaching nearly 200 cm/s in the Whitter-Narrows region connecting the San Gabriel and LA basins. The level of amplification is lower in CVM-Si23, and significantly lower in CVM-H11.9.0.

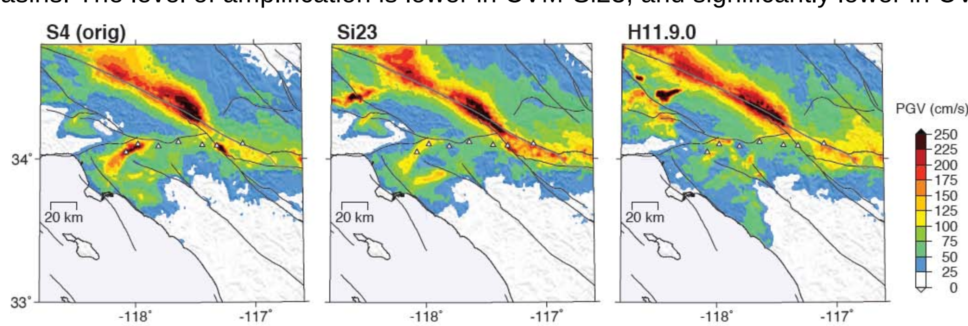


Figure 3.17. ShakeOut ground motion comparison Panels below show PGV simulated for alternative CVMs. At left (CVM-S4) is the original ShakeOut (Graves et al, 2008). Middle panel uses CVM-Si23 and right panel is for CVM-H11.9.0. The LA basin region shows very strong amplification for CVM-S4. The level of amplification is noticeably lower in CVM-Si23, and it is significantly lower in CVM-H11.9.0.

6. Fault and Rupture Mechanics (FARM)

The Fault and Rupture Mechanics Group focuses on understanding rupture mechanics through a combination of modeling, experiments and field observations. Improvements in computational capabilities are making it possible to model dynamic rupture propagation on geometrically realistic fault structures. Similarly, technical advances in experimental and analytical equipment are opening up new opportunities for investigating the deformation processes during quasi-static and dynamic conditions in both laboratory and natural samples. Progress in this area is diverse; however, several themes remain at the forefront.

a. Material, Geometrical, and Stress Heterogeneity: Considerable effort has been focused on how heterogeneous fault stress and fault structure (e.g., roughness and large-scale segmentation) influence seismicity and rupture propagation. New calculations indicate that supershear ruptures are actually more likely on rough faults than smooth faults (Bruhat et al.), an effect opposite of conventional wisdom (Figure 3.18). The role of fault roughness on the distribution of seismicity was investigated in the laboratory by Becker et al., who found that the power-law exponent that describes the decay of AE with distance from the slip surface depends on roughness as well as normal stress. Ben-Zion and colleagues investigated links between the generation of a low-velocity damage zone and rupture dynamics. The role of fault structure on inelastic, "off-fault" deformation was studied in idealized scenarios (e.g., Kang and Duan), in addition to focused regional studies of the San Jacinto fault zone (Ben-Zion). New models also show the limitations of modeling multi-strand fault surfaces with a single fault surface (Shaw et al.).

The level of background stress, stress heterogeneity, and heterogeneity of fault zone properties influence both rupture propagation and the distribution of aftershocks. Shi found that a through-going rupture is more likely for a non-uniform/stochastic initial fault stress than if the regional stress is uniform for the San Gorgonio Pass fault system (Figure 3.19).

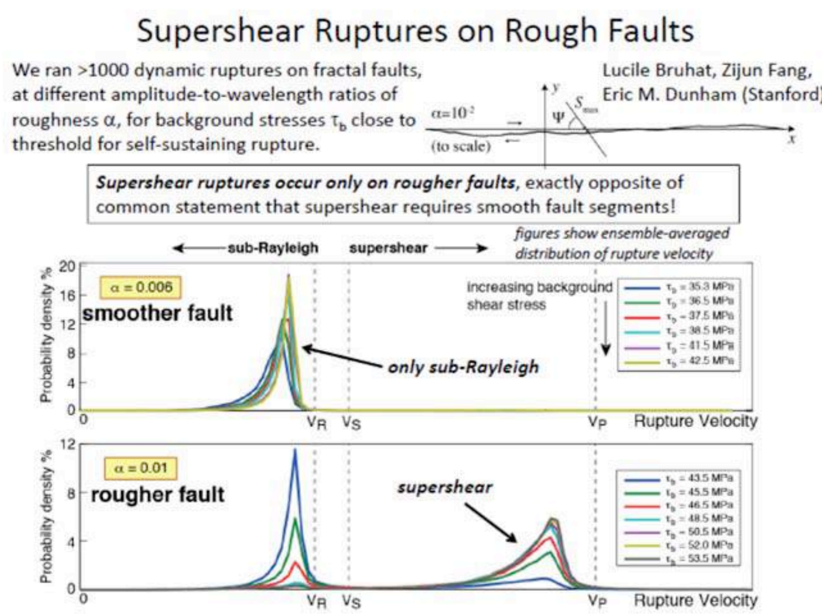


Figure 3.18. Supershear rupture is favored on rough faults (lower panel).

b. The Deep Roots of Faults: Understanding rupture processes at the base of the seismogenic zone remains critical for evaluating the hazard from large events in Southern California. These properties have been studied by incorporating more realistic (i.e., thermally activated creep) lower crustal fault rheologies into earthquake cycle models. Lapusta and Jiang illustrate how the history of such ruptures may be identified by a lack of microseismicity at the base of the seismogenic zone (Figure 3.20). Physically realistic models of viscous deformation have also been used to constrain the spatial and temporal evolution of post-seismic creep. These models provide a way to estimate stress magnitudes at the base of the seismogenic zone and the mechanics of stress transfer from plate motion to mature fault zones (Fialko). Several studies have continued to investigate the slip and deformation behavior of the deeper and/or higher temperature regions of fault zones based on a combination of geodetic (San Jacinto Fault; Lindsey et al), and analyses of seismic velocity (Brawley sequence, Helmberger; Parkfield, Thurber).

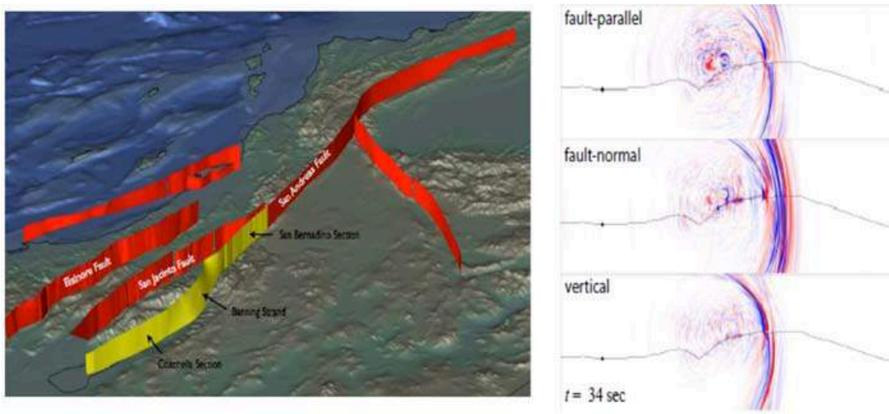


Figure 3.19. 3D modeling of dynamic rupture along the San Gorgonio Pass section of the San Andreas, to assess the plausibility of through-going ruptures. The dynamic rupture scenarios based on CFM-v4 fault geometry. Through-going rupture is more likely with stochastically variable, rather than uniform, initial stress.

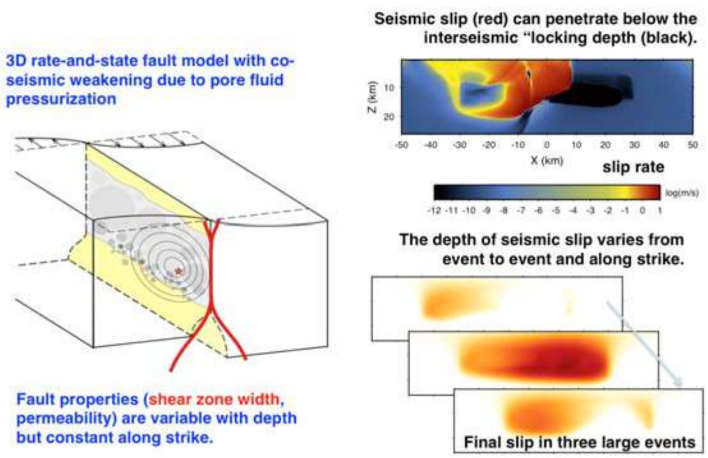


Figure 3.20. The seismogenic depth is typically defined based on microseismicity or inferences of the locking depth. Simulations by Lapusta and Jiang show that seismic slip in large events can penetrate deeper. They consider a 3D elastic bulk with a for which a rate-weakening region is surrounded by rate-strengthening areas. The fault has depth-variable shear zone width (red). The extent of seismic slip is determined by where thermal pressurization stops being efficient, not by the rate-and-state transition between weakening and strengthening. The efficiency of thermal pressurization depends on a competition between the shear-zone width and permeability as well as on the slip rate and slip of dynamic rupture itself. As a result, seismic slip can penetrate below the traditionally defined seismogenic depth. The depth extent of large seismic events varies both along the strike and in time, from one event to another.

c. Mechanisms of Dynamic Weakening: Dynamic weakening mechanisms continue to be a focus of experimental, theoretical and geological studies. Platt et al. found that thermal pressurization and thermal decomposition provide multiple ways to propagate a rupture. Slip pulses dominated by thermal decomposition have a distinctive slip rate profile, with peak slip rates near the trailing edge of the rupture. Schmitt and Segall compared how flash heating and thermal pressurization influence earthquake nucleation and rupture on faults with low background stress. Their calculations suggest that thermal pressurization is required to explain the observed relationship between fracture energy and slip. New laboratory experiments have been performed to characterize the processes responsible for flash weakening in gouge (Proctor et al.) and thermal pressurization (Figure 3.21, Goldsby & Tullis). SCEC activities provided synergy between analysis of these new data and the physical models for dynamic weakening (Platt et al.). In addition, the role of thermally activated contact processes has now been included into STZ models of gouge deformation (Carlson and colleagues). These studies provide new insights into the physical processes responsible for dynamic weakening, and rationale for their inclusion into earthquake cycle and rupture models. Further tests on the impact of dynamic weakening on natural faults is presaged by the calibration of new fault slip thermometers that incorporate analyses of thermally induced changes in organic compounds within fault gouge (Savage and Polissar).

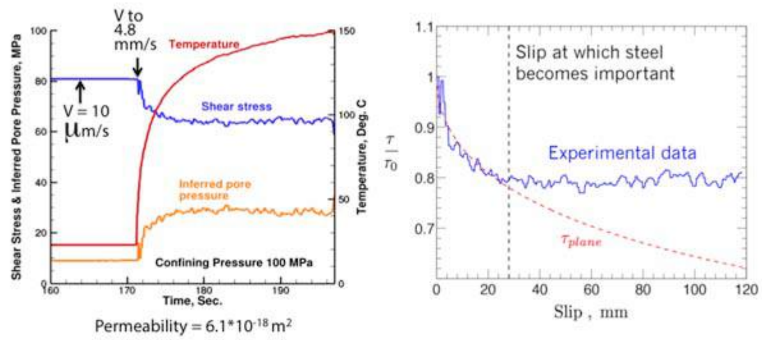


Figure 3.21. Left, from Goldsby and Tullis, shows observed reduction in strength and inferred increase in pore-fluid pressure for diabase experiment upon a velocity step increase, assuming that all changes of shear stress were due to changes in fluid pressure. Inferred temperatures calculated using FEM model are also shown in the data plot. Right shows fit of the initial part of the shear stress decay to prediction of the decay of shear stress, τ, from its initial value. Although the theoretical prediction continues to decline, after about 28 mm of slip the experimental data level out, which may be due to the steel sample grip preventing the temperature from rising as it would for the rock half-space assumed by Rice (2006). The right half of the figure (Platt) shows estimate of the slip at which the steel becomes important.

7. Southern San Andreas Fault Evaluation (SoSAFE)

Advances in SoSAFE research included the publication of important papers on San Andreas and San Jacinto paleoseismology and development of new paleoseismic studies on these faults. Several new studies in San Gorgonio Pass fomented a new investigation into strain patterns across this complex zone.

Paleoseismic Studies: Work published on the Frazier Mountain site (Scharer et al., 2014; Figures 3.22, 3.23) proposes that ruptures as large as the M7.7-7.9 historic earthquake in 1857 are not the norm across the Carrizo, Big Bend and Mojave sections of the San Andreas Fault. Combining earthquake ages and paleo-displacements where available, up to 75% of the ruptures are less than 300 km long. Tests of this result are underway at two paleoseismic sites located 50 km to either side of Frazier Mountain. The first is a new site at the southern end of the Carrizo section (Akciz et al., 2014). Trenching there revealed active faulting is restricted to the east side of a wide sag pond, and dating of three paleoearthquakes is underway. The second is the Elizabeth Lake paleoseismic site, where work in 2014 established that four to five earthquakes have occurred there since 1200 A.D. (Bemis et al., 2014) The Elizabeth Lake paleoseismic record will provide important constraints on paleo-ruptures on the Mojave section for the last 1500 years.

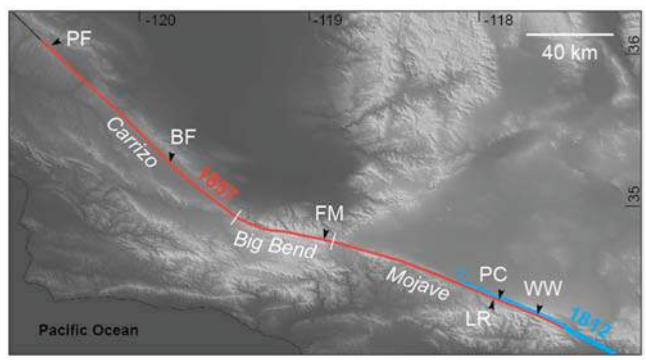


Figure 3.22. Paleoseismic sites on the 1857 rupture of the San Andreas Fault.

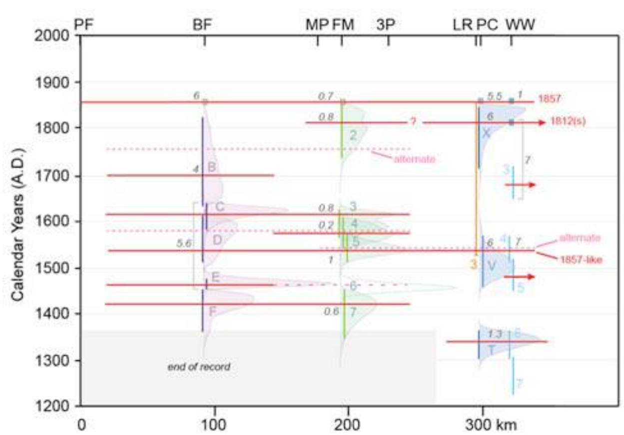


Figure 3.23. Rupture history on 1857 stretch of SAF.

On the San Jacinto fault, the Mystic Lake site now comprises a 2000-year record of paleoearthquakes. Onderdonk et al. (2014) show that large earthquakes in this period recur every 160-190 years on the Claremont fault, and that the longest interval was ~200 years. In comparison to Rockwell et al. (2014) at the Hog Lake site on the Clark fault, it appears that most of the earthquakes are not correlative in time, suggesting that most ruptures do not jump the 4 km step between these strands.

a. Deformation in San Gorgonio Pass: Several slip rate studies focused in the San Gorgonio Pass Special Fault Study Area are leading to a revision of strain patterns across this complex region. On the Banning strand of the southern SAF, two new slip rate sites suggest a dramatic increase in slip rate, from <1.5 mm/yr at the eastern end (Blisniuk et al., 2013) to 11.1 +3.1/-3.3 mm/yr nearer to San Gorgonio Pass (Gold et al., 2014). This increase in the horizontal slip rate on the Banning strand is mirrored by an increase in the vertical slip rate, which is being investigated with ^{10}Be catchment averaged erosion rates and slip rates across uplifted fans in the Indio Hills (Scharer et al., 2014). On the Mission Creek strand, new estimates from the Pushawalla site in the central Indio Hills overlap with the upper end of published estimates from Biskra Palms oasis (12-22 mm/yr, Behr et al., 2010).

In San Gorgonio Pass, several groups are investigating the rate of vertical uplift at several time scales. In trench exposures, slip per event is <1 m (Wolff et al., 2014), leading to a ~6000 year slip rate of only ~2 mm/yr. In contrast, the rates from Millard Canyon appear to be much higher. A Holocene terrace is offset by two fault splays by ~4 m, and Pleistocene terrace surfaces are offset hundreds of meters (Heermance et al., 2014). New dating of these surfaces and resultant slip rates will be a major focus of the San Gorgonio Pass Workshop in 2014.

Improvements to the subsurface fault characterization in the CFM in San Gorgonio Pass are also underway, including: blind, sub-parallel, en echelon oblique faults beneath SGP, a new model for the San Gorgonio Pass thrust, new fault models for the Crafton Hills complex and secondary cross faults, revised Pinto Mountain and Morongo Valley faults, and newly defined detachment surfaces at mid and deep crustal levels beneath the San Jacinto and San Bernardino Mountains that dip towards, and interact with, the San Andreas fault in SGP (Nicholson et al., 2013; Plesch et al., 2014). This expanded CFM 3D fault set helps characterize a more complex fault geometry and pattern of fault interactions at depth than previously inferred from projecting near-surface data down-dip, or modeling GPS and potential field data alone.

Work is also ongoing to investigate dynamic rupture models in the Pass region and in parallel, developing an approach for estimating absolute stress from stressing rates produced by forward models. Using assumptions about recurrence interval and stress drop on ground-rupturing earthquakes, (those that would be observable in the paleoseismic record), it appears that fault interaction contributes to loading on faults through the San Gorgonio Pass (Cooke et al., 2014). This approach may provide different initial conditions for dynamic rupture models than derived by resolving the tectonic load on the fault surface.

b. Workshops: Two related workshops on high-resolution topography were partially supported by SoSAFE (and by UNAVCO and OpenTopography). The first was the VISES-SCEC Workshop on High Resolution Topography Applied to Earthquake Studies, which occurred mostly at ERI in Tokyo and had good participation from numerous Japanese colleagues. Several recommendations came from the workshop. Of relevance for SoSAFE, these include: a) There has been an interesting evolution of methodology for study of active faulting and topography. LiDAR has revolutionized many tasks and our ability to measure surface features at the fine scale at which the surface processes and earthquake deformation operate. b) Once faults are identified, reconstructing offset and deformed features is necessary. Uncertainty assessment in the reconstructions is an active research area. c) A substantial emphasis has been on surface rupture characterization in high-resolution topography acquired shortly after an earthquake. This effort includes airborne and terrestrial laser scanning data integration. Examination of tilted trees in the vegetation (Yoshimi) was a clever use of the three dimensional data to characterize surface deformation along the earthquake rupture. d) Topographic differencing along Japanese and the El Mayor-Cucapah earthquake ruptures is yielding exciting results that seem to document variable continuity of slip along fault surfaces in the upper several hundred meters below the Earth surface. These results are complementary with INSAR results. The various approaches for differencing (Iterative closest point, image correlation, pixel matching, particle image velocimetry, etc.) should be systematically compared.

The second workshop (held in San Diego) was the third of a series supported by SCEC over the years: Imaging and Analyzing Southern California's Active Faults with Lidar. It was well attended by SCEC scientists and many useful tutorials persist on the workshop web site.

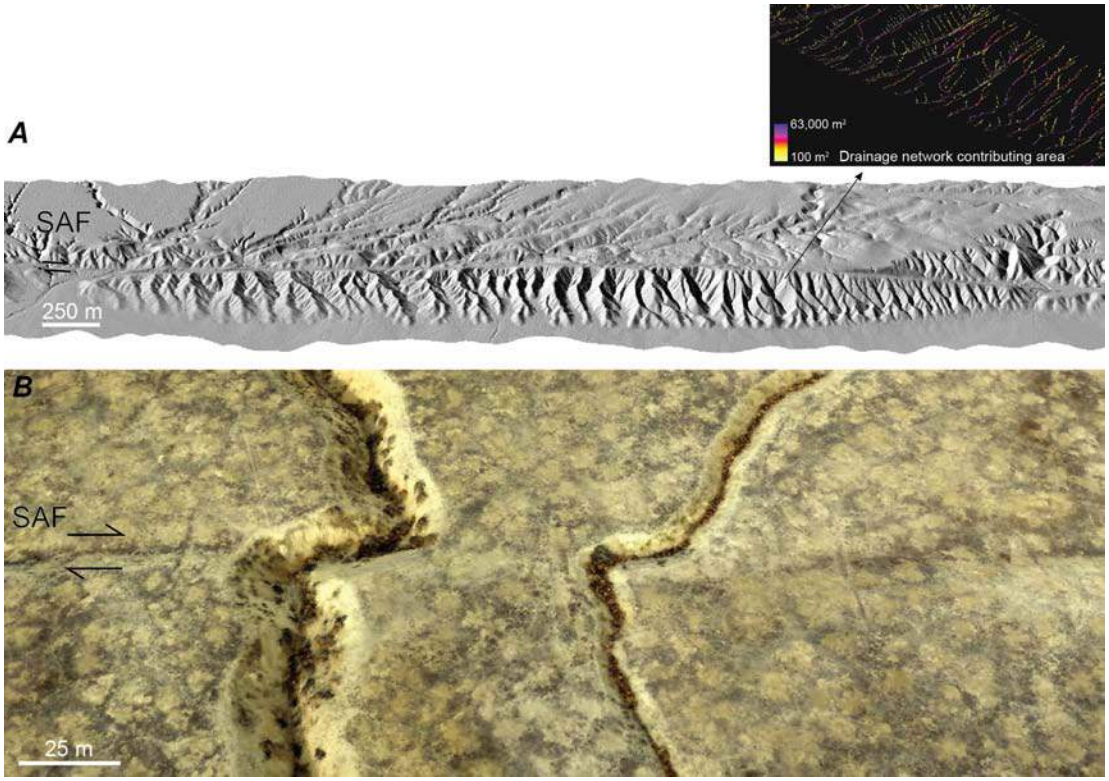


Figure 3.24. High-resolution topography and evidence of recent activity along the south-central San Andreas Fault (SAF): methodology demonstrated at the SoSAFE/SCEC workshops (Arrowsmith, 2014). A) The Dragon's Back pressure ridge shows progressive landscape response to rock uplift and offset relative to a fixed uplift zone in the SE (Hilley and Arrowsmith, 2008). Inset shows drainage network in uplift zone. B4 LiDAR topography processed at www.opentopography.org. B) Recent offsets along the SAF at Phelan Creeks. Image is from balloon aerial photography texture-mapped onto topographic model from Structure from Motion (Johnson, et al., 2014).

8. Stress and Deformation Over Time (SDOT)

SDOT's focus is our understanding of the mechanical behavior and structure of the southern California lithosphere and mantle on inter-seismic and geological timescales to understand fault loading and the time-evolution and formation of plate boundary systems.

a. Ventura Area Studies: As part of the Ventura SFSA effort, Marshall and others updated their work on geodetic data in the Ventura Basin area (Figure 3.25). This includes improved GPS error analysis and more complete InSAR coverage. Marshall et al. tested new fault geometries for the Ventura fault using boundary element codes. The geometry has a significant influence on the inferred long-term fault slip rate. Kaj Johnson constructed a kinematic plate flexure model for the western Transverse Ranges to estimate crustal shortening rates, inter-seismic and long-term uplift rates, and fault slip rates (Figures 3.26). This work shows that dipping faults in the western Transverse Ranges accommodate at least 12 mm/yr of reverse slip. The model shows 1-3 mm/yr of subsidence in the Ventura Basin and 1-3 mm/yr of uplift of the Santa Ynez mountains, consistent with GPS observations.

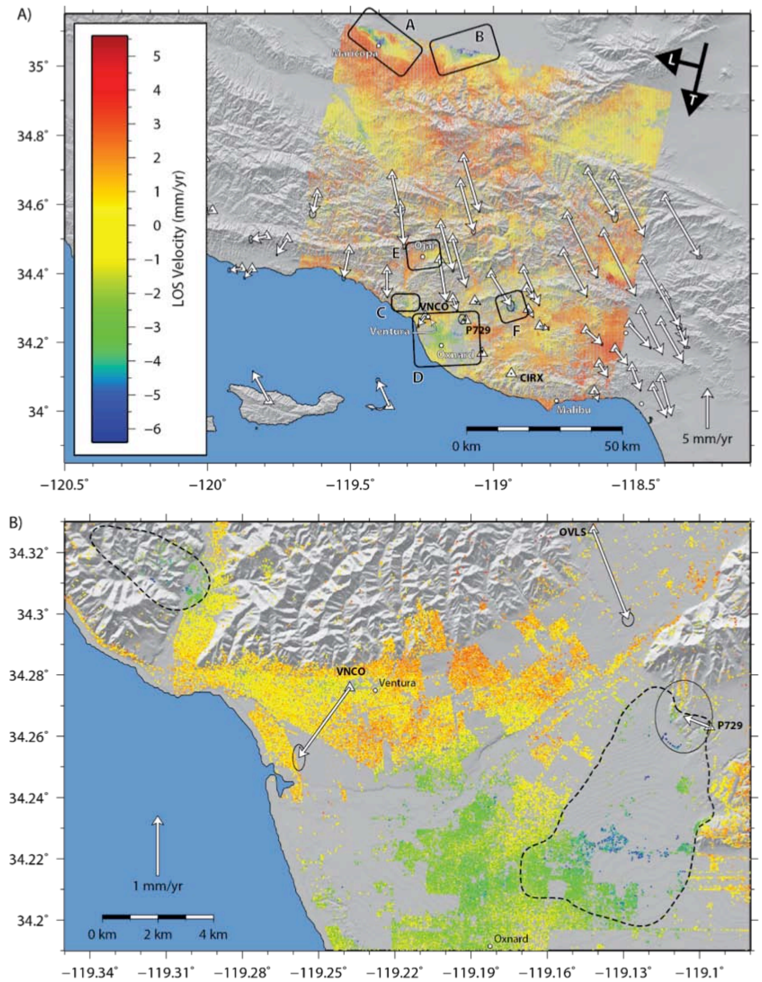


Figure 3.25. Improved, joint geodetic constraints from GPS and InSAR. Localized anthropogenic deformation is labeled (from work by Scott Marshall et al.).

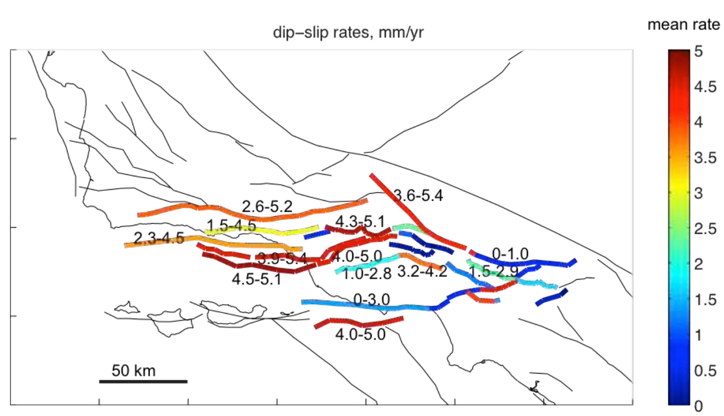


Figure 3.26. Estimated dip-slip rates on reverse faults in the western Transverse Ranges (from Johnson et al.).

b. Fault Slip Estimates from Geodetic Data: McGill, Spinler, and Bennett developed new GPS site velocities from the San Bernardino Mountains and San Gorgonio Pass areas (Figure 3.27). Their analysis suggests that the San Andreas slips more slowly, and the Eastern California Shear Zone slips more rapidly than suggested by geologic observations.

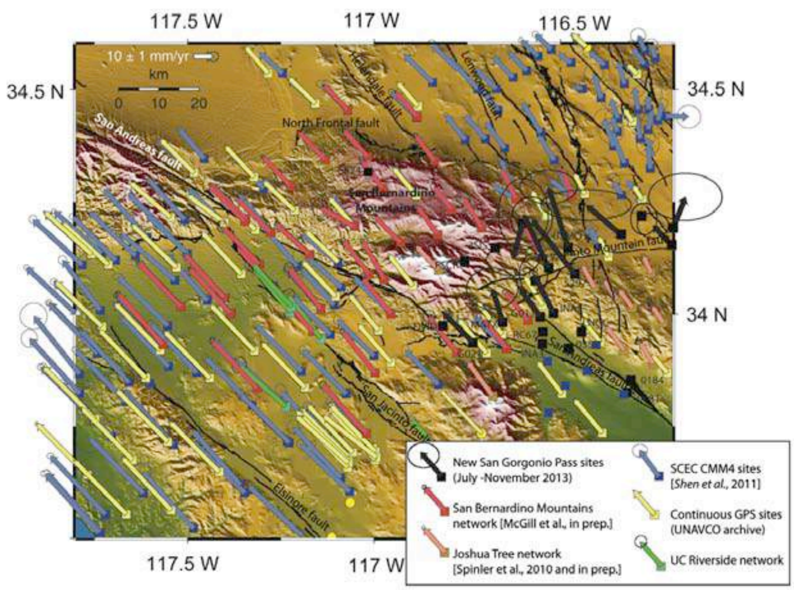


Figure 3.27. New GPS velocities from the San Bernardino Mountains and near San Gorgonio Pass (McGill et al.).

Williams developed a workflow that allows scientists to use PyLith-generated GF with McCaffrey's DEFNODE inversion code. Figure 3.28 shows the effect of material properties from the New Zealand-wide seismic velocity model (Eberhart-Phillips et al., 2010) when estimating slow slip along the Hikurangi margin (the Manawatu event from September-December, 2010). The homogeneous model requires about 40 mm more slip to match the observations, compared to the heterogeneous model and the seismic potency for the homogeneous model is about 23% larger than that for the heterogeneous model, which has important implications for the component of the slip budget accommodated by slow slip.

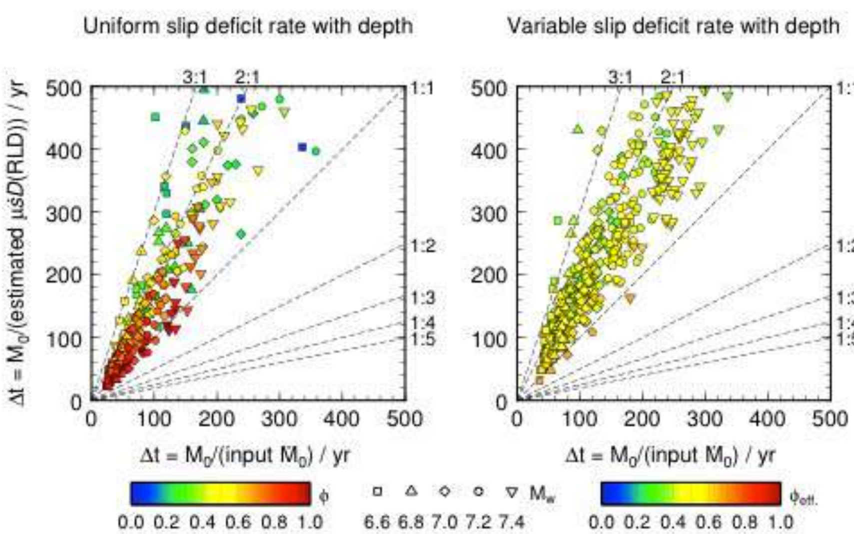


Figure 3.28. From Williams et al., the difference between inferred slip using homogeneous vs. heterogeneous material properties when inverting for slow slip along the Hikurangi subduction margin (Manawatu event from September-December, 2010).

Herring and Floyd examined comparisons of modeled earthquake recurrence intervals and geodetic estimates based on balancing moment release rates. They find that estimates of locking depth from geodetic data using a simple elastic dislocation model requires more consideration because a naive a inversion and direct interpretation may introduce an error of up to a factor of 2 on the recurrence interval estimate (Figure 3.29).

Community Stress Model: A web site with tools for inter-model comparisons and validation is now complete (Figure 3.30). A candidate release for a stress model based on focal mechanisms has been picked -the Yang and Hauksson (2013) model.

9. Earthquake Forecasting and Predictability (EFP)

The Earthquake Forecasting and Predictability (EFP) Group facilitates a range of studies aimed at improved data and methods for developing earthquake forecasting techniques and assessing earthquake predictability.

a. Earthquake Catalogs: Earthquake catalogs, the foundation for retrospective and prospective testing of earthquake forecast models, are an integral part of forecast models based on spatial-temporal seismicity patterns and a valuable resource for hypothesis development. The instrumental catalog for southern California dates back to 1932. This year's work on the southern California instrumental catalog included study of the December 2012 M6.3 offshore earthquake (Figure 3.31). This earthquake occurred in the oceanic lithosphere, west of the continental shelf. This area was previously considered aseismic, but the occurrence of the 2012 earthquake suggests that the Pacific- North America plate boundary possibly extends 400-500 km to the west of the San Andreas Fault, and may include deformation across the entire Continental Borderland and into the eastern edge of the oceanic Pacific

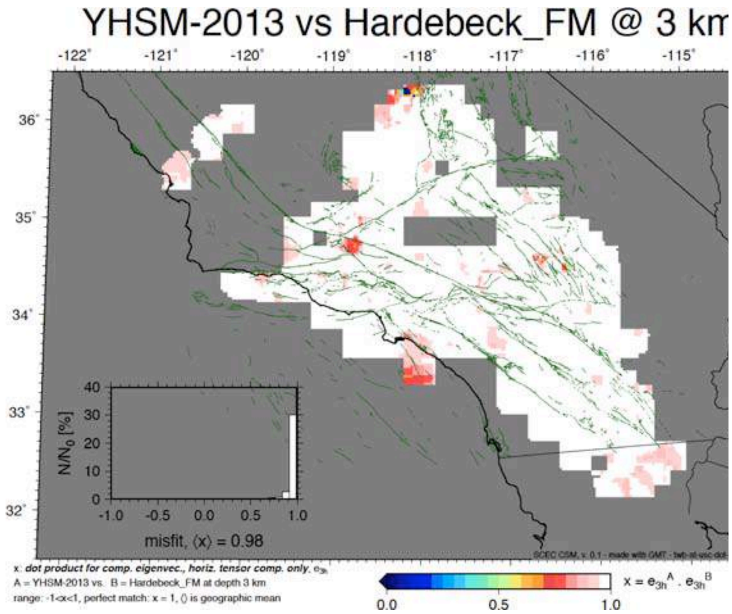


Figure 3.29. Estimated versus input recurrence times for various magnitudes of earthquake (symbol shape) and effective coupling coefficients (symbol color). The input recurrence time is the seismic moment of a given magnitude earthquake divided by the input moment deficit rate. The estimated recurrence time is the seismic moment divided by the moment deficit rate using the estimated

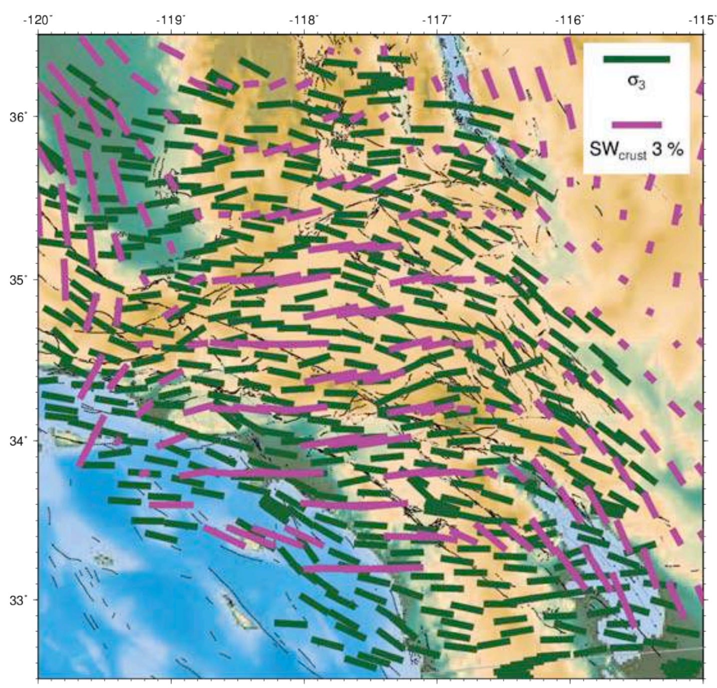


Figure 3.30. Axes of greatest extensional stress from the model by Yang and Hauksson (2013) and fast seismic anisotropy orientations within the crust from Lin et al. (2011). From work by Meghan Miller and Thorsten Becker.

plate (Hauksson et al, 2014).

b. Focused Regional Studies: Earthquake recurrence models usually assume uniform fault slip rate. McAuliffe et al (2013) investigated slip-rate variations on the Garlock Fault, by dating offset features using the newly-developed K-feldspar single grain "post-infrared IRSL" dating. They found evidence for increased slip rate for the central Garlock Fault over the last 2600 years, compared to the Holocene average rate, with minimum slip rates of 8.1-12.4 mm/yr. This supports the model that the Garlock fault exhibits transient strain accumulation with periods of increased slip and frequent earthquakes, separated by periods of little or no slip and few earthquakes.

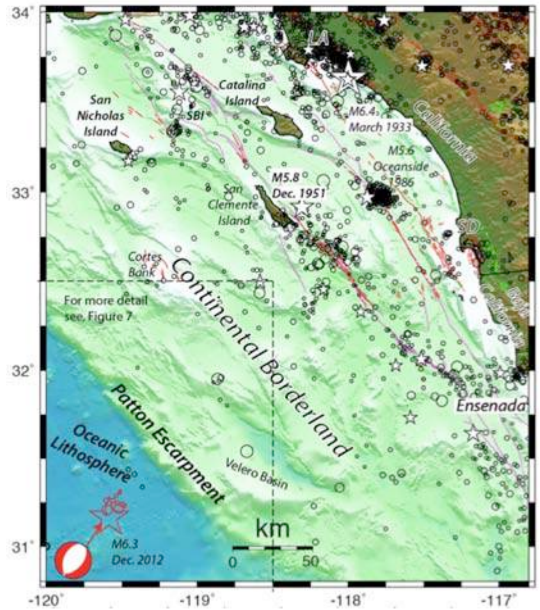


Figure 3.31. Map showing the bathymetry and topography from NGDC and GeoMapApp, SCSN M≥3.0 earthquake locations (1930 to 2013), (Hutton et al., 2010); and the 2012 W-phase moment tensor and relocated mainshock (red star) and aftershocks (red circles) of the December 2012 M6.3 offshore earthquake. LA – Los Angeles; SBI – Santa Barbara Island; SD – San Diego. Map courtesy of Egill Hauksson, Caltech.

Geothermal fields provide an intriguing location for earthquake predictability studies because one of the possible drivers of earthquake rate, the time history of the fluid volume, is known. Weiser et al (2013) studied 11 geothermal fields across California, looking for correlations between Benioff strain and geothermal field injection and production rates. Their results suggest that there is increased seismicity when a new geothermal field begins pumping, reduction when pumping ceases, and a relation between net pumping rate and earthquake rate. Increased seismicity generally follows a surplus in fluid volume, but in the Salton Sea, an increase in seismicity has also occurred following negative volume change.

Constraining the level of predictability of earthquake stress drop is an important problem with implications for earthquake physics and for the predictability of strong ground motion. Hauksson (2014) investigated the distribution of stress drop in southern California (Figure 3.32) and discovered spatially coherent patterns with similarities to the patterns of stress orientations observed by Yang and Hauksson (2013). A region of low stress drop extends from the Salton Trough north through the Eastern California Shear Zone, spatially coincident with a rotation in the regional stress field. Another region of low median stress drop and stress rotation is located to the west of the San Andreas fault, extending across the edges of the Los Angeles and Ventura basins. Medium to high stress drops occur along the major late Quaternary faults, and coincide with geometrical complexities, such as San Gorgonio Pass (Goebel et al., 2014).

The predictability of strong ground motion was also investigated through the study of fragile geologic features. Stirling and Rood (2013) hypothesized that the few fragile geologic features observed ~20 km from the San Andreas fault at Lovejoy Buttes may be statistical outliers that do not represent the typical ground motions experienced at this proximity to the San Andreas. They found that less fragile features are more abundant at Lovejoy Buttes. Their initial observations indicate that 0.35-0.6g may be a realistic estimate of maximum PGA at Lovejoy Buttes. While this is still less than the 10,000 year return period PGA estimates for this site from the US national seismic hazard model (~1g), the discrepancy is smaller than previous interpretations of the rare fragile geologic features.

c. Seismicity Patterns: P. Shearer and colleagues studied earthquake triggering models and their relationship to swarms and foreshock sequences. They identified several aspects of the space/time clustering of seismicity that cannot be explained with standard (i.e., ETAS) models, including details of the foreshock and aftershock behavior for small earthquakes (Chen and Shearer, 2013). The results support previous work that suggested that major California foreshock sequences are not caused by static stress triggering and may be driven by aseismic processes. Ongoing results of this work include a more detailed understanding of earthquake source properties and seismicity patterns.

Continuing collaborative research between USC and UNR led by Y. Ben-Zion and I. Zaliapin focused on spatio-temporal evolution of earthquake clustering and its relation to large earthquakes. The project results demonstrate increase of seismic clustering in the spatio-temporal vicinity of large events (M≥6.5) in southern California during 1981-2011 and the Duzce, M7.1, 1999 earthquake in Turkey. The results contribute to studies of earthquake predictability and to better understanding of the detailed structure of seismic catalogs in relation to physical properties of the crust.

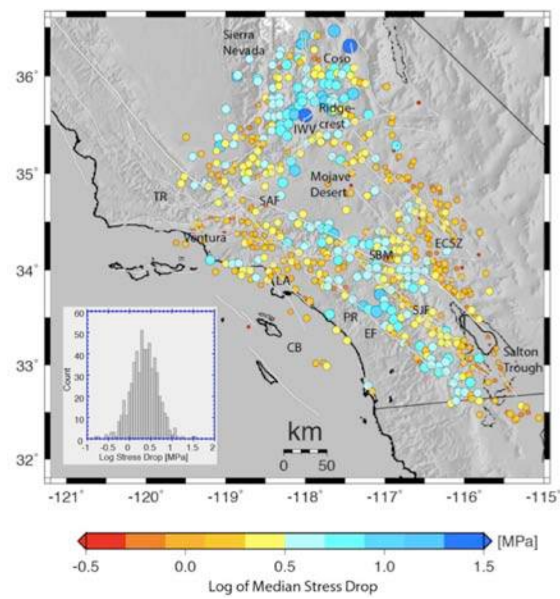


Figure 3.32. Map of the gridded median stress drops that were corrected for VS(z). The color and size of the symbols are proportional to the size of the logarithm of median stress drops. The (lower left) histogram shows the distribution of the logarithm of the median stress drops plotted on the map. CB – Continental Borderland; ECSZ – Easter California Shear Zone; EF – Elsinore fault; IWV – Indian Wells Valley; LA – Los Angeles; PR – Peninsular Ranges; SAF – San Andreas fault; SBM – San Bernardino Mountains; SJF – San Jacinto fault; TR- Transverse Ranges. Figure courtesy of Egill Hauksson, Caltech.

d. Collaboratory for the Study of Earthquake Predictability (CSEP): The EFP group continued research towards improving the earthquake forecast methods within the CSEP project. Particular attention has been paid to further development and validation of hybrid earthquake forecasting models (Figure 3.33). For instance, a set of rigorous procedures were applied to the investigation of hybrid earthquake forecasting models in New Zealand and California (Rhoades et al., 2014). These studies consistently demonstrated the superiority of hybrid models, based on a range of different ideas or data inputs, over individual models, based on a single idea and data input. The developed ideas and approaches will be further substantiated by independent prospective testing of the hybrid models in the CSEP testing centers.

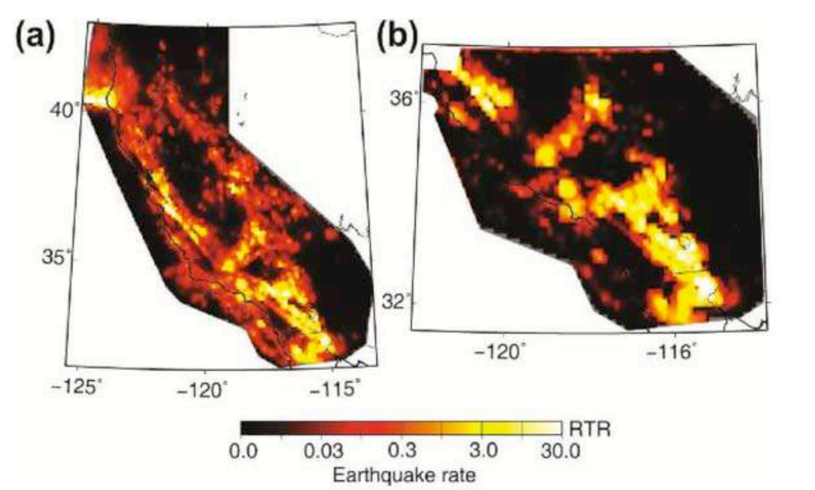


Figure 3.33. Map of earthquake rates, relative to reference (RTR), in the best three-model hybrids from the RELM experiment for (a) the whole of California; and (b) southern California. In the reference model, one earthquake per year is expected to exceed any magnitude m in an area of 10^m km^2. From Rhoades et al. (2014).

e. Earthquake Simulators: A multi-institutional collaborative project led by T. Tullis focused on comparison, validation, and verification of earthquake simulators. This project offers understanding of the interaction between earthquakes in a large system of faults through physics-based simulations of long series of earthquakes in all of California. The results offer the possibility of understanding what are the most important factors determining the temporal and spatial pattern of seismicity. A half-day workshop was held on Sunday afternoon, September 8, prior to the 2013 SCEC Annual Meeting. The workshop included both those who are participating in the SCEC Earthquake Simulators TAG, and those with general interest in the topic. The participants discussed the problems of fault-to-fault rupture jumping, multi-fault simulations based on the UCERF3 deformation models, as well as the plans for the future work.

10. Ground-Motion Prediction (GMP)

The primary goal of the Ground-Motion Prediction Focus Group is to develop and implement physics-based simulation methodologies that can predict earthquake strong-motion waveforms over the frequency range 0-10 Hz. Both media and source characterization play a vital role in ground-motion prediction and are important topics for GMP.

a. Towards more realistic models. Song developed a statistical framework for the earthquake rupture process for physics-based ground motion simulation, including a stochastic model that governs the finite source process with 1-point and 2-point statistics of kinematic source parameters and a pseudo-dynamic rupture model generator (SongRMG, Ver 1.0). Assinaki validated nonlinear site response prediction methodologies for SCEC Broadband Ground Motion Simulations. Bradley has generated broadband ground motion simulations for the Canterbury earthquakes with nonlinear effective-stress modeling of surficial soils. Withers et al. modeled frequency-dependent anelastic attenuation in southern California. Withers et al. have implemented frequency-dependent Q in the finite-difference code AWP-ODC, and has shown that a power-law formulation of Q as Q^n with n=0.6-0.8 provides a much closer fit to short-period ground motion intensities in southern California, as opposed to constant-Q formulations.

Sleep studied nonlinear attenuation in the uppermost few hundred meters and ambient intact rock and regolith as fragile geological features. He inferred past shaking from strong Love waves (expressed as peak ground velocity) from the shear wave velocity as a function of depth within the sedimentary basins of Greater Los Angeles. The results include a framework for connecting failure, damage, and nonlinear attenuation when dynamic stress exceeds frictional strength. Also, lowering the ground water levels below Los Angeles by pumping decreases the nonlinear attenuation, doubling the amplitude of large surface waves impinging from the San Andreas fault.

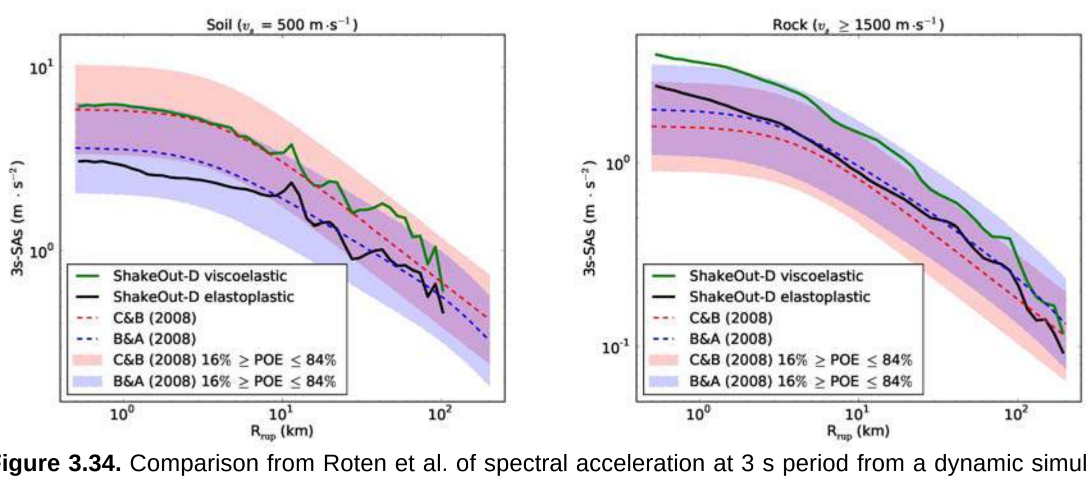


Figure 3.34. Comparison from Roten et al. of spectral acceleration at 3 s period from a dynamic simulation of M7.8 Shakeout, with (viscoleastic, black) and without (elastoplastic, green) off-fault nonlinear effects to leading GMPEs, for rock sites. Notice how the elastoplastic results are much closer to the GMPE medians, as compared to the viscoelastic results. This is in agreement with the results by Roten et al. (2014), suggesting that long-period ground motions for large earthquakes may be significantly affected by nonlinear effects.

b. Wave Propagation in Complex, Nonlinear Media: Roten et al. (2014) and additional recent results on viscoelastic and viscoplastic simulations of the M7.8 ShakeOut scenario on the southern San Andreas fault show that off-fault plasticity can significantly reduce peak ground motions for both rock and soil sites. The results are robust for end-member cohesion models. As compared to the viscoelastic results, elasto-plastic simulations generate long-period peak motions much closer to leading GMPEs (and 3.34).

c. Stochastic Descriptions of Basin Velocity Structure: Shaw et al. (Harvard) and Olsen and Savran (SDSU) have constrained the parameters needed to generate statistical distributions of small-scale heterogeneities in the crust using sonic log data from the Los Angeles basin. Both studies find standard deviations from the mean depth trends of 5-10% and vertical correlation lengths of 50-150 m. Horizontal correlations lengths are less constrained by data but tend to be much longer (hundreds of meters to kilometers). Assuming a von Karman distribution, Hurst numbers of 0.0-0.1 best characterize the distributions; however, there are indications that the statistical distribution may be markedly non-Gaussian. Statistical distributions of small-scale heterogeneities with these parameters can amplify or de-amplify ground motions by up to a factor of two; however, small-scale scattering included in the wave propagation for the 2008 Mw 5.4 Chino Hills earthquake, improves the goodness-of-fit (GOF) between data and synthetics by only 5-10%. On the other hand, they find that shallow sources located on the boundary of a sedimentary basin can generate bands of strong amplification aligned in the direction of the ray paths. The nature of these bands depends strongly on the incidence angle of the waves into the sediments. Moreover, this banded amplification pattern is absent for sources deeper than 1-2 km, consistent with the results for the Chino Hills earthquake. The majority of the scattering recorded in ground motions appears to originate as path effects as waves propagate through the basins, as compared to local site-specific scattering. Lower-velocity sediments and the deep crust contribute approximately equally to the strength of the scattering recorded in ground motion records.
Long-Period Effects on the BBP: Efforts are underway to explore why the (1D) broadband platform simulations often obtain relatively poor fit to data for the long-period ground motions (>1s). Preliminary results for hybrid simulations of the M5.4 Chino Hills earthquake show improved fits long-period PSAs when 3D velocity structure is used (R. Taborda, J. Bielak, D. Gill, F. Silva, P. Small, P. Maechling, Figure 3.35). The results suggest that including 3D basin crustal amplification effects into the long-period ground motions computed by the platform is important and should be explored further.

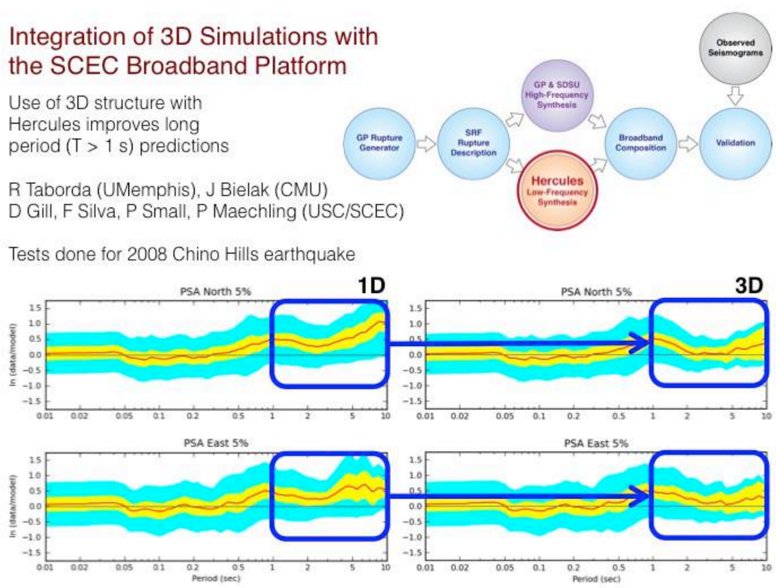


Figure 3.35. Efforts are underway to understand why the (1D) broadband platform simulations often obtain relatively poor fit to data for the long-period ground motions (>1s). An interface is being built to incorporate 3D low-frequency synthetics into the BBP. Preliminary results for hybrid simulations of the M5.4 Chino Hills earthquake show improved fits long-period PSAs when 3D velocity structure is used (Taborda et al., 2014).

d. Exploring Basin Amplification Using the Ambient Seismic Field: Denolle et al. (2014) studied Kanto Basin amplification by exploiting information carried by the ambient seismic field. They used 375 Hi-Net borehole seismometers across central Honshu as virtual sources and 296 MeSO-Net shallow-borehole seismometers within the basin as receivers to map the basin impulse response. They find a linear relationship between vertical ground motion and basin depth at periods of 2 – 10 seconds that could be used to represent 3D basin effects in ground motion prediction equations. They also find that the strength of basin amplification depends on the direction of illumination by seismic waves.

11. Earthquake Engineering Implementation Interface (EEII)

The implementation of SCEC research for practical purposes depends on interactions with engineering researchers and organizations, and with practicing engineers, building officials, insurers, emergency managers, and other technical users of our information.

a. Gauntlets for Validating Ground Motion Simulations: SCEC worked to develop validation "gauntlets" that simulations should pass through to be considered viable for use in engineering applications, such as building-code analysis (simulations) of nonlinear building or site response. An important goal is to demonstrate how tailored to particular engineering applications such gauntlets must be, and the extent to which some validation gauntlets can cover a wide range of engineering applications. Burks and Baker (2014) have developed a validation gauntlet for the use of simulated ground motions in nonlinear response history analysis of 3D multi-degree-of-freedom buildings. This gauntlet consists of three validation tests that compare simple ground motion "proxy" parameters from simulated ground motions with corresponding empirical models. The simple parameters serve as proxies for the more complicated building response of interest, and the corresponding empirical models are robust against (or insensitive to) differences between the earthquake characteristics (e.g., magnitude) of simulated and historical ground motions. The three ground motion parameters are: (i) correlations of elastic spectral acceleration across multiple pair of spectral periods, (ii) ratios of maximum to median elastic spectral response acceleration across all horizontal ground motion orientations, and (iii) ratios of inelastic to elastic spectral displacement. This gauntlet of validation tests has been demonstrated for sample ground motions simulated by three different methods via the SCEC Broadband Platform.

b. Simulation Validation for Geotechnical Engineering Applications: A validation gauntlet for the use of simulated ground motions in geotechnical analysis of slope displacements and soil liquefaction is under development. These geotechnical responses are sensitive to ground motion duration--a property of simulated ground motions that has not previously been well studied. Thus, durations from simulated ground motions have been compared with a corresponding empirical model. This work has identified bias in the most recent available empirical model for duration, with respect to more-recently recorded ground motions. This has further led to development of an updated empirical model for duration that is now beginning to be compared with simulated ground motions (Stewart & Afshari, 2014).

c. Tutorial Session for Earthquake Engineering Outreach: To broaden the impact of SCEC's Ground Motion Prediction work, we developed and delivered a special session on Simulations at the 10th National Conference on Earthquake Engineering on July 22nd in Anchorage. Attended by approximately 100 academic and practicing engineers, the session presented an overview of SCEC's simulation approaches, computational infrastructure, and validation efforts. A lively panel discussion followed the presentations, where the audience had a chance to probe the SCEC speakers more deeply. Norm Abrahamson, Jack Baker, Nico Luco, Rob Graves, Phil Maechling and Kim Olsen were the SCEC scientists presenting at this session, and they also developed an overview paper summarizing the content presented at the session (Baker et al. 2014).

12. Working Group on California Earthquake Probabilities (WGCEP)

The Working Group on California Earthquake Probabilities (WGCEP) is charged with developing official, consensus, and time-dependent earthquake forecast models for California. The effort builds on a long tradition of previous WGCEPs (e.g., models published in 1988, 1990, 1995, 2003, and 2008), and involves explicit collaboration between SCEC, the USGS, and CGS, with considerable funding from the California Earthquake Authority. The previous (UCERF2) forecast was published in 2008. Since that time we have worked on the next model, UCERF3, for which the main goals have been to: 1) relax segmentation and include multi-fault ruptures; 2) compute more self-consistent long-term elastic-rebound-based probabilities; and 3) include clustering effects in acknowledgement that aftershocks and triggered events can be large and damaging. The latter (spatiotemporal clustering) will bring us into the realm of Operational Earthquake Forecasting (OEF). The need for these enhancements was exemplified by recent earthquakes, including the 2011 M9 Tohoku earthquake (segmentation), both the 2010 M7.2 El Mayor-Cucapah and 2012 M8.6 Sumatra earthquakes (multi-fault ruptures), and the 2011 M6.3 Christchurch earthquake (clustering). Progress on each of these goals is outlined below.

a. UCERF3-TI, The Time-Independent Model: The backbone of UCERF3 is the long-term, time-independent model (UCERF3-TI), published as a USGS Open-File Report on Nov. 5, 2013, and includes a main report, 20 appendices, and various supplements (*http://pubs.usgs.gov/of/2013/1165/*). The main report and one of the appendices have also been published in a peer-reviewed journal (Field et al., 2014; Page et al., 2014). The primary achievement for this model component was relaxing fault segmentation and including multi-fault ruptures, both limitations of UCERF2. The rates of all earthquakes were solved for simultaneously, and from a broader range of data, using a system-level "grand inversion" that is both conceptually simple and extensible. The inverse problem is large and underdetermined, so a range of models was sampled using simulated annealing. New analysis tools were developed for exploring solutions. Epistemic uncertainties were accounted for using 1440 alternative logic tree branches, necessitating access to supercomputers. The most influential uncertainties include alternative fault slip rates, a new smoothed-seismicity algorithm, alternative values for the total rate of M≥5 events, and different scaling relationships, virtually all of which are new. For the first time, three deformation models based on inversions of geodetic and geologic data, provided slip-rate constraints on faults previously excluded due to lack of geologic data. The grand inversion has demonstrated serious challenges to the Gutenberg-Richter hypothesis for individual faults. UCERF3-TI is still an approximation of the system, however, and the range of models is limited (e.g., constrained to stay close to UCERF2). Nevertheless, UCERF3-TI removes the apparent UCERF2 over-prediction of M6.5-7 earthquake rates and also includes types of multi-fault ruptures seen in nature. Although UCERF3-TI fits the data better than UCERF2 overall, there may be areas that warrant further site-specific investigation.

b. UCERF3-TD, The Long-Term, Time-Dependent Model: This model, which builds on UCERF-TI, includes long-term, time-dependent probabilities based on Reid's elastic-rebound hypothesis. The new methodology supports magnitude-dependent aperiodicity and accounts for the historic open interval on faults that lack a date-of-last-event. Epistemic uncertainties are represented with a logic

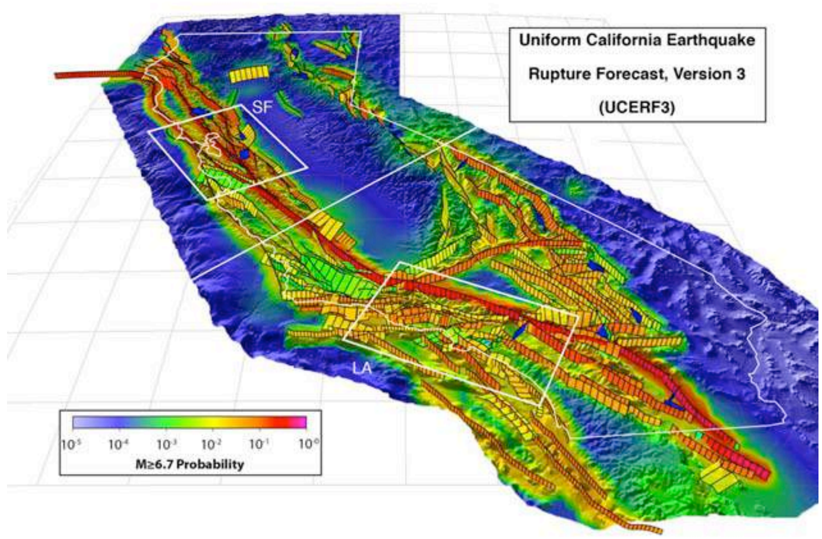


Figure 3.36. 3D perspective view of UCERF3-TD, where colors depict the mean "participation probability" – the likelihood that each point will experience one or more M ≥ 6.7 earthquakes in the 30 years following 2014, where participation means that some point on the rupture surface is within about 5 km. The small black rectangular elements represent the 2,606 fault subsections used in the forecast (for one of the two fault models, FM3.1). The influence of the Cascadia megathrust is not shown on this map.

tree, producing 5,760 different forecasts. For 30-year M≥6.7 probabilities, the most significant changes from UCERF2 are a threefold increase on the Calaveras Fault and a threefold decrease on the San Jacinto Fault. The changes are due mostly to differences in the time-independent models (slip rates), with relaxation of segmentation and inclusion of multi-fault ruptures being particularly influential. Probability model differences are also influential, with implied gains (relative to a Poisson model) being higher in UCERF3. Accounting for the historic open interval is one reason. Another is an effective 27% increase in the elastic-rebound-model weight. The factors influencing differences between UCERF2 and UCERF3, as well as the relative importance of logic-tree branches, vary throughout the region, and depend on the hazard metric of interest (e.g., M≥6.7 probability changes may not translate to hazard). This sensitivity, coupled with the approximate nature of the model, means the applicability of UCERF3 should be evaluated on a case-by-case basis. Overall, UCERF3 represents the best available model for forecasting California earthquakes. Three papers describing UCERF-TD have been reviewed by the Scientific Review Panel and submitted to the Bulletin of the Seismological Society of America for publication. Figure 3.36 shows the probability that each area in California will participate in M≥6.7 earthquakes over the next 30 years.

c. UCERF3-ETAS, Spatiotemporal Clustering for OEF: With the time-independent model published, which relaxes segmentation and includes multi-fault ruptures, and the long-term time-dependent model in review, which incorporates elastic rebound, SCEC has turned attention to spatiotemporal clustering. In recognition that triggered events can be large and damaging, the ultimate goal is to deploy an Operational Earthquake Forecast (OEF) for California, now listed as one of the USGS's strategic-action priorities (*http://pubs.usgs.gov/of/2012/1088*; page 32). To this end, we added an Epidemic Type Aftershock Sequence (ETAS) component to UCERF3 (UCERF3-ETAS). This model represents a merging of ETAS with finite-fault based forecasts, as well as the inclusion of elastic rebound. Inclusion of elastic-rebound is critical to representing spatiotemporal clustering correctly. Without it, ~85% of large triggered events simply re-rupture the same fault, which is not observed in nature. UCERF3-ETAS is currently being “test-driven”. The model will subject to more rigorous testing (e.g., via CSEP) in the coming year.

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

The Collaboratory for the Study of Earthquake Predictability (CSEP) provides a controlled and transparent research infrastructure for the prospective and blind evaluation of earthquake forecasting and prediction methods.

a. Construction of Optimal Multiplicative Hybrid Models: Rhoades et al. (2014) examined the performance of multiplicative hybrid models based on the suite of 5-year forecasting models submitted to the Regional Earthquake Likelihood Models (RELM) experiment. They constructed optimal multiplicative hybrids involving the best individual model (Helmstetter et al. smoothed seismicity) as a baseline and one or more conjugate models. Many two-model and three-model hybrids show appreciable information gain (log probability gain) per earthquake relative to the best individual model. The information gains of the best multiplicative hybrids are greater than those of additive hybrids (including Bayesian ensemble models) constructed from the same set of models. The gains tend to be larger when the contributing models involve different concepts or data. Multiplicative hybrids will be useful for assimilating other earthquake-related observations into forecasting models and for combining forecasting models at all time-scales.

b. Evaluation of 3-month Forecasting Models for California: Schneider et al. (2014) evaluated seven 3-month models for California, consisting of contrasting versions of the Every Earthquake a Precursor According to Scale (EEPAS) and Proximity to Past Earthquakes (PPE) modeling approaches. The study was complemented by several residual-based methods, which provide detailed spatial information. The testing period covered June 2009-September 2012. Though all models fail to capture seismicity during an earthquake sequence, spatio-temporal differences between models emerged. The best-performing model has strong time- and magnitude-dependence and weights all earthquakes equally as medium-term precursors of larger events. Models with this time- and magnitude-dependence offer a statistically significant advantage over simpler models. In addition, models that down-weight aftershocks when forecasting larger events do not overpredict following an observed earthquake sequence.

c. Extending CSEP to Testing of Ground-Motion Predictions and Hazard: The team at GFZ has continued to work on the integration of ground-motion testing into the CSEP software system. The component for testing intensity-prediction equations is almost complete. As a case study to show the potential of this kind of testing, Mak et al. (in revision) have presented a concise and detailed evaluation of Italian intensity-prediction equations. A case study on ground-motion prediction equations in Japan is in preparation. Testing the USGS hazard map against *Did You Feel It?* data and shakemaps is underway.

d. Collaboration with the Global Earthquake Model: CSEP is working with the Global Earthquake Model (GEM) project in the field of testing ground-motion prediction equations and hazard. Testing of the USGS hazard model is a direct result of the Powell Center Group meeting, which was held by the USGS and GEM in 2013 and targeted the testability of hazard models. With the development of the GEAR seismicity model for GEM at UCLA, CSEP will continue this collaboration by testing the GEAR model.

e. Prototype Experiments to evaluate External Forecasts and Predictions: Two prototype experiments are in development to import and evaluate external forecasts and predictions generated outside of CSEP and may be based on seismic, electromagnetic or other data sets that CSEP cannot provide internally. The first experiment involves the QuakeFinder group led by Tom Bleier, where an xml-based template to register predictions within CSEP I sunder prediction algorithm M8 algorithm: M. Rierola and J. Zechar (ETH) are collaborating with Kossobokov (Moscow & IPG Paris) to register and evaluate predictions retrospectively and prospectively within CSEP. M8 predictions starting in 1985 were evaluated retrospectively against the PDE earthquake catalog using the gambling score of Zhuang (2010). Preliminary results showed unacceptable features of the score: an strategy of always declaring alarms would outperform the reference Poisson model as well as M8 predictions, most likely as a result of skewed returns (wins are unlimited, losses are limited to the ante). An improved parimutuel gambling score mtho (Zechar and Zhuang, 2014), is now being investigated for the purpose of evaluating M8.

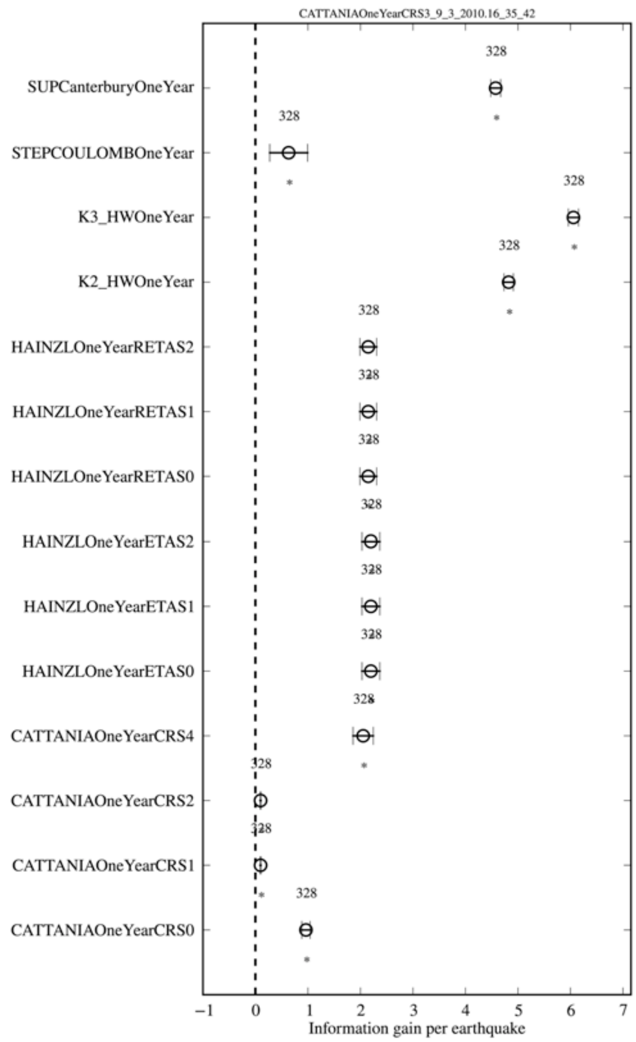


Figure 3.37. Information gain of a 1-year forecast by a Coulomb/Rate-State model by Cattania et al. against other statistical and physics-based forecasts starting right after the 2010 Darfield earthquake. For the considered 1-year period, the Coulomb model outperforms all other forecasts, including those of a hybrid STEP/Coulomb model, ETAS models with various spatial triggering kernels and various other Coulomb models. The gain shown is calculated with the model on the left as the reference model, i.e. positive gains show superior performance by the Coulomb model named in the title.

f. Retrospective Canterbury Experiment: The M7.1 Darfield, New Zealand, earthquake triggered a complex earthquake cascade that provides an ideal opportunity to study earthquake triggering and the predictive skill of statistical and physics-based forecasting models. CSEP New Zealand and the European FP7 project REAKT are collaborating to conduct a retrospective evaluation of a variety of short-term forecasting models during the Canterbury earthquake sequence. The statistical models includes variants of the ETAS model, non-parametric kernel smoothing models, and the Short-Term Earthquake Probabilities (STEP) model. The physics-based models include variants of the Coulomb stress triggering hypothesis, which are embedded either in Dieterich's (1994) rate-state formulation or in statistical Omori-Utsu clustering formulations (hybrid models). Initial results of 1-year forecasts beginning after the Darfield event indicate that Coulomb/rate-state models that propagate the uncertainty of input parameters and data through to forecasts obtain the largest information gains (Figure 3.37), while a suite of ETAS models perform best when 1-year forecasts are updated after each of the largest earthquakes in the sequence.

g. VISES-Funded Collaboration with CSEP Japan: Werner et al. (in preparation) calibrated two forecasting models from the California testing region to Japanese seismicity. In collaboration with the Earthquake Research Institute (ERI), parameters of the two models were estimated for the three different CSEP-Japan testing regions to generate retrospective forecasts that will be compared to extent prospective models within CSEP-Japan. The two models were developed by Helmstetter & Werner (2012) and employ space-time kernels to smooth seismicity for time-independent forecasting. The models build on the success of the Helmstetter (adaptive smoothing) model that performed well in the RELM experiment. The methods circumvent the need for declustering an earthquake catalog by estimating the distribution of rates with space-time kernels and choosing the median as the predictor of the future rate in each spatial cell. The models will be installed in the 3-month, 1-year and 3-year forecast groups of the Japan testing center for prospective evaluation (Figure 3.38). The prospective predictive skills will be compared to California results to infer the extent to which skills are affected by local tectonic setting.

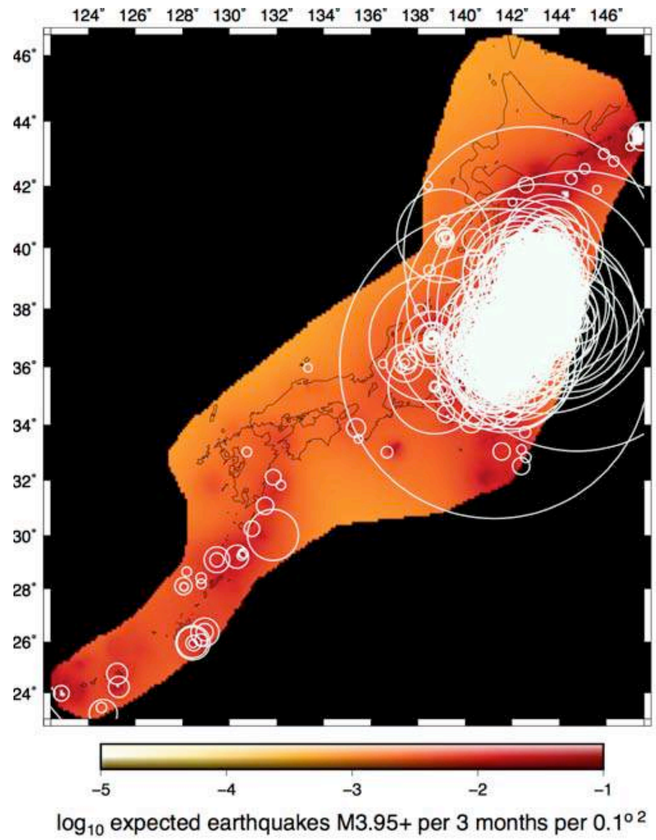


Figure 3.38. 3-month forecast for the AllJapan testing region of CSEP Japan along with observed earthquakes between February and April 2011, including the M9 Tohoku earthquake sequence. The forecast was generated with a space-time smoothed seismicity model, named Conan (Helmstetter & Werner, 2012) that is already under evaluation in California. Retrospective evaluations and comparisons against California will increase our understanding of the influence of tectonic setting on the model's forecasting skill.

B. Communication, Education and Outreach Accomplishments

SCEC's Communication, Education, and Outreach (CEO) program complements the SCEC Science Plan, fostering new research opportunities and ensuring the delivery of research and educational products to the general public, government agencies, the broader geoscience community, engineers, students, businesses, and the media. SCEC CEO addresses the third element of SCEC's mission: *Communicate understanding of earthquake phenomena to the world at large as useful knowledge for reducing earthquake risk and improving community resilience.*

The theme of the CEO program during SCEC4 is *Creating an Earthquake and Tsunami Resilient California.* This includes: increased levels of preparedness and mitigation; expanded partnerships with research and practicing engineers, building officials, and others; routine training and drills; financial preparedness; and other ways to speed recovery and enhance future resilience. Each of these activities benefit from advances in earthquake science, by SCEC scientists and others (while tsunami research is not be a focus of SCEC, tsunami education and preparedness is an element of the CEO program and the ECA). The goal is to prepare individuals and organizations for making decisions (split-second through long-term) about how to respond appropriately to changing seismic and related hazards, including tsunami warnings and new technologies such as operational earthquake forecasts and earthquake early warning.

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

SCEC CEO is organized into four interconnected thrust areas:

- **Implementation Interface** connects SCEC scientists with partners in earthquake engineering research, and communicates with and trains practicing engineers and other professionals;
- **Public Education and Preparedness** thrust area educates people of all ages about earthquakes, and motivates them to become prepared;
- **K-14 Earthquake Education Initiative** seeks to improve earth science education and school earthquake safety;
- **Experiential Learning and Career Advancement** provides research opportunities, networking, and more to encourage and sustain careers in science and engineering.

SCEC CEO is led by SCEC's associate director for CEO Mark Benthien, with Bob deGroot managing Experiential Learning and Career Advancement programs, John Marquis as digital products manager and webmaster, Jason Ballman as Communications Specialist, David Gill as web developer, several contractors for ECA and ShakeOut activities, and a legion of USC student assistants and interns each year. The Earthquake Engineering Implementation Interface between SCEC and its research engineering partners is led by Jack Baker (Stanford) (who serves on the Planning Committee) and Jacobo Bielak (Carnegie Mellon). Several other SCEC scientists also are regularly involved in program development, intern mentorship, and other roles. A new subcommittee of the SCEC Advisory Council now reviews the CEO program each year.

SCEC also continues to expand its CEO activities through partnerships with groups in academia and practice. The Earthquake Country Alliance (ECA), created and managed by SCEC, continues to grow and serve as a model for multi-organizational partnerships that we plan to establish within education and among practicing and research engineers.

SCEC CEO has been very successful in leveraging its base funding with support from the California Earthquake Authority (CEA), FEMA, CalEMA, 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. Since 2010 FEMA has provided SCEC and its Earthquake Country Alliance partners nearly $1.5 million for ECA activities and national ShakeOut coordination. The CEA has spent several million dollars on radio, TV, print, and online advertising which features ShakeOut promotion each year. SCEC's intern programs have also been supported with more than $1.3 million in additional support from several NSF programs and a private donor, and NASA supports SCEC's "Vital Signs of the Planet" teacher development program via a subcontract through JPL.

1. Implementation Interface

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

a. Research Engineering Partnerships

SCEC produces a large body of knowledge about the seismic hazard in California that enhance seismic hazard maps, datasets, and models used in building codes and engineering risk assessments. The Earthquake Engineering Implementation Interface led by Jack Baker and Jacobo Bielak provides the organizational structure for creating and maintaining collaborations with research engineers, in order to ensure SCEC's research activities are aligned with their needs. These activities include rupture-to-rafters simulations of building response as well as the end-to-end analysis of large-scale, distributed risk (e.g., ShakeOut-type scenarios). Analysis of the performance of very tall buildings in Los Angeles using end-to-end simulation remains a continuing task that requires collaboration with both research and practicing engineers through PEER and other organizations. An important Technical Activity Group in SCEC4 is the Ground Motion Simulation Validation (GMSV) group, led by Nico Luco, which is developing procedures for the validation of numerical earthquake simulations that are consistent with earthquake engineering practice. Our goal of impacting engineering practice and large-scale risk assessments require even broader partnerships with the engineering and risk-modeling communities, which motivates the activities described next.

b. Activities with Technical Audiences

The Implementation Interface also develops mechanisms for interacting with technical audiences that make decisions based on understanding of earthquake hazards and risk, including practicing engineers, geotechnical consultants, building officials, emergency managers, financial institutions, and insurers. This will soon include expansion of the Earthquake Country Alliance to include members focused on mitigation, policy, and other technical issues. SCEC is also planning training sessions and seminars for practicing engineers and building officials to introduce new technologies (including time-dependent earthquake forecasts), discuss interpretation and application of simulation records, and provide a forum for SCEC scientists to learn what professionals need to improve their practice. An example is the annual SEAOSC *Buildings at Risk Summits* which SCEC has co-organized since 2011 in both Los Angeles and San Francisco (with SEAONC). The 2014 conference is titled "Strengthening our Cities" and will be held on October 20 in Los Angeles. Also on September 18 SCEC/ECA is supporting the "Earthquake 2014 Business Preparedness Summit" with FLASH, Safe-T-Proof, Simpson Strongtie, and several other partners, an event which will launch a new FEMA QuakeSmart recognition program for businsses that demonstrate mitigation they have implemented. We are also collaborating with EERI, NEES, PEER, and others. These activities will increasingly be online, with frequent webinars and presentations and discussions recorded and available for viewing online.

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

2. Public Education and Preparedness

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

a. Earthquake Country Alliance (ECA)

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 Associate Director for CEO Mark Benthien serves as Executive Director of the ECA. To participate, *visit www.earthquakecountry.org/alliance*.

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 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*, *www.terremotos.org*), and has managed the printing of the "Putting Down Roots" publication series throughout the state. This past year a special "Northridge Earthquake Virtual Exhibit" was added to the ECA site with "Northridge Near You" animations created by SCEC UseIT interns, and interviews with people who experienced the Northridge earthquake across southern California. Similar "Near You" animations are being made for the Loma Prieta 25th anniversary.

An additional new website, www.tsunamizone.org was also created in 2014 for National Tsunami Preparedness Week in March, with support from NOAA via CalOES. The site is essentially a clone of the ShakeOut model, allowing registration of tsunami preparedness activities, educational content including inundation maps, and much more. The initial site was created for California but the plan is to expand the site to be national if not international. For now this is condidered an ECA activity but when expanded nationally its "home" in the ECA will be reevaluated (this is similar to other activities where ECA is reaching out beyond California.)

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.

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 the following ECA sector-based committees to develop customized materials and activities:

- Businesses
- Communications
- EPIcenters (museums, parks, libraries, etc.)
- Evaluation
- Fire Advisory Cmte. (2013 subtheme)
- Public Sector
- Healthcare
- K-12 Schools
- Non-Profits and Faith-Based Organizations
- Seniors and People with Disabilities
- Speakers Bureau (Southern California)

The ECA public-private partnership is the primary organizational structure within the Public Education and Preparedness thrust area. Due to the success of the ShakeOut, the ECA is now statewide and includes three established regional alliances. In September, 2011 the relationship between SCEC and the ECA (managed by SCEC since it's inception in Southern California in 2003) was cemented via a Memorandum of Understanding specifying SCEC as the administration headquarters of the statewide alliance and SCEC'S Associate Director for CEO as ECA's Executive Director. The MOU describes SCEC's roles and responsibilities in managing the ECA under the direction of a Steering Committee comprised of three representatives of the three regional alliances in Southern California, the Bay Area, and the North Coast. The Great California ShakeOut has been the primary collaborative activity so far, but additional activities with measurable outcomes are also managed or planned by the ECA. This planning builds on a California Office of Emergency Services earthquake communications plan developed in 2009 that emphasizes the value of a statewide collaboration.

Each ECA organization, including SCEC, independently determines the commitment of the their own resources, including human, technical, and financial resources, as they carry out the fundamental actions of this voluntary, non-binding Agreement. As the home of ECA, SCEC allocates appropriate staff and administrative resources (phones, mailing, etc.) and may seek additional funding for these resources in partnership with the ECA. SCEC provides mechanisms for managing ECA-specific funding and resources that are not co-mingled with other SCEC funding, and works with ECA leadership to ensure that such resources are allocated appropriately.

<u>ECA 5-year goals (2012-2017):</u>

- Further develop the awareness of, engagement in, and support for the ECA among internal audiences
- Cultivate collaboration among stakeholder Alliance members
- Build and maintain a community of earthquake / tsunami-ready Californians who, by demonstrating their readiness activities within their social circles, can help foster earthquake readiness as a social movement as well as all-hazard preparedness
- Expand the community of earthquake / tsunami-ready Californians by reaching out to those who are not yet engaged in earthquake/tsunami readiness activities

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 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. In October 2014 ECA received the "Excellence in Disaster Preparedness" award from the American Red Cross, Orange County, CA.

b. ShakeOut Earthquake Drills

Great ShakeOut Earthquake Drills 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

USGS “ShakeOut Scenario” developed by a team of more than 300 experts led y Dr. Lucy Jones). ShakeOut communicates scientific and preparedness information based on 30 years of research about why people choose to get prepared. Its purpose is to motivate everyone, everywhere to practice earthquake safety (“Drop, Cover, and Hold On”), and to get prepared at work, school, and home.

For the ShakeOut Scenario 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. While intended to be held only once, requests from ShakeOut participants prompted partners and state agencies to expand the event statewide as an annual ShakeOut drill on the third Thursday of October. More than 6.9 million Californians participated in October, 2009. This date is ideal for schools and follows National Preparedness Month in September, allowing for significant media 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, non-profit organizations, government offices, neighborhoods, and individuals. Each year participants are encouraged to incorporate additional elements of their emergency plans into their ShakeOut drill.

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, and Central US (AL, AR, GA, IN, IL, KY, MI, MO, OK, SC, TN)

2012: 19.4 million
All above plus:
AK, AZ, Southeast (DC, GA, MD, NC, SC, VA), UT, WA, Puerto Rico, Japan (central Tokyo), New Zealand, Southern Italy (US naval bases and surrounding areas), and a new “Global” site for all other areas.

2013: 24.9 million
All above except New Zealand, plus:
Rocky Mountain region (CO, WY, MT), HI, OH (now in the Central U.S.), WV & DE (now in the Southeast region), Northeast region (CT, PA, MA, ME, NH, NJ, NY, PA, RI), American Samoa, U.S. Virgin Islands, Commonwealth of Northern Marianas Islands. Charlevoix region of Quebec, and expansion across Japan.

2014: 26.6 million
All above plus New Mexico, Yukon, all Quebec, and participation in 59 countries via coordination of Aga Khan Development Network

In addition to its lead role in organizing the California ShakeOut, SCEC manages a growing network of ShakeOut Regions across the country and around the world (see www.shakeout.org). In order to develop and maintain the ShakeOut brand and reduce potential confusion between the different drills, SCEC works with officials in these regions and for most hosts the website for their drill. This approach serves to standardize earthquake messaging nationally and internationally, and allow groups to share best practices for recruiting participation, such as the use of social networking sites. Some ShakeOuts rely more heavily on SCEC, while some are managing more of their content, reviewing registrations, and more actively communicating with participants. For example, as part of activities for the New Madrid earthquake bicentennial, the Central U.S. Earthquake Consortium (CUSEC) organized the first multi-state drill in April 2011, with 3 million participations across eleven states. CUSEC also now coordinates the SouthEast ShakeOut which had its kick-off event at the damaged Washington Monument on the one-year anniversary of the 2011 Mineral, VA, earthquake.

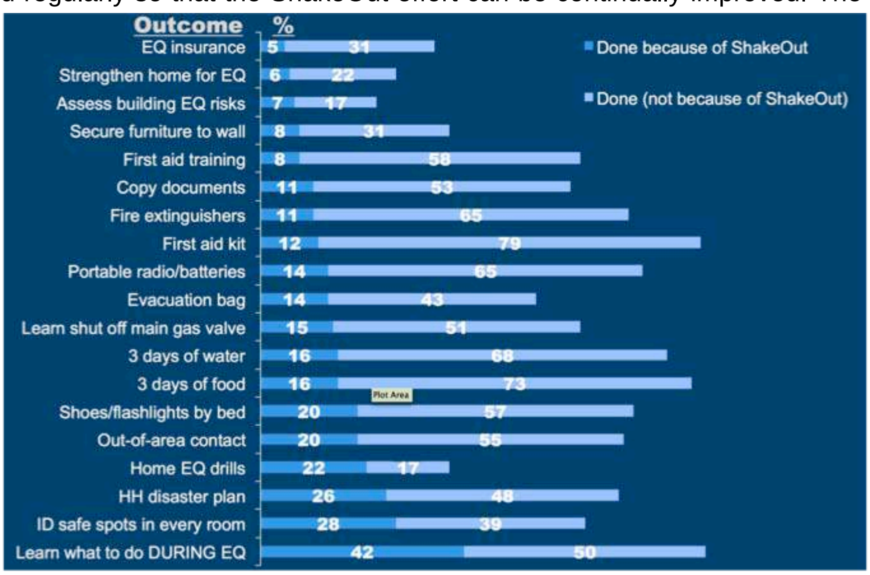
As of September, 2014, 25 Official ShakeOut Regions (each with their own website managed by SCEC) now span 45 states and territories, three Canadian provinces, New Zealand, Southern Italy (U.S. Naval bases), and a rapidly growing number of Japanese cities and prefectures. All of these areas are holding ShakeOut drills annually (see the global homepage at *www.shakeout.org*), except New Zealand (every few years). In addition, people and organizations in any other state or country can now register to be counted in the overall global total each year. ShakeOut websites are now online in English, Spanish, French, Italian, and Japanese. We are developing outreach materials to encourage other countries to participate, includng Iran (which has annual earthquake drills in its schools involving several million people).

Recruitment is well underway for the 2014 ShakeOut on October 16 at 10:16 a.m., with over 9.1 million participants registered in California and more than 13.7 million worldwide as of September 1 Including drills held earlier in 2013, already more than 17.5 million people worldwide have have registered in 2014. Our goal is to exceed 30 million participants

FEMA provides support to SCEC to manage each region's ShakeOut website, create materials, and provide other assistance. However, each ShakeOut is only successful when state or regional public and private partners work together to recruit participation. One reason for ShakeOut's success has been its practice of localizing content for each region, so that organizers and participants take ownership of their ShakeOut (even though all websites and materials are centrally managed). FEMA's multidisciplinary "Whole Community" approach is essential, with customized information provided for more than 20 audience categories (schools, families, businesses, government, nonprofit organizations, museums, etc.). Each registered participant receives e-mail reminders as well as drill instructions, preparedness and mitigation information, and access to a variety of resources available on their region's ShakeOut website. These include comprehensive drill manuals, an audio file to play during the drill, and downloadable posters, flyers, and artwork.

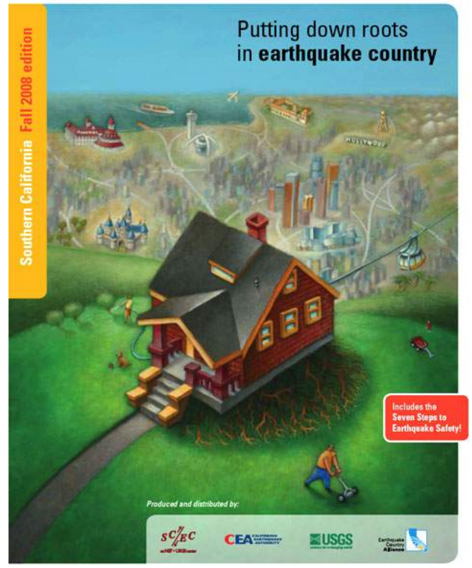
The ShakeOut has been the focus of significant media attention and has gone a long way to encourage dialogue about earthquake preparedness in California. Through the ShakeOut, the ECA does more than simply inform Californians about their earthquake risk; it has become an infrastructure for providing earthquake information to the public and involving them in community resiliency, teaching people a life-saving response behavior while fostering a sense of community that facilitates further dialogue. In addition to registered participants, millions more see or hear about ShakeOut via broad news media coverage. ShakeOut generates thousands of news stories worldwide each year and has been featured on the front page of the *New York Times,* on many national and local morning television programs, and even in late-night talk shows. This media attention encourages dialogue about earthquake preparedness.

While assessing participation via registration and showcasing ShakeOut activities have been essential from the start, surveys are providing insights into what participants are learning and improving in terms of preparedness and mitigation. A state-sponsored survey of California household earthquake preparedness in 2008 will hopefully be repeated regularly so that the ShakeOut effort can be continually improved. The ECA Evaluation Committee conducts and encourages additional social science research specific to the ShakeOut.



In the future, operational earthquake forecasts should create additional interest for the ShakeOut drills and increase participation and preparedness in general (as well as interest in earthquake science). The ShakeOut drills are also an excellent structure to prepare Californians to respond to earthquake early warnings. For the warnings to be effective, individuals, organizations, and governments must be trained in how to respond appropriately given their situation. Also, the Shakeout drills continue to be an annual exercise of SCEC's post-earthquake response plan. The slogan of the ECA is "we're all in this together" and as far as ShakeOut goes, "we've only just begun."

c. Putting Down Roots in Earthquake Country

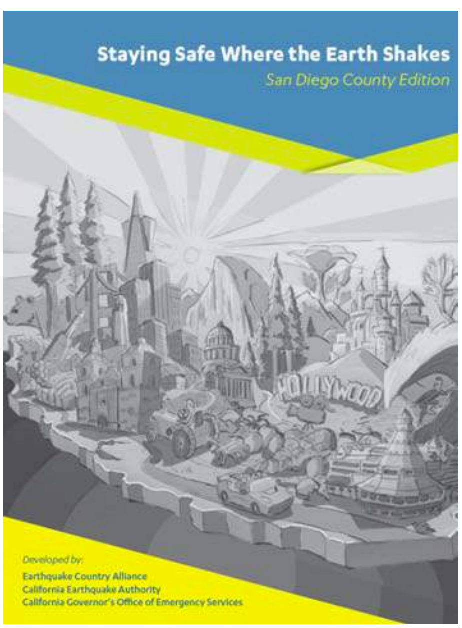


Putting Down Roots in Earthquake Country, a 32-page handbook, has provided earthquake science, mitigation, and preparedness information to the public since 1995. *Roots* was first updated in 2004, including the creation of the *Seven Steps to Earthquake Safety* to organize the preparedness content. Since 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.

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

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

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). 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 (*www.earthquakecountry.org*).



This print and online publication series remains very popular and likely will be replicated in additional regions during SCEC4, similar to new versions produced since 2005. The existing versions will continue to be updated and improved with new science and preparedness information. For example, tsunami content was added in 2011 to the Southern California version of the handbook, based on content created for the 2009 version of *Living on Shaky Ground.* This is a similar document published by the Redwood Coast Tsunami Workgroup that now also includes the SCEC/ECA *Seven Steps to Earthquake Safety.*

Research results related to earthquake forecasting are already included in the handbook, and this information will be updated as operational earthquake forecasts and earthquake early warning become a reality in California.

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

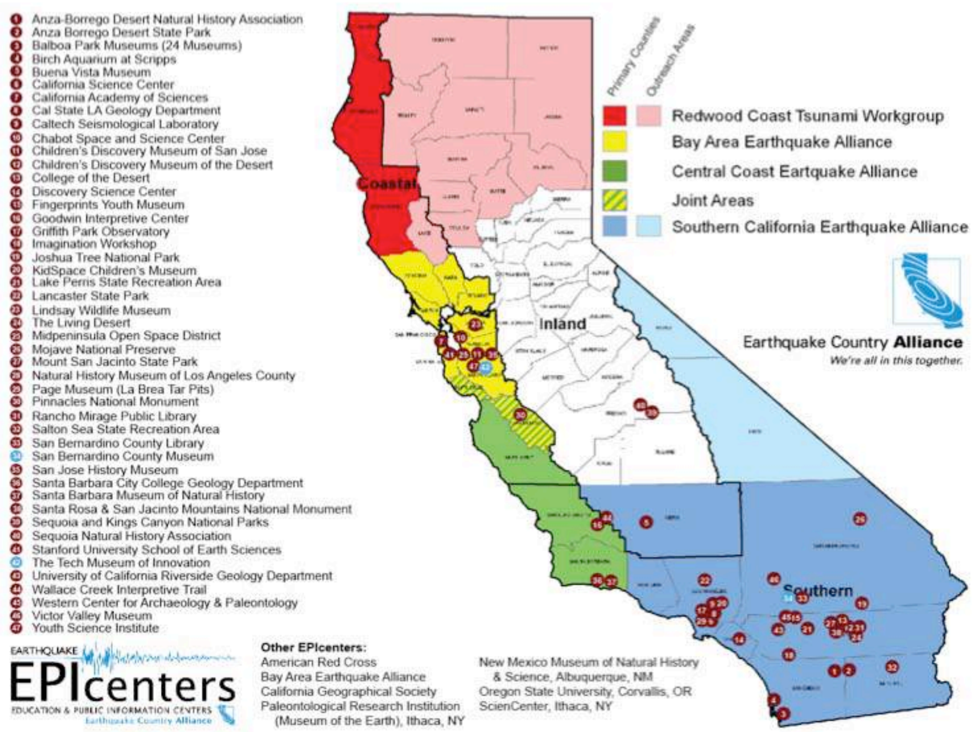
For example, in 2013 the California Earthquake Authority and California Office of Emergency Services supported the development of the lastest booklet in the *Putting Down Roots* series, *Staying Safe Where the Earth Shakes*. Subject matter experts from ECA organizations worked together to simplify the *Seven Steps to Earthquake Safety* and local earthquake and tsunami hazard descriptions into a booklet with half the number of pages of other booklets, which can be more easily translated into multiple languages and was produced for 8-10 regions of the state. In Fall 2014 all versions will be available from the ECA website, and CEA will provide support to SCEC for customizing booklets (logos, text) for government agencies or organizations who will then print booklets for their own distribution.

d. Earthquake and Tsunami Education and Public Information Centers (EPIcenters)

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, a temporary earthquake exhibit at the UCSD Birch Aquarium, and most recently with the San Bernardino County Museum (SBCM) we are developing an interpretive site at Pallett Creek. The expansion of these partnerships, especially with the SBCM in 2007, led SCEC to create the Earthquake and Tsunami *Education and Public Information Center* (EPIcenter) 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. Each implements a variety of activities including displays and talks related to the ShakeOut and other activities year round. The California network of more than 60 institutions is coordinated by SCEC's Robert de Groot with Kathleen Springer (San Bernardino County Museum, Redlands) and Candace Brooks (The Tech Museum, San Jose) coordinating Network activities in Southern and Northern California respectively. Kathleen is also a member of the statewide Steering Committee of the Earthquake Country Alliance.

These partners share a commitment to encouraging earthquake and tsunami preparedness. They help coordinate Earthquake Country Alliance activities in their county or region (including ShakeOut), lead presentations or organize events in their communities, develop educational displays, or in other ways provide leadership in earthquake and tsunami 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.



SCEC CEO has also established relationships with institutional partners in other states (2 in Oregon, 2 in Alaska, 1 in Arizona, and 3 in New England) Growth has been enhanced through the collaboration with the Cascadia EarthScope Earthquake Education and Tsunami Education Program (CEETEP) and the EarthScope Interpreters workshops in Oregon, Washington, and Alaska (see K-12 Education Initiative below for more details). Recently the Network has been collaborating with the Central United States Earthquake Consortium to create an EPIcenter network for the Central U.S. The following are highlights of 2014 activities:

- San Bernardino County Museum (SBCM): In 2006 SCEC embarked on a long-term collaboration with SBCM in Redlands, California, beginning with the development and implementation of the *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*. Then 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.

Community members are greeted by Shakeout banners as they enter the San Bernardino County Museum to participate in the ShakeOut Drill.

  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*. The Hall is a major expansion of this important cultural attraction and center of science education 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 cornerstone of this new informal learning framework is the creation of the Hall of Geological Wonders Learning Treks Program (GeoTreks). The model outlines a K-12 field trip to the SBCM. A long-term goal of the program is to establish individual GeoTreks for different ages of school groups and Hall of Geological Wonders exhibits. The GeoTrek activity is based on Lesson Study, an educational approach using observations of student learning to inform small, incremental improvements to the lesson. Lesson Study focuses on a specific, observable learning goal, determined prior to the activity chosen to address the particular aspect of learning.

  The SBCM/SCEC collaboration continues to evolve with the development of an innovative approach in museum exhibit experiences, The visitor is invited to stand on the San Andreas fault at Pallett Creek. Over the last two years SBCM and SCEC interns created the prototype of a field guide series, *The San Bernardino County Museum Discover Your Backyard Field Guides,* which interprets Pallett Creek in Valyermo, CA, widely known as "the Rosetta Stone of Paleoseismology". A re-excavated "trenchcrop" at Pallett Creek provides the basis for the field guide, which includes basic geological background as well as lithologic and chronologic data about earthquake events as revealed at the outcrop. This is a unique approach to informal learning, whereby visitors gain information both in a museum setting, then firsthand in the field, making their own discoveries and connections.

- Quake Catcher-EPIcenter Network: SCEC has enhanced earthquake programming and resources through working with institutions to enhance programs aimed at floor facilitation, live interactions, and the professional development of educators at all levels. For example SCEC has expanded the Quake Catcher Network of low-cost seismic sensors with installations at over 26 EPIcenter locations in California and Oregon, and more than 100 at schools in each west coast state including Alaska. Sensors have been installed at all high schools in the Lake Elsinore Unified School District. Installation of sensors in the Chaffey Joint Union High School District started in October 2013. The goal is to establish several K-12 sensor stations around a given EPIcenter as a means to build long-term educational partnerships around the ShakeOut, citizen science, and an opportunity to enrich standards-based K-12 curriculum. We have found that free-choice learning institutions are hungry for new programming that will engage science educators and their students in "citizen science" projects. SCEC is collaborating with the USGS, Stanford, NEES, and the California Geological Survey, and various members of the EPIcenter network to establish a QCN professional development program for science educators to be administered by free-choice learning institutions across the Network. Once the teachers are trained to use QCN as research and classroom learning tool, we will build a "citizen science" community among those teachers (and their students) using the local EPIcenter as a hub. The first hub has been established at the San Bernardino County Museum in Redlands.

- "Native California is Earthquake Country!" Initiative: SCEC has worked with the Sherman Indian High School (SIHS) in Riverside, CA, to develop earthquake awareness and preparedness messaging, beginning with translation of "Drop, Cover, and Hold On" into many Native American languages. The translations were then featured in two posters; one for the school with languages of tribes from across the U.S. with students attending the school (displayed in classrooms and dormitories at the school) and a "Native California is Earthquake Country" poster which will be distributed to Native American cultural centers, administrative buildings, and schools throughout California. In 2014 SCEC also worked with SIHS to film "The Turtle Story," a Native American accounting of how earthquakes occur, told by storyteller and USC alumna Jacque Tahuka-Nunez (tribal descendant of the Acjachemen Nation). The story comes from the Gabrielino-Tongva Tribe, a California Indian Tribe also known as the San Gabriel Band of Mission Indians.
- Other Activities: Recent EPIcenter activities include completion of the Science Spectacular Earthquake Program (co-developed with the California Science Center) and San Andreas fault content for the IRIS "Active Earth" display, and an earthquake and tsunami workshop for Southern California educators was hosted by the Cabrillo Marine Aquarium in Spring, 2014. New EPIcenter exhibits have also recently been completed at the California Academy of Sciences, San Francisco, and the earthquake themed highway reststop in Marston, MO. Ongoing projects include the Hatfield Marine Science Center in Newport, OR and San Diego Mesa College.

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

e. Media Relations

SCEC scientists are increasingly called upon for interviews by local, national, and international reporters and documentary producers. This is especially true after earthquakes, even those in other countries. As a result the demand on SCEC scientists after a large California earthquake will be even greater than in previous earthquakes. In 2014 SCEC staff developed new procedures for post-earthquake media coordination. In addition, the breadth of SCEC's research, including its information technology programs and the development of time-dependent earthquake forecasting, is also increasing the need for expanded media relations. New strategies and technologies are being developed to meet these demands.

For example, SCEC is implementing use of a media relations service for identifying and connecting with reporters nationwide. The service maintains current contact information for reporters and assignment editors and allows us to distribute and track news releases (rather than relying on USC or other partners). SCEC has used a companion service from the same provider for tracking coverage of SCEC and ShakeOut news.

Social media capabilities have also being expanded in SCEC4 (*twitter.com/scec* now has 517 followers, and *facebook.com/scec* has 2,124 "likes") under the management of SCEC's new Communciation Specialist Jason Ballmann (whose hiring is the result of increased support from FEMA). The SCEC Youtube Channel (*youtube.com/scec)* is now regularly supplemented with new content. will soon include the use of podcasts, webinars and other virtual news conferences, and other technologies. SCEC and the ECA are increasing the availability of multi-lingual resources (materials, news releases, experts, etc.) to more effectively engage all media, including foreign media. Summer and school-year internships for journalism or communications students assist CEO staff in developing these technologies and resources.

An important component to our media relations strategy will be media and risk communication training for the SCEC Community. Training will likely be held each year at the SCEC Annual Meeting (the first was in 2012). New content management software for SCEC's web pages will allow members of the community to create online summaries of their research, along with video recordings of presentations, as part of a new experts directory. SCEC will partner with USGS, Caltech, and other partners to offer annual programs that educate the media on how to report earthquake science, including available resources, appropriate experts, etc. The first two were held in January 2014 as part of the 20th Anniversary of the Northridge Earthquake (a media training workshop at Caltech and a press conference at USC).

3. K-14 Earthquake Education Initiative

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

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

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

SCEC's approach is as follows. First, we facilitate learning experiences and materials for use with real earthquakes and the ShakeOut drill. This will include online resources and activities, appropriate for various subjects (science, math, geography, etc.) for teachers to download immediately after large earthquakes and prior to the ShakeOut, to be hosted on SCEC's website and also shared with IRIS, UNAVCO, USGS and others for their similar teachable moment resource webpages (similarly as our coordination with IRIS and EarthScope on the Active Earth display). Second, SCEC and our education partners will develop learning materials that complement traditional standards-based instruction with regional and current earthquake information. Teacher workshops will be offered to introduce these resources to educators at all levels, and will include follow-up activities over the long-term to help implement the content. Evaluation will be conducted across all activities, perhaps involving education departments at SCEC institutions. These activities are described below.

a. 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 and leadership in organizations such as the National Association of Geoscience Teachers, the Coalition for Earth System Education, and local and national science educator organizations such as the California Science Teachers Association (CSTA). Improvement in the teaching and learning about earthquake science hinges on improvement in Earth science education in general. Hence, SCEC contributes to the science education community through participation on outreach committees and work groups wherever possible, co-hosting meetings, workshops, and building long-term sustained partnerships.

National Science Teachers Association and California Science Teachers Association (CSTA). Earthquake concepts are found in national and state standards documents and SCEC is on the leading edge of engaging eduation professionals as the New Generation Science Standards and Common Core State Standards are implemented SCEC participates in national and statewide science educator conferences to promote innovative earthquake education and communicate earthquake science and preparedness to educators in all states. In 2011 and 2013 SCEC participated in the planning committee for the annual California Science Education Conference hosted by CSTA. For the 2013 conference SCEC sponsored a keynote talk given by 2007 USEIT intern alumus Emmett McQuinn. McQuinn and his team at IBM won first place in the Illustration Category in the 2012 International Science & Engineering Visualization Challenge for the image *The Connectivity of a Cognitive Computer Based on the Macaque Brain*. Since 2009 SCEC has hosted a field trip for the conference and in 2013, SCEC and the San Bernardino County Museum hosted a field trip along the San Andreas fault. This will be conducted again in December, 2014 as part of the combined NSTA/CSTA meeting in Long Beach. The trip will be co-hosted by SCEC and the InSight Vital Signs of the Planet Program.

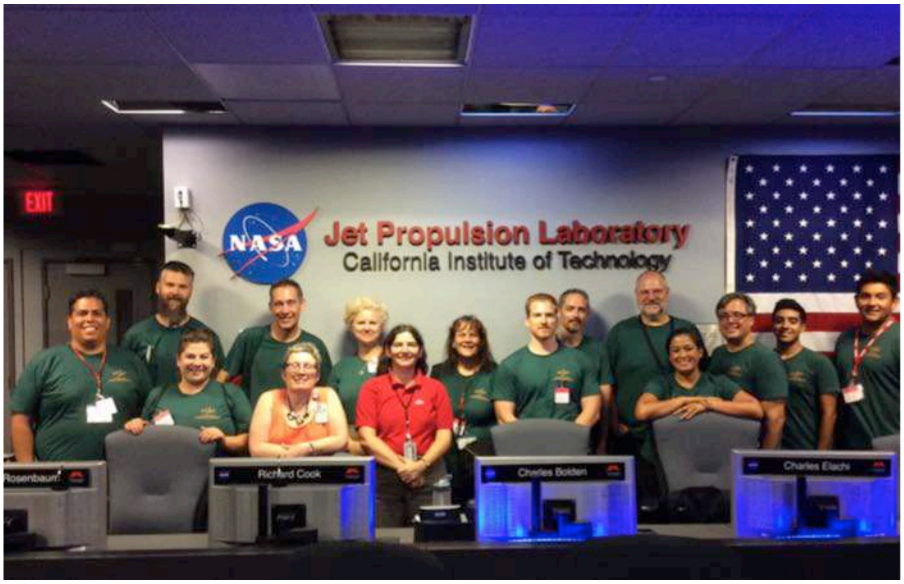
EarthScope Partnership. SCEC has collaborated with EarthScope since 2009, when the two organizations co-hosted a San Andreas Fault workshop for park and museum interpreters at the San Bernardino County Museum. SCEC continues to collaborate with the EarthScope workshops for Interpreters by providing educational expertise and capitalizing on the synergism of the ShakeOut drills throughout the United States (SCEC participated in the Fall 2013 EarthScope Interpreters workshop being held at Acadia National Park in advance of Maine's participation in the ShakeOut). In summer 2013 SCEC participated in the first Cascadia EarthScope Earthquake and Tsunami Education Program (CEETEP) program held at the Hatfield Marine Science Center in Newport, OR. At these workshops SCEC provides resources and information about SCEC science, ShakeOut resourcess, and the Quake Catcher Network. Workshop convenors have found that the ShakeOut is an important event that helps promote their program and vice versa. For example, a group of teachers from the Oregon coast (Lincoln County) worked with education staff at Hatfield to host a 2013 ShakeOut day which included visiting tsunami exhibits, a drop, cover and hold on drill, and a talk about the science of the Cascadia subduction zone. In 2014 SCEC participated in additional workshops in Aberdeen and Forks (Washington), and in Alaska. The final CEETEP workshop will be hosted by SCEC, EarthScope, and Humboldt State University in Arcata in summer, 2015.

CGS Workshops. SCEC is collaborating with the California Geological Survey to conduct education workshops at ECA EPIcenters (focusing on aquaria) in California. Cabrillo Marine Aquarium in San Pedro, CA, hosted the first Earthquake and Tsunami workshop in spring, 2014, and more are being planned. SCEC and CGS also regularly co-host a booth at the California Science Teachers Association annual meetings.

b. Teacher Professional Development

InSight Vital Signs of the Planet (VSP) Program. Starting in 2013 the partnership with Sally McGill expanded as part of SCEC's lead role in the Education and Public Outreach program for *InSight* (Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport), a NASA Discovery Program mission that will place a geophysical lander on Mars to study its deep interior in 2016. For this mission SCEC developed the *'Vital Signs of the Planet'* professional development program, a standards-based middle and high school research experience and curriculum development program offering strong connections to STEM research.

VSP expands on a collaboration that began in 2009 between SCEC and the Cal State San Bernardino/EarthScope RET program led by Dr. Sally McGill. During the course of each summer 7-10 high school teachers and their students conducted campaign GPS research along the San Andreas and San Jacinto faults. SCEC facilitated the education portion of the project through the implementation of the professional development model called Lesson Study. This allowed for interaction with the teachers for an entire year following their research. In their second year teachers and students participated in the SCEC Annual Meeting by participating in meeting activities and presenting their research at one of the evening poster sessions.



2014 InSight Vital Signs of the Planet participants on a field trip to the Jet Propulsion Laboratory.

VSP is now a three-week summer institute that provides 10-15 educator fellows with authentic experiences in scientific inquiry, encourages instructional improvement in schools, and fosters deep engagement with local underserved communities. The Summer Institute is 3 weeks long which includes seminars, field research, field trips, and curriculum development. The program is centered around a 5-day field research component in partnership with California State University, San Bernardino using survey mode GPS to monitor tectonic deformation in Southern California, and are installing QCN sensors in their classrooms. In 2014, ten science educators and four students participated and their posters are displayed at the 2014 SCEC Annual meeting. Teacher participants also help plan and implement the workshop for science educators held in conjunction with the SCEC Annual Meeting, where they share the research lessons they developed. During the fall these lessons are test taught at the schools and revised. Each lesson will also be developed into a lending kit that can be shared among all current participants and alumni of the program.

c. Other Activities

Plate Tectonics Kit. This 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.

4. Experiential Learning and Career Advancement (ELCA)

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

a. Undergraduate Internships

The ELCA program in SCEC4 is built on the foundation of our long-established USEIT and SURE internship programs that challenge undergraduates with real-world problems that require collaborative, interdisciplinary solutions. Each summer they involve over 30 students (including students at minority-serving colleges and universities and local community colleges). The interns experience how their skills can be applied to societal issues, and benefit from interactions with professionals in earth science, engineering, computer science, and policy. Some interns continue their research during the academic year (especially USC students).

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. 268 interns have been supported since 1994. 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. Since 2002, 264 students have participated. 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). The Grand Challenge for the 2014 USEIT program was to *develop SCEC-VDO and GIS tools for exploring and evaluating the aftershock hazards implied by the new Uniform California Earthquake Rupture Forecast (UCERF3).* These evaluations were guided by using M7 rupture scenarios developed for the 25th Anniversary of the 1989 Loma Prieta earthquake.

These students from colleges and universities across the country participated in the 2014 UseIT summer program at USC. Several will be attending the Annual Meeting to present posters, demos, and animations.

These internship opportunities 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. 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.

Since 2002, over 1500 eligible applications for SCEC internship programs were submitted (at *www.scec.org/internships*), with more than 450 internships awarded in current and past programs. Leveraging of additional funding has allowed SCEC to double the number of internships offered each year (38 in 2014). 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% in recent years. 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.

b. Additional Programs

These undergraduate internship programs are the centerpiece of a high school to graduate school career pathway for recruiting the best students, providing them with high-quality research, education, and outreach experiences, and offering career mentoring and networking opportunities.

At the high school level, this effort is closely linked with SCEC's K-14 Earthquake Initiative and its programs such as *InSight Vital Signs of the Planet***.** The goal is to provide activities that expose high school students to earthquake research, inquiry-based curricula, and interactions with SCEC scientists. Students who have participated in SCEC research experiences during high school that have now advanced to college are now beginning to participate in USEIT or a SURE. Two high school stuents participated in the 2014 Insight VSP program.

For graduate students, we are considering how to provide support for master's level (including new Ph.D. students) internships that provide unique opportunities. This will include support for cross-disciplinary computer science research by master's students similar to the SCEC ACCESS program (which completed in 2010). Students may participate in the USEIT program as mentors, conduct research with scientists at other SCEC institutions than their own school, and participate in CEO activities such as media relations, curricula development, and program evaluation.

For graduate students and post-docs, the effort being considered will be focused on collaboration, networking, and employment opportunities, as most are supported by their institution, or with SCEC research funding. Social networking will allow interaction across institutions and research projects. Students will be encouraged to interact within the SCEC "collaboratory" regardless if they or their advisor has received SCEC research funding. In addition to research and education/outreach opportunities, mentoring will be offered to help ELCA participants consider career possibilities, and longitudinal tracking of alumni will provide data on how students are progressing.

The final element of the ELCA program is career advancement opportunities for early-career researchers, including post-docs, young faculty, and research staff. We will highlight employment opportunities via SCEC's email list and on the SCEC website, and perhaps also post CVs of early career researchers seeking positions. We may also provide travel support for early career researchers to give presentations at conferences and department lectures nationwide, and provide presentation materials so that they can highlight their role in SCEC. Also, SCEC leadership positions, especially the planning committee, provide opportunities for exposure and career advancement. See the CEO Metrics and Milestones chart for current demographics.

IV. SCEC Goals and Objectives

A. 2015 Science Collaboration Plan

1. What's New This Year

There is one major, and a number of minor, changes throughout the document. The most substantial changes are

- A call for effort to support a new initiative, the Central California Seismic Project (CCSP), that has as its goal to assess the effectiveness of physics-based seismic wavefield modeling in reducing path-effect uncertainties.
- The 2015 Collaboration Plan recognizes that we do not anticipate developing additional Special Fault Study Areas (SFSAs) in SCEC4.
- An explicit call for simulations of earthquake ruptures such as those defined in the Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3).
- A more detailed description of collaboration with the engineering community in validation of ground motion simulations and physics-based probabilistic seismic hazard models.
- InSAR-only and GPS-only geodetic models are now encouraged by the geodesy group, particularly if they include a plan for assessing whether their results are in agreement or conflict with other data types.
- An explicit call for archiving geodetic data.
- A pathway for inclusion of operational transient detection algorithms into a testing framework.
- A call for new approaches for assimilating real-time high-rate GPS, seismic data, and other potential observations into rapid source characterization.
- An explicit call for requests for allocations of computational resources, where appropriate.
- A call to incorporate new data (especially from the Salton Seismic Imaging Project) into the Community Velocity Models (CVMs) with validation of improvements for ground-motion prediction.
- A call for attention to the science of off-fault plasticity and its potential effect on earthquake rupture and seismic wave propagation.
- A call to place more emphasis on ground motion validation for engineering metrics at high frequencies, on basin effects, and on the potential impact of distributed ground motions on extended infrastructure.

For more specific guidance on each of these changes please see the relevant section of the Collaboration Plan.

2. Disciplinary Activities

The Center will sustain disciplinary science through standing committees in Seismology, Tectonic Geodesy, Earthquake Geology, and Computational Science. These committees will be responsible for planning and coordinating disciplinary activities relevant to the SCEC Science Collaboration Plan, and they will make recommendations to the SCEC Planning Committee regarding the support of disciplinary infrastructure. High-priority disciplinary objectives are detailed below.

a. Seismology

Objectives. The objectives of the Seismology group are to gather data on the range of seismic phenomena observed in southern California and to integrate these data into models of fault slip. Of particular interest are proposals that foster innovations in network deployments, data collection, real-time research tools, and data processing. Proposals that provide community products that support one or more of the SCEC4 goals or those that include collaboration with network operators in Southern California are especially encouraged. Proposers should consider the SCEC resources available including the Southern California Earthquake Data Center (SCEDC) that provides extensive data on Southern California earthquakes as well as crustal and fault structure, the network of SCEC funded borehole instruments that record high quality reference ground motions, and the pool of portable instruments that is operated in support of targeted deployments or aftershock response.

Example Research Strategies

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

Priorities for Seismology

- ***Tremor.*** Tremor has been observed on several faults in California, yet it does not appear to be ubiquitous. We seek proposals that explore the distribution and source characteristics of tremor in California and those that explore the conditions necessary for the generation of seismically observable tremor.
- ***Low-cost seismic network data utilization and archiving.*** Several groups are developing seismic networks that use low-cost MEMS accelerometers. We seek proposals that would address development of seismological algorithms to utilize data from these networks in innovative ways. We also seek proposals that would develop metadata and archiving models for these new semi-mobile networks, as well as archive and serve these data to the SCEC user community.
- ***Short-Term Earthquake Predictability.*** We seek proposals that develop new methods in earthquake statistics or analyze seismicity catalogs to develop methods for determining short-term (hours to days) earthquake probability gain.
- ***Seismicity studies in the two SFSA; Ventura and San Gorgonio.*** We seek proposals that use earthquake data to map the structure and seismotectonics of these regions as part of the SFSA community effort.

b. Tectonic Geodesy

Tectonic Geodesy activities in SCEC4 will focus on data collection and analysis that contribute to improved earthquake response and to a better understanding of fault loading and stress transfer, the causes and effects of transient deformation, and the structure and evolution of fault zones and systems. The following are research strategies aimed at meeting these broad objectives:

- ***Contribute to the development of a Community Geodetic Model (CGM).*** The goal of this effort is to develop a geodetic time series data product for southern California that leverages the complementary nature of GPS and InSAR observations. This will require development of optimal methods for combining GPS and InSAR data, characterizing seasonal/hydrologic/anthropogenic signals, incorporating new data, and accounting for earthquake effects as needed. Proposals should demonstrate coordination with the current activities and established timeline of the CGM project. Proposals that target participation in ongoing GPS and InSAR time series analysis comparison exercises, compilation of a comprehensive set of campaign and continuous GPS time series for southern California, or identification of optimal approaches for mitigating temporally and spatially correlated noise in GPS or InSAR time series are particularly encouraged. More information can be found here: *http://collaborate.scec.org/cgm*.
- **Analysis of geodetic data to address specific SCEC4 research targets.** Studies addressing geodetic/geologic slip rate discrepancies, assessing the role of lower crust/upper mantle processes in driving fault loading, developing more physically realistic deformation models, providing input to the development of Community Stress Models, and constraining physics-based models of slow slip and tremor are encouraged, as are studies that pursue integrated use of geodetic, geologic, seismic, and other observations targeting special fault study areas. Proposals that include collection of new data should explicitly motivate the need for such efforts. In compliance with SCEC's data policy, data collected with SCEC funding must be made publicly available upon collection by archiving at an appropriate data center, preferably UNAVCO (contact Jessica Murray (jrmurray@usgs.gov) for further information on archiving). Annual reports should include a description of archive activities.
- **Improve our understanding of the processes underlying detected transient deformation signals and/or their seismic hazard implications through data collection and development of new analysis tools.** Work that advances methods for near-real-time transient detection and applies these algorithms within the SCEC transient detection testing framework to search for transient deformation in southern California is encouraged. Approaches that can be automated or semi-automated are the highest priority, as is their inclusion in the testing framework now in place at SCEC (contact Rowena Lohman (rbl62@cornell.edu) for details on how to address this in the proposal). Extension of methods to include InSAR and strainmeter data and, when available, the CGM is also a priority. Work that develops means for incorporating the output of transient detection algorithms into time-dependent earthquake forecasting is encouraged.
- ***Develop and apply algorithms that use real-time high-rate GPS data in concert with seismic data for improved earthquake response.*** We encourage proposals that explore new approaches for assimilating real-time high-rate GPS, seismic data, and other potential observations into efforts to rapidly characterize earthquake sources. Also of interest is the development and application of rigorous retrospective and prospective tests to evaluate algorithm performance.

c. Earthquake Geology

Objectives. The Earthquake Geology Disciplinary Committee promotes studies of the geologic record of the Southern California natural laboratory that advance SCEC science. Its primary focus is on the Late Quaternary record of faulting and ground motion, including data gathering in response to major earthquakes. Geologic observations provide important contributions, either directly or indirectly, to all six of the fundamental problems in earthquake physics identified in the SCEC4 proposal. Earthquake Geology also fosters research activities motivated by outstanding seismic hazard issues, understanding of the structural framework and earthquake history of special fault study areas (see Section 8, Problem 4), or will contribute significant information to the statewide Unified Structural Representation. Collaborative proposals that cut across disciplinary boundaries are encouraged.

Example Research Strategies

- Gathering well-constrained slip-rates on the southern California fault system, with emphasis on major structures (Problem 1).
- Mapping and analysis of fault-zone properties where the seismogenic zone or brittle-ductile transition has been exhumed (Problems 1a, 3b).

- Paleoseismic documentation of earthquake ages and displacements, with emphasis on long paleo-seismic histories, slip-per-event, and slip-rate histories, including a coordinated effort to develop slip rates and slip-per-event history of southern San Andreas fault system (Problem 2a, in collaboration with the SoSAFE focus group).
- Improve understanding of the architecture and tectonic activity of the Ventura and San Gorgonio Pass special fault study areas (Problem 4a), such as using B4 and other lidar data sets to better define fault traces, fault activity, and geologic structure.
- Improve the statewide community fault model in areas of inadequate fault representations or where new data is available, such as using high-resolution topographic data sets to better define fault traces, spatial uncertainty, and stochastic heterogeneity of fault geometry (Problem 4c).
- Quantifying along-strike variations in fault roughness, complexity, strain localization, and damage in relation to the rupture propagation processes, including evaluation of the likelihood of multi-fault ruptures (Problem 4b).
- Validation of ground motion prediction through analysis and dating of precariously balanced rocks and other fragile geomorphic features (Problem 6).

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

- C-14: University of California at Irvine (John Southon, jsouthon@uci.edu) and Lawrence Livermore National Laboratory (Tom Guilderson, tguilderson@llnl.gov),
- OSL: University of Cincinnati (Lewis Owen, lewis.owen@uc.edu) and Utah State University (Tammy Rittenour, tammy.rittenour@usu.edu), and
- Cosmogenic: Lawrence Livermore National Laboratory (Susan Zimmerman, zimmerman17@llnl.gov).

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

Data Reporting Requirements. Studies under Earthquake Geology gather diverse data that are at times challenging to consistently archive per NSF data reporting requirements. Under SCEC4, PIs will be required to provide full reporting of their geochronology samples, including raw data, interpreted age, and geographic/stratigraphic/geomorphic context (what was dated?). This reporting requirement will be coordinated with the geochronology infrastructure program. A priority for SCEC4 is to define additional, achievable goals for geology data reporting to be followed by Earthquake Geology community.

Priorities for Earthquake Geology

- Support integrative research at the Ventura and San Gorgonio Pass special fault study areas. A specific need for this upcoming year is to analyze existing lidar data sets for these areas and assess whether new data are needed.
- Prioritize and coordinate research objectives with respect to SoSAFE focus group goals, targets for slip-rate studies, and mechanisms to achieve progress on exhumed fault-zone problems.
- Define consistent and achievable data reporting requirements for Earthquake Geology in SCEC4. Archive data from SCEC3.
- Improve understanding of the seismogenic faults along the coast and offshore.

d. Computational Science

Objectives. The Computational Science group promotes the use of advanced numerical modeling techniques and high performance computing (HPC) to address the emerging needs of SCEC users and application community on HPC platforms. The group works with SCEC scientists across a wide range of topics to take advantage of rapidly changing computer architectures and algorithms. It also engages and coordinates with national HPC labs/centers and vendors in crosscutting efforts enabling large-scale computing milestones. The group encourages research using national supercomputing resources, and supports students from both geoscience and computer science backgrounds to develop their skills in the area. Projects listing Computational Science as their primary area should involve significant software-based processing or high performance computing in some way; research utilizing standard desktop computing should list the most relevant non-Computational Science disciplinary or focus group as the primary area.

Computational Requirements. If your proposed research will require substantial SCEC computing resources or allocations, the Planning Committee requests that your SCEC proposal include a brief summary of computational requirements that includes the following information:

- The scientific goal of your computational research,
- The scientific software you plan to use or develop,
- A list of computations you plan to run,
- The estimated computing time you believe will be required, and
- The computer resources you plan to use to perform your simulations.

Note that XSEDE startup allocations can be requested from NSF (*https://www.xsede.org/allocations*).

Example Research Strategies

- Porting and optimization of HPC codes, required to reach SCEC research goals, and utilize hybrid programming models, combined with shared memory directives (e.g. OpenMP) and/or accelerator-programming APIs (e.g. OpenACC, pthreads) and languages (e.g. OpenCL, CUDA) to take advantage of advanced multi-core, many-core and/or next-generation heterogeneous architectures.
- Novel algorithms for earthquake simulation, particularly those that either improve efficiency and accuracy or expand the class of problems that can be solved (e.g., adaptive mesh refinement).
- Optimization of earthquake-cycle simulators that can resolve the faulting processes across the range of scales required to investigate stress-mediated fault interaction, including those caused by dynamic wave propagation, generate synthetic seismicity catalogs, and assess the viability of earthquake rupture forecasts.
- Tools and algorithms for uncertainty quantification in large-scale inversion and forward-modeling studies, for managing I/O, data repositories, workflow and data analysis, fault tolerance, and advanced seismic data format.
- Data-intensive computing tools, including but not limited to InSAR and geodesy, 3D tomography, cross-correlation algorithms used in ambient noise seismology, and other signal processing techniques used, for example, to search for tectonic tremor.

Key Problems in Computational Science

- Seismic wave propagation
    - o Validate SCEC community velocity models.
    - o Develop high-frequency simulation methods and investigate the appropriate upper frequency limit of deterministic ground motions.
    - o Extend existing simulation methodologies to a set of stochastic wavefield simulation codes that can extend the deterministic calculations to frequencies as high as 20 Hz, providing the capability to synthesize “broadband” seismograms.
    - o Develop wave propagation codes incorporating more advanced media response, including inelastic material response and scattering by small-scale heterogeneities and topography.

- Tomography
  - o Assimilate regional waveform data into the SCEC community velocity models.
- Rupture dynamics
  - o Evaluate proposed fault weakening mechanisms in large-scale earthquake simulations, determine if small-scale physics is essential or irrelevant, and determine if friction law parameters can be artificially enhanced without compromising ground motion predictions.
  - o Evaluate different representations of earthquake source complexity, including stress heterogeneity, variability in frictional properties, fault geometrical complexity, and dynamic rupture propagation in heterogeneous media.
- Scenario earthquake modeling
  - o Model a suite of scenario ruptures, incorporating material properties and fault geometries from the unified structural representation projects.
  - o Isolate causes of amplified ground motions using adjoint-based sensitivity methods.
- Data-intensive computing
  - o Develop computational tools for advanced signal processing algorithms, such as those used in ambient noise seismology and tomography, as well as InSAR and other forms of geodesy.
- Engineering applications
  - o Investigate the implications of ground motion simulations results by integrating observed and simulated ground motions with engineering-based building response models. Validate the results by comparison to observed building responses.
  - o Facilitate the “rupture-to-rafters” modeling capability to transform earthquake risk management into a Cyber Science and Engineering discipline.

3. Interdisciplinary Focus Areas

Interdisciplinary research will be organized into seven science focus areas: Unified Structural Representation (USR), Fault and Rupture Mechanics (FARM), Stress and Deformation Over Time (SDOT), Earthquake Forecasting and Predictability (EFP), Ground Motion Prediction (GMP) Southern San Andreas Fault Evaluation (SOSAFE) and Earthquake Engineering Implementation Interface (EEII). Collaboration within and across focus areas is strongly encouraged.

a. Unified Structural Representation (USR)

The Unified Structural Representation group develops three-dimensional models of active faults and earth structure (velocity, density, attenuation, etc.) for use in fault-system analysis, ground-motion prediction, and hazard assessment. This year’s efforts will focus on (1) making improvements to existing community models (CVM, CFM) that will facilitate their uses in SCEC science, education, and post-earthquake response planning; (2) developing methods to represent smaller scale features, such as stochastic variations of seismic velocities and attenuation structure; and (3) improving IT tools that are used to deliver the USR components to the user community.

- ***Community Velocity Model (CVM).*** Improve the current SCEC CVMs, with emphasis on more accurate representations of Vp, Vs, density, attenuation, and basin structure. Incorporate new data (especially results from the Salton Sea Imaging Project) into the CVMs with validation of improvements for ground-motion prediction. Perform 3D waveform tomographic inversions and ambient noise analysis for evaluating and improving the CVMs. Develop and apply procedures (i.e., goodness-of-fit measures) for evaluating new models with data (e.g., waveforms, gravity) to distinguish alternative representations and quantify model uncertainties; apply these methods for well-recorded earthquakes in southern California to delineate areas where CVM updates are needed. Develop databases, models, and model building tools that will help facilitate expansion of the CVMs to statewide and plate-boundary scale velocity representations. These efforts should be coordinated with the SCEC CME special project.
- ***Community Fault Model (CFM).*** Improve and evaluate the CFM and statewide CFM (SCFM), placing emphasis on defining the geometry of major faults that are incompletely, or inaccurately, repre-

sented in the current model, and on faults of particular concern, such as those that are located close to critical facilities. Refine representations of the linkages among major fault systems. Extend the CFM to include spatial uncertainties and stochastic descriptions of fault heterogeneity. Evaluate the new CFM version (5.0) with data (e.g., seismicity, seismic reflection profiles, geologic slip rates, and geodetic displacement fields) to distinguish alternative fault models. Update the CFM-R (rectilinear fault model) to reflect improvements in the CFM. Develop new tools and formats for making the CFM geometries and properties available to the user community. Work on the statewide CFM in regions outside the SCEC CFM should be coordinated with the appropriate agencies (e.g., USGS for central and northern CA).

- ***Unified Structural Representation (USR).*** Develop better IT mechanisms for delivering the USR, particularly the CVM parameters and information about the model's structural components, to the user community for use in generating and/or parameterizing numerical models. Generate maps of geologic surfaces compatible with the CFM that may serve as strain markers in crustal deformation modeling and/or property boundaries in future iterations of the USR.

b. Fault and Rupture Mechanics (FARM)

The primary mission of the Fault and Rupture Mechanics focus group in SCEC4 is to develop physics-based models of the nucleation, propagation, and arrest of dynamic earthquake rupture. We specifically solicit proposals that will contribute to the six fundamental problems in earthquake physics defined in the SCEC4 proposal and enhance understanding of fault system behavior through interdisciplinary investigation of the special fault study areas. We encourage researchers to address this mission through field, laboratory, and modeling efforts directed at characterizing and understanding the influence of material properties, geometric irregularities and heterogeneities in stress and strength over multiple length and time scales, and that will contribute to our understanding of earthquakes in the Southern California fault system.

Priorities for FARM

- Investigate the importance of different dynamic weakening and fault healing mechanisms, and the slip and time scales over which these mechanisms operate (3a, 3b, 3c, 3e).
- Determine the properties of fault cores and damage zones (1a, 1b, 3a, 3b, 4a, 4b) and characterize their variability with depth and along strike (1a, 1b, 4a, 4b) to constrain theoretical and laboratory studies, including width and particle composition of actively shearing zones, signatures of temperature variations, extent, origin and significance of on- and off-fault damage, healing, and poromechanical behavior.
- Determine the relative contribution of on- and off-fault damage to the total earthquake energy budget (3c, 4a, 4b), and the absolute levels of local and average stress (3e). Collaboration with the Community Stress Model (CSM) TAG is encouraged.
- Develop, test, and apply innovative source-inversion strategies to image the space-time rupture evolution of earthquakes reliably, propose source-inversion methods with minimal assumptions, and provide robust uncertainty quantification of inferred source parameters; propose and develop new SIV benchmarks, and generate synthetic data of various types (seismic, static, far-field, near-field) in cooperation with other SCEC groups; collaboration with the Technical Activity Group (TAG) on Source Inversion Validation (SIV) is encouraged.
- Develop realistic descriptions of heterogeneity in fault geometry, rock properties, stresses and strains, and tractable ways to incorporate heterogeneity in numerical models of single dynamic rupture events and multiple earthquake cycles (3e, 3f, 4b, 4d, 6b). Test dynamic rupture modeling that incorporates these heterogeneities first by verifying the computational algorithms with benchmark exercises of the Dynamic Rupture Code Verification Technical Activity Group (TAG), then by comparing the results with geological and geophysical observations.
- Understand the significance of fault zone characteristics and processes for fault dynamics (3a, 3b, 3c) and formulate constitutive laws for use in dynamic rupture models (3d).

- Evaluate the relative importance of fault structure and branching, material properties, interseismic healing, fluid processes and prior seismic and aseismic slip to earthquake dynamics, in particular, to rupture initiation, propagation, and arrest, and the resulting ground motions (3c, 3d, 3f).
- Characterize earthquake rupture, fault loading, degree of localization, role of fluids and constitutive behavior at the base of and below the seismogenic zone (1a, 1b, 1e, 4a).
- Develop observations of slow slip events and non-volcanic tremors in southern California and understand their implications for constitutive properties of faults and overall seismic behavior (3a, 5a-5e).
- Assess the predictability of rupture direction and directivity of seismic radiation by collecting and analyzing field and laboratory data (4a, 4b), and conducting theoretical investigations to understand implications for strong ground motion.
- Develop physics-based models that can describe spatio-temporal patterns of seismicity and earthquake triggering (2e, 4e).
- Explore similarities between earthquakes and offshore landslide sources with the goal of better understanding their mechanics and the tsunami hazard from sources in southern California.

c. Stress and Deformation Over Time (SDOT)

The focus of the interdisciplinary focus group Stress and Deformation Over Time (SDOT) is to improve our understanding of how faults are loaded in the context of the wider lithospheric system evolution. SDOT studies these processes on timescales from 10s of Myr to 10s of yrs, using the structure, geological history, and physical state of the southern California lithosphere as a natural laboratory. The objective is to tie the present-day state of stress and deformation on crustal-scale faults and the lithosphere as a whole to the long-term, evolving lithospheric architecture, through 4D geodynamic modeling, constrained by the widest possible range of observables from disciplines including geodesy, geology, and geophysics.

One long-term goal is to contribute to the development of a physics-based, probabilistic seismic hazard analysis for southern California by developing and applying system-wide deformation models of lithospheric processes at time-scales down to the earthquake cycle. These deformation models require a better understanding of a range of fundamental questions such as the forces loading the lithosphere, the relevant rock rheology, fault constitutive laws, and the spatial distribution of absolute deviatoric stress. Tied in with this is a quest for better structural constraints, such as on density, Moho depths, thickness of the seismogenic layer, the geometry of lithosphere-asthenosphere boundary, as well as basin depths, rock type, temperature, water content, and seismic velocity and anisotropy.

Priorities for SDOT

- Contributions to our understanding of geologic inheritance and evolution, and its relation to the three-dimensional structure and physical properties of present-day crust and lithosphere. Contributions to efforts of building a 4D model of lithospheric evolution over 10s of Myr for southern California.
- Seismological imaging of crust, lithosphere and upper mantle using interface and transmission methods with the goal of characterizing the 3D distribution of isotropic and anisotropic wave speed variations.
- Contributions to the development of a Community Stress Model (CSM), a set of spatio-temporal (4D) representations of the stress tensor in the southern California lithosphere. In particular, we seek compilations of diverse stress constraints (e.g. from borehole or anisotropy measurements), geodynamic models that explore the coupling of side, gravity, and basal loading to observed geodetic strain-rates and co-seismically imaged stress, and studies that explore regional, well-constrained settings as test cases for larger scale models.
- General geodynamic models of southern California dynamics to allow hypothesis testing on issues pertaining to post-seismic deformation, fault friction, rheology of the lithosphere, seismic efficiency, the heat flow paradox, stress and strain transients, fault system evolution, as tied in with stress and deformation measurements across scales.
- Development of models of interseismic and earthquake cycle deformation, including efforts to estimate slip rates on southern CA faults, fault geometries at depth, and spatial distribution of slip or moment deficits on faults. Assessments of potential discrepancies of models based on geodetic, geo-

logic, and seismic data. Development of deformation models (fault slip rates and locking depths, off-fault deformation rates) in support of earthquake rupture forecasting.

- Research into averaging, simplification, and coarse-graining approaches across spatio-temporal scales, addressing questions such as the appropriate scale for capturing fault interactions, the adequate representation of frictional behavior and dynamic processes in long-term interaction models, fault roughness, structure, complexity and uncertainty. Modeling approaches may include analytical or semi-analytical methods, spectral approaches, boundary, finite, or distinct element methods, and a mix of these, and there are strong links with all other SCEC working groups, including FARM, Earthquake Simulators, and USR.

d. Earthquake Forecasting and Predictability (EFP)

The Earthquake Forecasting and Predictability (EFP) focus group coordinates five broad types of research projects: (1) the development of earthquake forecast methods, (2) the development of testing methodologies for evaluating the performance of earthquake forecasts, (3) expanding fundamental physical or statistical knowledge of earthquake behavior that may be relevant for forecasting earthquakes, (4) the development and use of earthquake simulators to understand predictability in complex fault networks, and (5) fundamental understanding of the limits of earthquake predictability.

We seek proposals that will increase our understanding of how earthquakes might be forecast, to what extent and precision earthquakes are predictable, and what is a physical basis for earthquake predictability. Proposals of any type that can assist in this goal will be considered. In order to increase the amount of analyzed data, and so decrease the time required to learn about predictability, proposals are welcome that deal with global data sets and/or include international collaborations.

For research strategies that plan to utilize the Collaboratory for the Study of Earthquake Predictability (CSEP), see Section 11 to learn of its capabilities. Successful investigators proposing to utilize CSEP would be funded via core SCEC funds to adapt their prediction methodologies to the CSEP framework, to transfer codes to the externally accessible CSEP computers, and to be sure they function there as intended. Subsequently, the codes would be moved to the identical externally inaccessible CSEP computers by CSEP staff who will conduct tests against a variety of data as outlined in the CSEP description.

Priorities for EFP

- Support the development of statistical or physics-based real-time earthquake forecasts.
- Utilize and/or evaluate the significance of earthquake-cycle simulator results. See sections on WGCEP and CSEP for more details.
- Study how to properly characterize and estimate various earthquake-related statistical relationships (including the magnitude distribution, Omori law, aftershock productivity, etc.).
- Focus on understanding patterns of seismicity in time and space, as long as they are aimed toward understanding the physical basis of earthquake predictability.
- Develop useful measurement/testing methodology that could be incorporated in the CSEP evaluations, including those that address how to deal with observational errors in data sets.
- Develop approaches to test the validity of the characteristic earthquake vs. Gutenberg-Richter earthquake models as they are used in seismic hazard analysis.

e. Ground-Motion Prediction (GMP)

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

neering Implementation Interface, EEII) and CME (Special Project) - consult these sections for additional GMP-related research priorities.

Priorities for GMP

- Developing and/or refining physics-based simulation methodologies, with particular emphasis on high frequency (1-10 Hz and higher) approaches. This work could include implementation of simulation methodologies onto the Broadband Simulation Platform, or implementation of more efficient approaches in wave and rupture propagation schemes (in collaboration with CME), allowing accurate simulation of higher frequency ground motion in models with lower seismic wave speeds. Determine spectral and spatial limits for simulating deterministic high-frequency wave propagation.
- Waveform modeling of past earthquakes to validate and/or refine the structure of the Community Velocity Models (CVMs) (in collaboration with USR). This includes exploration and validation of the effects of statistical models of structural and velocity heterogeneities on the ground motion, the significance of the lowest (S-wave) velocities as frequencies increase, the significance of including geotechnical layers (GTLs) in the CVMs, and development and validation of improved (possibly frequency-dependent) attenuation (intrinsic or scattering) models in physics-based simulations (in collaboration with USR). Quantify uncertainty in the CVM structure and its impact on simulated ground motions.
- Develop and implement new models or implement existing models for frequency-dependent site effects into the SCEC BroadBand Platform (site effects module). Because site-specific profiles are rarely available for large scale simulations, the priority will be given to models that can work with generic site profiles or that use simplified site factors (e.g. empirical Vs30-based factors for example). Models that require a site profile as input will also be considered. The site effects models are to be applied so as to produce time series that include site effects.
- Incorporate off-fault plasticity into physics-based ground motion simulation methodologies, quantify uncertainties, and validate the effects using observations from large earthquakes.
- Development of more realistic implementations of dynamic or kinematic representations of fault rupture, including simulation of higher frequencies (up to 10+ Hz). Possible topics include simulation of dynamic rupture on nonplanar faults and studying the effects of fault roughness on the resulting synthetic ground motion, and development of kinematic representations based on statistical models constrained by observed and/or dynamic ruptures. This research could also include the examination of current source-inversion strategies and development of robust methods that allow imaging of kinematic and/or dynamic rupture parameters reliably and stably, along with a rigorous uncertainty assessment. Close collaboration with the Technical Activity Group (TAG) on Source Inversion Validation (SIV) is encouraged. Construct Equivalent Kinematic Source (EKS) models that approximate the effects of near-fault nonlinearities in a linear scheme and test the EKS model in CyberShake. Projects that involve dynamic earthquake rupture simulations should involve preliminary code testing using benchmarks developed by the Dynamic Rupture Code Verification Technical Activity Group (TAG).
- Investigate the importance of including 3D basin effects on ensemble averaged long-period ground motions on the BroadBand Platform, e.g., by comparing ensemble averages of long-period (<~1Hz) ground motions computed in 1D and 3D crustal models for events included in the GMSV.
- Verification (comparison against theoretical predictions) and validation (comparison against observations) of the simulation methodologies with the objective to develop robust and transparent simulation capabilities that incorporate consistent and accurate representations of the earthquake source and three-dimensional velocity structure. Comparison of synthetic ground motions from deterministic and stochastic approaches to data for overlapping bandwidths. Close collaboration with the Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV).

f. Southern San Andreas Fault Evaluation (SoSAFE)

The SCEC Southern San Andreas Fault Evaluation (SoSAFE) Project aims to increase knowledge of slip rates, paleoearthquake ages, and slip distributions of past earthquakes, for the past two thousand years on the southern San Andreas fault system. From Parkfield to Bombay Beach, and including the San

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

Priorities for SoSAFE

- Lengthen existing paleoearthquake chronologies or start new sites in key locations along the fault system that will improve understanding of the last 2000 years of this fault system.
- Determine slip rates at many time scales, so that possible system-level interaction can be documented.
- Obtain the best possible measurements of geomorphic slip distributions from past earthquakes by developing field, LiDAR, or SfM datasets and validate the different measures or test uncertainties determined by each method.
- Explore chronometric, geomorphic, or statistical approaches to linking geomorphic offsets to dated paleoearthquakes.
- Use novel methods for estimating slip rates from geodetic data.
- Investigate methodologies for integrating paleoseismic (including geomorphic measures of slip) and geologic data into rupture histories. For example, studies may improve or inform interactions between SoSAFE results and scenario rupture modeling or rupture forecasts.

Requests for geochronology support (e.g., to date 12 radiocarbon samples) are encouraged and shall be coordinated with Earthquake Geology; a portion of SoSAFE funds will be contributed towards joint support for dating. We also welcome proposals that seek to add other data (such as climate variations) to earthquake chronologies, which may be used to improve age control, understanding of the formation of offset features, or site-to-site correlation of events.

Research by single or multi-investigator teams will be supported to meet priority scientific objectives related to the mission of the SoSAFE Interdisciplinary Focus Group. SoSAFE objectives also foster common longer-term research interests and facilitate future collaborations in the broader context of a decade-long series of interdisciplinary, integrated and complementary studies on the southern San Andreas Fault system such as those targeted by teams investigating Special Fault Study Areas.

g. Earthquake Engineering Implementation Interface (EEII)

The purpose of the Earthquake Engineering Implementation Interface is to create and maintain collaborations with research and practicing engineers, much as the Seismic Hazard and Risk Analysis focus group did during SCEC3. These activities may include ground motion simulation validation, rupture-to-rafters simulations of building response as well as the end-to-end analysis of large-scale, distributed risk (e.g., ShakeOut-type scenarios). Our goal of impacting engineering practice and large-scale risk assessments require even broader partnerships with the engineering and risk-modeling communities, which motivates the activities described next.

Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV). A TAG focused on validation of ground motion simulations for use in engineering applications is developing and implementing testing/rating methodologies, via collaboration between ground motion modelers and engineering users. The workshops and research of this TAG to date have identified the efforts below as potential priority activities in this area. See the Ground-Motion Prediction (GMP) and the Community Modeling Environment (CME) sections of the Collaboration Plan for related research priorities. Proposals on these topics will be reviewed with all other SCEC proposals in January of 2015. Interested researchers are invited to visit the GMSV TAG wiki (*http://collaborate.scec.org/gmsv/*) and contact Dr. Nicolas Luco (nluco@usgs.gov) and Dr. Sanaz Rezaeian (srezaeian@usgs.gov) to discuss opportunities for coordinated research. Note that any PIs funded to work on GMSV-related projects will become members of the TAG and will be required to coordinate with each other, in part via participation in monthly conference calls and annual workshops/meetings.

- Develop validation methodologies that use relatively simple metrics (e.g., significant duration), and demonstrate them with existing simulated ground motions and their recorded counterparts. Such research must be coordinated with the SCEC Broadband Platform Validation Project.

- Develop validated and efficient methods for either i) adjusting ground motion time series simulated by the Broadband Platform to account for the local site conditions at historical earthquake stations; or ii) de-convolving recorded ground motion time series to a reference site condition corresponding to that for simulated ground motions.
- Develop and demonstrate validation methodologies that use common models of structures of interest (e.g. multi-degree-of-freedom nonlinear models of building or geotechnical systems) for particular engineering applications. Such research must be coordinated with the validation efforts of the Software Environment for Integrated Seismic Modeling (SEISM) project.
- Develop and demonstrate validation methodologies for the use of CyberShake ground motion simulations in developing probabilistic and deterministic hazard maps for building codes and other engineering applications. In particular, investigations of observed versus simulated region-specific path effects for small-magnitude earthquakes in Southern California are encouraged. Such research must be coordinated with the Committee for Utilization of Ground Motion Simulations (UGMS).
- Research important ground motion or structural (e.g. building or geotechnical system) response parameters and statistics that should be used in validation of simulations. Demonstrate similarities and differences between otherwise parallel validation tests/ratings using these ground motion or structural response parameters.
- Demonstrate validation methodologies with ground motions simulated with deterministic and stochastic methods above 1 Hz.
- Improve ground motion simulations by closely collaborating with modelers on iterative applications of validation methodologies.

Improved Hazard Representation

- Develop improved hazard models that consider simulation-based earthquake source and wave propagation effects that are not already well reflected in observed data. These could include improved methods for incorporating rupture directivity effects, basin effects, and site effects in the USGS ground motion maps, for example. The improved models should be incorporated into OpenSHA.
- Use broadband strong motion simulations, possibly in conjunction with recorded ground motions, to develop ground motion prediction models (or attenuation relations). Broadband simulation methods must be verified (by comparison with simple test case results) and validated (against recorded strong ground motions) before use in model development. The verification, validation, and application of simulation methods must be done on the SCEC Broadband Simulation Platform. Such developments will contribute to the future NGA-H Project. .
- Investigate bounds on the median and variability of ground motions for a given earthquake scenario.

Ground Motion Time History Simulation

- Develop acceptance criteria for simulated ground motion time histories to be used in structural response analyses for building code applications or risk analysis. This relates closely to the GMSV section above.
- Assess the advantages and disadvantages of using simulated time histories in place of recorded time histories as they relate to the selection, scaling and/or modification of ground motions for building code applications or risk analysis.
- Develop and validate modules for simulation of short period ground motions (< 1 sec) for incorporation in the SCEC Broadband Platform.
- Develop and validate modules for the broadband simulation of ground motion time histories close to large earthquakes, and for earthquakes in the central and eastern United States, for incorporation in the SCEC Broadband Platform.
- Develop and validate modules for nonlinear site response, including criteria for determining circumstances under which nonlinear modeling is required. Incorporate the modules into the SCEC Broadband Platform.
- Compare simulated versus recorded ground motions for different models of the regional geologic structure.

Collaboration in Structural Response Analysis

- Infrastructure Systems. Assess the performance of distributed infrastructure systems (e.g., water, electrical and transportation) using simulated ground motions. Evaluate the potential impact of basin effects, rupture directivity, spatial distribution of ground motion, or other phenomena on risk to infrastructure systems.
- Tall Buildings and Other Long-Period Structures. Enhance the reliability of simulations of long period ground motions in the Los Angeles region using refinements in source characterization and seismic velocity models, and evaluate the impacts of these ground motions on tall buildings and other long-period structures (e.g., bridges, waterfront structures).
- End-to-End Simulation. Interactively identify the sensitivity of structural response to ground motion parameters and structural parameters through end-to-end simulation. Buildings of particular interest include non-ductile concrete frame buildings.
- Reference Buildings and Bridges. Participate with PEER investigators in the analysis of reference buildings and bridges using simulated broadband ground motion time histories. The ground motions of large, rare earthquakes, which are poorly represented in the NGA strong motion database, are of special interest. Coordination with PEER can be done through Yousef Bozorgnia (yousef@berkeley.edu).
- Earthquake Scenarios. Perform detailed assessments of the results of scenarios such as the ShakeOut exercise, and the scenarios for which ground motions were generated for the Tall Buildings Initiative (including events on the Puente Hills, Southern San Andreas, Northern San Andreas and Hayward faults) as they relate to the relationship between ground motion characteristics and structural response and damage.

Ground Deformation

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

Risk Analysis

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

Other Topics

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

4. Special Projects and Initiatives

The following are special projects for which SCEC has obtained funding beyond the core program. This Collaboration Plan is not for those funds, which are committed; rather it is for SCEC core funding for research projects that are consonant with these special projects. This is consistent with SCEC policy that requires that special projects be aligned with core SCEC goals.

a. Working Group on California Earthquake Probabilities (WGCEP)

Following the 2008 release of the Uniform California Earthquake Rupture Forecast version 2 (UCERF2), the WGCEP has completed the time-independent component of UCERF3 (which relaxes segmentation and includes multi-fault ruptures), and is working on finishing the UCERF3 time-dependent components (including spatiotemporal clustering in acknowledgment that triggered events can be damaging). As the latter will require robust interoperability with real-time seismicity information, UCERF3 will bring us into the realm of operational earthquake forecasting (OEF). These models are being developed jointly by SCEC, the USGS, and CGS, in close coordination with the USGS National Seismic Hazard Mapping Program, and with support from the California Earthquake Authority (CEA). We are also starting to plan for UCERF4, which we anticipate will utilize physics-based simulators to a greater degree (see last bullet below).

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

- Evaluate fault models in terms of the overall fault connectivity at depth (important for understanding the likelihood of multi-fault ruptures) and the extent to which faults represent a well-define surface versus a proxy for a braided deformation zone.
- Evaluate existing deformation models, or develop new ones, in terms of applicability of GPS constraints, categorical slip-rate assignments (based on "similar" faults), applicability of back-slip methods, and other assumptions. Of particular interest is the extent to which slip rates taper at the ends of faults and at fault connections.
- Evaluate the UCERF3 implication that 30% to 60% of off-fault deformation is aseismic.
- Help determine the average along-strike slip distribution of large earthquakes, especially where multiple faults are involved (e.g., is there reduced slip at fault connections?).
- Help determine the average down-dip slip distribution of large earthquakes (the ultimate source of existing discrepancies in magnitude-area relationships). Are surface slip measurements biased with respect to slips at depth?
- Develop a better understanding of the distribution of creeping processes and their influence on both rupture dimension and seismogenic slip rate.
- Contribute to the compilation and interpretation of mean recurrence-interval constraints from paleoseismic data and/or develop site-specific models for the probably of events going undetected at a paleosiesmic site.
- Develop ways to constrain the spatial distribution of maximum magnitude for background seismicity (for earthquakes occurring off of the explicitly modeled faults).
- Address the question of whether small volumes of space exhibit a Gutenberg Richter distribution of nucleations (even on faults).
- Develop improved estimates (including uncertainties) of the long-term rates of observed earthquakes for different sized volumes of space.
- Refine our magnitude completeness estimates (as a function of time, space, and magnitude). Develop such models for real-time applications (as will be needed in operational earthquake forecasting).
- Develop methods for quantifying elastic-rebound based probabilities in un-segmented fault models.
- Help quantify the amount of slip in the last event, and/or average slip over multiple events, on any major faults in California (including variations along strike).
- Develop models for fault-to-fault rupture probabilities, especially given uncertainties in fault endpoints.
- Explore the UCERF3 "Grand Inversion" with respect to: possible plausibility filters, relaxing the UCERF2 constraints, not over-fitting data, alternative equation-set weights, applying a characteristic-slip model, and applicability of the Gutenberg Richter hypothesis on faults (see report at www.WGCEP.org).
- Develop applicable methods for adding spatiotemporal clustering to forecast model s(e.g., based on empirical models such as ETAS). Are sequence-specific parameters warranted?
- Determine if there is a physical difference between a multi-fault rupture and a separate event that was triggered quickly.
- Develop more objective ways of setting logic-tree branch weights, especially where there are either known or unknown correlations between branches.

- Develop easily computable hazard or loss metrics that can be used to evaluate and perhaps trim logic-tree branches.
- Develop techniques for down-sampling event sets to enable more efficient hazard and loss calculations.
- Develop novel ways of testing UCERF3, especially ones that can be integrated with CSEP.
- Study and test the behavior of computational earthquake-cycle simulators, envisioning that they could become essential ingredients in future UCERF projects and a cornerstone of SCEC5. The goal is to develop the capability of simulators to be able to contribute meaningfully to hazard estimates. Examples of important tasks:
- Study and test, using code verification exercises and more than one code, the sensitivity of simulator results to input details including fault-system geometry, stress-drop values, tapering of slip, methods of encouraging rupture jumps from fault to fault, cell size, etc.
- Develop physically realistic ways of simulating off-fault seismicity.
- Add additional physics into simulators, for example, the inclusion of high-speed frictional weakening and of off-fault viscoelastic and heterogeneous elastic properties.
- Develop alternate methods of driving fault slip besides “back-slip”.
- Make access to existing simulators easy for new users, including adequate documentation and version numbers, examples of input and output files for initial testing, and access to analysis tools. Publicize availability.
- Develop new approaches to designing simulators and/or of making them more computationally efficient, including the use of better algorithms, point source Greens functions, and GPUs.
- Develop validation tools for simulators, utilize existing UCERF data comparison tools with them, and develop capabilities for simulators to interact with UCERF infrastructure.
- Develop the capability of simulators to deal with UCERF and SCEC CFM fault geometries, both for rectangular and triangular cell representations.
- Create statewide synthetic earthquake catalogs spanning 100 My using as many different simulators as possible, in order to generate statistically significant behavior on even slow-slipping faults. Use small time-steps to permit evaluation of short-term clustering.
- Use these catalogs as synthetic laboratories for CSEP testing as described under CSEP.
- Data-mine these catalogs for statistically significant patterns of behavior. Evaluate whether much-shorter observed catalogs are statistically distinguishable from simulated catalogs. Consider and explore what revisions in simulators would make simulated catalogs indistinguishable from observed catalogs.
- Develop and test a variety of statistical methods for determining the predictability of the of earthquakes in these simulated catalogs.
- Compute other data types such as gravity changes, surface deformation, InSAR images, in order to allow additional comparisons between simulated results and observations.

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

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

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

Priorities for CSEP

- Canterbury experiment: finalizing the retrospective evaluation of physics-based and statistical forecasting models during the 2010-12 Canterbury, New Zealand, earthquake sequence by (i) using Bayesian approaches to construct optimal ensemble models, (ii) comparing against extent prospective models, (iii) transitioning models to prospective evaluation, including in other regions;
- Global CSEP experiments: developing and testing global models, including, but not limited to, those developed for the Global Earthquake Model (GEM);
- Strengthening testing and evaluation methods: developing computationally efficient performance metrics of forecasts and predictions that (i) account for aleatory variability and epistemic uncertainties, and (ii) facilitate comparisons between a variety of probability-based and alarm-based models (including reference models);
- Advancing Operational Earthquake Forecasting (OEF): (i) developing forecasting methods that explicitly address real-time data deficiencies, (ii) updating forecasts on an event basis and evaluating forecasts with overlapping time-windows or on an event basis, (iii) improving short-term forecasting models, (iv) developing prospective and retrospective experiments to evaluate OEF candidate models;
- Earthquake rupture simulators: developing experiments to evaluate the predictive skills of earthquake rupture simulators, against both synthetic (simulated) and observed data (see also the WGCEP section);
- External Forecasts and Predictions (EFP): developing and refining experiments to evaluate EFPs (generated outside of CSEP), including operational forecasts by official agencies and prediction algorithms based on seismic and electromagnetic data;
- Induced seismicity: developing models and experiments to evaluate hypotheses of induced seismicity, e.g. in the Salton Trough or in Oklahoma, including providing data access to injection/depletion rates and other potentially pertinent data;
- Hybrid/ensemble models: developing methods for forming optimal hybrid and ensemble models from a variety of existing probability-based or alarm-based forecasting models;
- Hazard models: developing experiments to evaluate seismic hazard models and their components (e.g., ground motion prediction equations);
- Coulomb stress: developing forecasting models based on the Coulomb stress hypothesis that can be tested retrospectively and prospectively within CSEP;
- Developing methodology to forecast focal mechanisms and evaluating the skill of such forecasts;
- Testing paleo-based forecasts: developing experiments to prospectively test the fault rupture and earthquake probabilities implied by paleoseismic investigations of California faults (e.g., testing probabilities of future ruptures at paleoseismic sites where numerous ruptures have been documented, the relative effectiveness of proposed fault segment boundaries at stopping ruptures, and the relative frequency of on-fault and off-fault ruptures in California) (see also the WGCEP and SoSafe sections).

General Contributions

- Establishing rigorous procedures in controlled environments (testing centers) for registering prediction procedures, which include the delivery and maintenance of versioned, documented code for making and evaluating predictions including intercomparisons to evaluate prediction skills;
- Constructing community-endorsed standards for testing and evaluating probability-based, alarm-based, fault-based, and event-based predictions;
- Developing hardware facilities and software support to allow individual researchers and groups to participate in prediction experiments;
- Designing and developing programmatic interfaces that provide access to earthquake forecasts and forecast evaluations.
- Providing prediction experiments with access to data sets and monitoring products, authorized by the agencies that produce them, for use in calibrating and testing algorithms;

- Characterizing limitations and uncertainties of such data sets (e.g., completeness magnitudes, source parameter and other data uncertainties) with respect to their influence on experiments;
- Expanding the range of physics-based models to test hypotheses that some aspects of earthquake triggering are dominated by dynamic rather than quasi-static stress changes and that slow slip event activity can be used to forecast large earthquakes;
- Working to develop testable fault-based forecasting models;
- Evaluating hypotheses critical to forecasting large earthquakes, including the characteristic earthquake hypothesis, the seismic gap hypothesis, and the maximum-magnitude hypothesis;
- Conducting workshops to facilitate international collaboratories;

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

c. Community Modeling Environment (CME)

The Community Modeling Environment is a SCEC special project that develops improved ground motion forecasts by integrating physics-based earthquake simulation software, observational data, and earth structural models using advanced computational techniques including high performance computing. CME projects often use results, and integrate work, from SCEC groups including Interdisciplinary Focus Groups Technical Activity Groups. The SCEC research community can contribute research activities to CME by providing scientific or computational capability that can improve ground motion forecasts.

Examples of CME research includes development of earth structural models, curation of data sets to support forecast validation, and development of scientific software that simulates physical processes in the earth including dynamic ruptures (such as those that are verified in the Dynamic Rupture Code Verification Technical Activity Group (TAG)), and wave propagation simulations. Proposals are encouraged that work towards improving the accuracy of the statewide community velocity model (SCVM).

CME computationally based research projects include three types of forecast evaluation and testing systems; transient detection and forecast evaluation, earthquake early warning earthquake parameter and ground motion forecast evaluation, and short-term earthquake forecast evaluation.

CME is developing ground motion simulations that produce broadband seismograms. These simulation tools include rupture generators, low frequency wave propagation models, high frequency stochastic models, non-linear site response modules, and validation capabilities including assembled observational strong motion data sets and waveform-matching goodness of fit algorithms and information displays. Proposals that enhance our ability to extend ground motion simulations to higher frequencies through high frequency source generation models, and stochastic models of source, propagation, and site effects are encouraged.

Ground motion simulation validation computational and organizational tools are needed to establish repeatable validation of ground motion simulations to engineering standards. Research in this area would contribute to the efforts under the ground motion simulation validation TAG.

CME is working to improve probabilistic seismic hazard calculations. CME physics-based PSHA research requires a high resolution 3D velocity model for California, a pseudo-dynamic rupture generator capable of generating an extended earthquake rupture forecast from UCERF3.0, highly efficient reciprocity-based seismogram calculations, and probabilistic hazard model information system providing access to calculation results. Proposals that develop improved pseudo-dynamic models, including parameterizations that include the possibility of super-shear rupture, are encouraged. Proposals that seek to use existing CyberShake simulations as a research database are encouraged.

d. Virtual Institute for the Study of Earthquake Systems (VISES)

NSF has funded a new effort within SCEC to broaden and deepen our collaborations with Japanese earthquake scientists. A particular emphasis will be to broaden the participation of early career scientists. Collaborative research funded through VISES should have relevance for research questions of concern to the SCEC core program. Examples of relevant research activities include testing earthquake forecast models, numerical simulation of earthquake ground motion to high frequencies, ground motion simulation using dense networks of high-dynamic range sensors, and geodynamical studies of fault interaction and deformation. Travel support to Japan for early career scientists developing collaborations with colleagues in Japan is a priority for funding under the VISES program. (NOTE: Funding for successful proposals for travel to Japan will be handled from the SCEC office. Your proposed budget should not include overhead.)

e. Central California Seismic Project (CCSP)

The largest uncertainties in the estimation of the catastrophic risks to California utilities come from the seismic hazard uncertainties at low exceedance probabilities. Recent analyses indicate that these are dominated by the uncertainties in path effects; i.e., in the prediction of strong ground motions at a fixed surface site from specified seismic sources. SCEC has joined the Pacific Gas & Electric Company (PG&E) in developing a long-term research program aimed at reducing the uncertainties in path effects and other components of seismic hazard estimation.

A pilot project focused on the central coast of California will be initiated in 2015. The goal of this Central California Seismic Project (CCSP) is to assess the effectiveness of physics-based seismic wavefield modeling in reducing path-effect uncertainties. Currently planned first-year objectives of the program are fourfold:

- Analyze the existing seismic, geophysical, and geologic data for constraints on the 3D crustal structure of Central California. The seismic constraints include earthquake waveforms and ambient-field correlagrams; the geologic constraints include surface and subsurface data on basin, fault, and basement structure.
- Invert the seismic and geologic constraints to improve models of Central California crustal structure. Priority will be given to full-3D tomographic methods that can account for 3D wave propagation and the nonlinearity of the structural inverse problem.
- Deploy an array of temporary seismic stations in Central California to collect new earthquake and ambient-field data. Assess the efficacy of these data in reducing path-effect uncertainties and validating model-based uncertainty reductions.
- Compute large ensembles of earthquake simulations for central California sites that are suitable for probabilistic seismic hazard analysis (PSHA). Compare the simulation results with those from ground motion prediction equations (GMPEs). Use this modeling to understand the aleatory variability encoded by the GMPEs and to assess the epistemic uncertainties in the simulation-based PSHA.

The Planning Committee seeks additional effort in order to:

- Incorporate data from ocean bottom seismometer observations into improved community velocity models near- and off-shore Central California.
- Improve understanding of the fault system, both onshore and offshore, in Central California using precise earthquake locations, high-resolution geophysical imaging surveys, and other methods.
- Use observations of ground motion from local earthquakes, and dense recordings of ground motion (where available) to characterize the ability to predict the intensity of strong ground motion and its variability.
- Improve characterization of historical earthquakes in the region, including their location, mechanism, and finite-source characteristics (if relevant).

In evaluating CCSP-targeted proposals, the Planning Committee will consider the relevance of the proposed work to the overall project plan and the ability of investigators to deliver timely results during the pilot study. The PC will also consider novel approaches to the uncertainty-reduction problem in addition to those explicitly listed in the project plan. *Note: Terms of the master agreement funding CCSP limits indirect costs to 15%. Please use this rate only for CCSP proposals.*

f. National Partnerships through EarthScope

The NSF EarthScope project (*http://www.earthscope.org*) provides unique opportunities to learn about the structure and dynamics of North America. SCEC and the NSF EarthScope program encourage proposals that integrate the goals of the SCEC Science Plan with the many overlapping goals of the EarthScope Science Plan (*http://www.earthscope.org/ESSP*). Topics of interest include applying EarthScope observational resources to SCEC science and hazard problems; characterizing the crust and lithosphere of the natural laboratory of Southern California; exploring stress and deformation over time using EarthScope resources (including high resolution topography); testing hypothesis and enhancing models of earthquakes, faulting, and the rheology of the lithosphere; developing innovative contributions to identifying earthquake hazard and community response; and promoting Earth Science literacy in education and outreach in SCEC and EarthScope topic areas. These partnerships should seek to strengthen the connections across the organizations and leverage SCEC and EarthScope resources.

B. Communication, Education and Outreach Metrics and Milestones

See Appendix B for CEO Strategic Plan for description of the metrics and milestones below.

TBA=to be assessed or developed   DBR=data being reanalyzed   Period Year: Nov. 1 - Oct. 31

Table 1. Implementation Interface

	Target	Actual	Target	Actual	Target	Actual	Target	Actual
1.a. Research Engineering Partnerships	**2013**		**2014**		**2015**		**2016**	
1.a.001: Research engineers attending SCEC Annual Meeting and other research workshops	12	70	15	TBA	18		20	
1.a.002: Documented uses (citations, reports) of SCEC simulation models and other products in engineering research and risk assessments		TBA		TBA				
1.a.003: SCEC projects and collaborations involving research engineer (Given uncertainties in funding and participation we cannot commit to milestones)		16		TBA				
1.a.004: Partnerships with engineering and risk modeling organizations (with MOUs or other written partnership agreements) (As such partnerships depend on interest of the other organizations we cannot forecast milestones but will report progress each year)		0		0				
1.a.005: Jointly-funded projects with partner organizations (Given the uncertainty in funding we cannot commit to specific milestones, however this is a measure of the success of our Interface)		2		2				
1.b. Activities with Technical Audiences	**2013**		**2014**		**2015**		**2016**	
1.b.001: Practicing engineers, geotechnical consultants, building officials, emergency managers, insurers, etc. attending SCEC Annual Meeting and other research workshops annually	8	39	12	TBA	16		20	
1.b.002: Practicing engineers, geotechnical consultants, building officials, emergency managers, financial institution representatives, and insurers in the ECA (statewide, cumulative)	30	>100 TBA	50	>100 DBR	60		70	
1.b.003: Training sessions, seminars, and field trips for practicing engineers, building officials, etc. (organized by SCEC or co-sponsored) annually	1	2	2	2	4		6	

1.b.004: Online activities such as webinars, online trainings, and filmed presentations annually	1	0	2	0	3		4	
1.b.005: SCEC researchers (including students) participating in engineering/building code/etc. workshops and other activities (hosted by SCEC or other organizations) annually (This is an activity which we will promote however we have limited ability to require, so milestones cannot be specified (until a trend is determined))		10		TBA				
1.b.006: Documented technical, non-research uses of our models and informational resources (cumulative). *Uses include downloads, citations, etc.* *(As our capacity builds for documenting such use (perhaps quite complicated) we will report results, however milestones cannot be specified initially.)*		TBA		TBA				
1.b.007: Documented uses of SCEC tools/information in developing or conforming to building codes, guidelines, and standards (cumulative) (This is something we will develop the capacity to track, however because this can be limited by the frequency of code updates,etc., we cannot estimate milestones)		TBA		TBA				

Table 2. Public Education and Preparedness

2.a. Earthquake Country Alliance	**2013**		**2014**		**2015**		**2016**	
2.a.001: Registered ECA Associates (cumulative)	500	660	600	686	650		700	
2.a.002: Participants of functional and sector committees (annually)	60		80	150+	100		100	
2.a.003: Strategic Organizational Partners with MOUs (cumulative)	5	2	10	2	12		16	
2.a.004: Partner organizations (Associate or Strategic Organizations) that link to ShakeOut and ECA website (cumulative)	50	230	100	DBR	150		200	
2.a.005: New resources/programs for cultural/sector communities that have not yet been engaged (annually)	2	4	4	6	5		5	
2.a.006: ECA curricular resources for use by schools, colleges, and free-choice learning institutions to teach about earthquakes and preparedness (cumulative)	6	6	12	8	14		16	

2.a.007: Amount of funding (grants, donations) for ECA and its activities annually		$410K (FEMA)		$410K (FEMA)				
2.a.008: Unique visitors to each of ECA's websites (including the California ShakeOut site) and social media followers annually *Milestones will not be specified until trends can be forecasted.*	ShakeOut Twitter: 5148 follows ShakeOut Facebook: 7,925 likes		ECA: 89,000 ShakeOut CA: 203,000 ECA Twitter: 417 ECA Facebook: 712 ShakeOut Twitter: 5,802 ShakeOut Facebook: 8,225 ShakeOut YouTube: 150 subscribers					
2.a.009: Associates in each Alliance (cumulative) *Initial totals need to be confirmed, metric tracked internally (not reported)*	TBD		TBD	SoCal: 536 Bay Area: 163 Redwood Coast: 63	TBD		TBD	
2.a.010: Active functional and sector-based committees annually *Metric tracked internally (not reported)*	8	8	10	10	12		12	
2.a.011: People or organizations showcased as "ECA heroes" or "ShakeOut Spotlights", etc. annually *Metric tracked internally (not reported)*	15	0	20	0 (to be implemented)	25		25	
2.a.012: New tsunami documents and programs annually *Metric tracked internally (not reported)*	2	2	3	4	3		3	
2.b. ShakeOut Earthquake Drills	**2013**		**2014**		**2015**		**2016**	
2.b.001: California ShakeOut Participants annually	9.5 million	9.6 million	10 million	9.2 million as of 9/2/14	10.3 million		10.5 million	
2.b.002: California ShakeOut individual/family registrants annually *Included in overall California ShakeOut Participants above*	50,000	16,513	70,000	4,599 as of 9/2/14	100,000		120,000	
2.b.003:Participants in other U.S. ShakeOuts annually (While SCEC will be coordinating with ShakeOut Organizers in other countries, and in some cases hosting the websites for the drills, international participation is beyond SCEC's direct influence so this will be reported without specific milestones to achieve.)	5.0 million	11.3 million	5.5 million	5 million of of 9/2/14	6.0 million		6.5 million	
2.b.004: Participants in international ShakeOuts annually		3.8 million		3.5 million of of 9/2/14				

Including BC, Quebec, New Zealand, Japan, Central Asia, etc.								
2.b.005: ShakeOut drill franchises (cumulative) *(Specific milestones are not appropriate. While SCEC supports many franchises, we do not actively promote new ShakeOuts as a goal (i.e., more is not necessarily better). For example, consolidating multiple ShakeOuts in similar regions might reduce the overall total of distinct drills.*		23		27				
2.b.006: ShakeOut drill franchises at each level (1-5) *(New ratings system in development to specify what each franchise needs to be self-managing)*		TBA		TBA				
2.c. "Putting Down Roots" Publication Series	**2013**		**2014**		**2015**		**2016**	
2.c.001: Update and improve So Cal booklet with new science and preparedness information			✔	in 2015			✔	
2.c.002: Inclusion of updated earthquake forecasting information (UCERF3)			✔	in 2015			if available	
2.c.003: Area-specific versions in English (ShakeOut regions and Designated Media Areas)	1	1	12	12	15		15	
2.c.004: California versions in different languages or for other audiences (cumulative)	1	4	6	4	10		15	
2.c.005: Booklets (Roots, supplements, multi-langage versions) distributed annually *(Due to uncertain funding for printing, quantities to be printed/distributed cannot be listed as milestones)*		>30,000		>10,000 (low supply; more online now)				
2.c.006: Evaluation activities *Status will be reported, results may be in following year*		Reviewed with statewide prep. Survey		Assess business version		Assess multi-language versions		Reviewed with statewide prep. Survey
2.c.007: Inclusion of tsunami content in updated Bay area versions of the handbook (not SCEC managed, but ECA supported) *Metric tracked internally (not reported)*			✔	In SSWES				

2.c.008: Funding raised (sponsors, agencies) for developing and printing materials. *Metric tracked internally (not reported)*		>$300K (CalOES,CEA)	TBD	$0 so far	TBD		TBD	

2.d. Earthquake Education and Public Information Centers (EPIcenters)	**2013**		**2014**		**2015**		**2016**	
2.d.001: Participating museums, parks, and other free-choice learning venues in California and in other states (cumulative)	65	65 (60 CA)	75	68 (60 CA)	85		90	
2.d.002: Partner national organizations (e.g. research organizations, museum associations, etc.) (cumulative)	5	5	7	5	8		10	
2.d.003: SCEC-developed exhibits, interpretive trails, or programs in use (cumulative)	4	5	6	5	8		8	
2.d.004: EPIcenters and schools with QCN sensors	19	19+15 at schools	30	26 + >100 at schools	40		50	
2.d.005: EPIcenter field trips or other professional development field experiences (each year)	1	2	2	2	4		5	
2.d.006: EPIcenters using network materials (including materials from national organizations and the ShakeOut) (each year)	50	>30 (being checked)	65	50	70		85	
2.d.007: Partner participation in EPIcenter surveys (%, each year) (Participation is uncertain to forecast initially)		n/a		no survey				
2.d.008: Results of surveys (Once surveys are developed additional metrics may be added to this plan. Until then key results will be reported)		n/a		no survey				

2.e. Media Relations (Each milestone is split between SCEC Research and CEO-ECA topics)	**2013**		**2014**		**2015**		**2016**	
2.e.001: Traditional news advisories and releases	4 / 8	0 / 5	5 / 10	2 / 7	7 / 10		8 / 10	
2.e.002: Podcasts or online interviews (audio and/or video)	1 / 2	0 / 1	2 / 4	0 / 2	4 / 6		4 / 6	
2.e.003: Virtual news conferences / webinars	1 / 1	0 / 0	2 / 2	0 / 1	3 / 3		3 / 3	
2.e.004: People in SCEC Experts directory (with summaries/videos/etc.)	5	0	10	0	20		30	
2.e.005: Experts identified and trained for interviews in non-English languages	2 / 5	2 / 3	4 / 10	2 / 3	5 / 15		6 / 20	

2.e.006: Traditional news stories (online, print, radio, tv) (SCEC, ECA, ShakeOut) (No milestones until trends are understood)	SCEC: >50 but all not in database. ECA/ShakeOut: >1200		ALL ~70 (11/1-9/1; many more by 10/31)					
2.e.007: Social media posts/followers/etc. (SCEC) (As this will be determined by factors beyond our influence (earthquakes in particular) and also the growth of social media, we cannot provide targets until trends are tracked)	@SCEC: 269 tweets, 153 followers facebook.com/scec: XXX posts,1295 likes		@SCEC: 652 tweets, 517 followers; facebook.com/scec: 87 posts, 2124 likes; SCEC youtube: 55					
2.e.008: Non-English news advi-sories/releases (by language) (This will depend on the number of news stories and our capacity for translation (ideally through partner organizations, as fees can be high))		0		0				
2.e.009: Media and risk communication training seminars for SCEC community (and # of participants) (Having such trainings is a priority however it is not clear yet how many will be needed, how frequently, and how many people need to participate.)		1: 250 (at SCEC Annual Meeting)		1 (at SCEC Annual Meeting				
2.e.010: Programs to educate the media on how to report earthquake science (and number of participants) (As we develop this project we will be better able to estimate number of programs that we will offer. These may be best as small workshops, or might be offered as online webinars)		0		2 (Northridge Earthquake Anniversary)				

Table 3. K-14 Earthquake Education Initiative

3. K-14 Earthquake Education Initiative (all categories include materials developed in collaboration with SCEC partners)	**2013**		**2014**		**2015**		**2016**	
3.001: Event-based or "place-based" local/regional education opportunities (each year)	1	1	2	3	3		3	
3.002: Educational materials improved or created to provide information about local earthquake hazards and relevance for learning about earthquakes (per year)	1	2	2	3	4		4	
3.003: Educator workshops offered to introduce these resources to educators (each year)	1	1	2	10	3		3	
3.004: Educators participating in all programs	30	125	60	200+	90		90	

3.005: Participating educational and research organizations in the initiative (cumulative)	3	3	5	9	8		10	
3.006: New learning experiences and materials for use after large earthquakes (each year) (Specific milestones cannot be projected as this depends on the number of large earthquakes each year.)		TBA		2				

Table 4. Experiential Learning and Career Advancement

4. Experiential Learning and Career Advancement	2013		2014		2015		2016	
4.001: Participants (each summer) in SCEC undergraduate internship programs, based on current funding levels and potential leveraging (see note in text above)	30	24 UseIT 10 SURE	30	21 UseIT 17 SURE	30		30	
4.002: Students involved in academic-year research or outreach projects (SCEC/ShakeOut/etc.) (each year)	10	18	12	17	15		15	
4.003: % Undergraduate interns who are women / % underrepresented minorities (each year)	40 / 20	38 / 38	50 / 25	56 / 49	50 / 25		50 / 25	
4.004: High school students provided research, education or outreach experiences, (each year)	4	4	6	2	6		8	
4.005: Master's level opportunities (each year)	2	5	4	4	5		6	
4.006: Early career researcher presentations supported (each year)	2	2	3	1	4		4	
4.007: Intern alumni in graduate school or having graduate degrees (Participation in SCEC is only one factor that may contribute to these metrics, so specific milestones are not appropriate)		DBR		DBR				
4.008: Intern alumni in STEM professions or internships (cumulative) (Participation in SCEC is only one factor that may contribute to these metrics, so specific milestones are not appropriate)		DBR		DBR				
4.009: Employment or internship opportunities that are shared via SCEC email or website (each year) (This depends on external partners and other factors beyond SCEC's control)		Will be tracked within new SCEC website		9				

4.010: Early career researchers active in SCEC (criteria: anyone within 12 years of their highest post-secondary degree. Will be revised to 10 years in 2014. (Hiring at SCEC institutions is beyond SCEC control, however knowing the total number and having communication with them will allow us to monitor and support progress)	Total active in SCEC (attended 2013 Annual Meeting or submitted proposal in 2013): 584 Early career: 314	Total active in SCEC (attended 2014Annual Meeting or submitted proposal in 2014): 650 Early career: 363				
4.011: % of women/ underrepresented minorities in SCEC leadership positions	(women): 8 of 32 Planning Committee members, 5 of 19 Board Members, 5 of 11 Advisory Council members (minorities): 4 of 32 Planning Committee members, 2 of 19 Board Members, 0 of 11 Advisory Council members	(women): 9 of 33 Planning Committee members, 5 of 19 Board Members, 4 of 11 Advisory Council members (minorities): 4 of 33 Planning Committee members, 2 of 19 Board Members, 0 of 11 Advisory Council members				

V. Publications

This section lists the publications recorded in the SCEC community database between November 2013 to November 2014. Each publication is preceded by its SCEC publication number.

A. Journal Articles (132 total)

1938 Agnew, D. C., and F. K. Wyatt (2014). Dynamic Strains at Regional and Teleseismic Distances. *Bulletin of the Seismological Society of America*, under review.

1931 Agnew, D.C. (2014). Variable Star Symbols for Seismicity Plots. *Seismological Research Letters*, 85, p. 775-780, DOI: 10.1785/0220130214.

1846 Akciz, S. O., L. Grant Ludwig, O. Zielke, and J R. Arrowsmith (2014). 3D investigation of a 5m deflected channel along the San Andreas fault in the Carrizo Plain. *Bulletin of the Seismological Society of America*, 104, DOI: 10.1785/0120120172.

1997 Anderson, J. G. (2014). The Composite Source Model for Broadband Simulations of Strong Ground Motions . *Seismological Research Letters*, accepted.

1986 Assimaki, D., and R. Taborda (2014). Site-specific response in validation studies of physics-based earthquake simulations. *Seismological Research Letters*, 85, p. 470.

2006 Avouac, J.-P., F. Ayoub, S. Wei, J.-P. Ampuero, L. Meng, S. Leprince, R. Jolivet, Z. Duputel, and D. Helmberger (2014). Seismic slip boosted on a misoriented fault bend during the 2013, Mw7.7 Balochistan Earthquake. *Earth and Planetary Science Letters*, 391, p. 128-134.

1795 Baltay, A. S. and G. C. Beroza (2013). Ground motion prediction from tremor. *Geophysical Research Letters*, 40, p. 6340-6345, DOI: 10.1002/2013GL058506.

1951 Barall, M., and R.A. Harris (2014). Metrics for Comparing Dynamic Earthquake Rupture Simulations. *Seismological Research Letters*, submitted.

1800 Barrett, S. A. and G. C. Beroza (2014). An Empirical Approach to Subspace Detection. *Seismological Research Letters*, accepted.

1971 Beeler, N.M., G. Hirth, A. Thomas, and R. Burgmann (2014). Effective stress, friction and deep crustal faulting. *Journal of Geophysical Research*, in preparation.

1822 Bennett, S.E.K., M.E. Oskin, and A. Irionodo (2013). Transtensional rifting in the proto–Gulf of California near Bahía Kino, Sonora, México. *Geological Society of America Bulletin*, 125, p. 1752-1782, DOI: 10.1130/B30676.1.

1799 Böse, M., R.W. Graves, D. Gill, S. Callaghan, and P. Maechling (2014). CyberShake-Derived Ground-Motion Prediction Models for the Los Angeles Region with Application to Earthquake Early Warning. *Geophysical Journal International*, 198, p. 1438-1457, DOI: 10.1093/gji/ggu198.

1987 Bradley, A.M. (2014). Software for efficient static dislocation-traction calculations in fault simulators. *Seismological Research Letters*, 85, p. 1358-1365, DOI: 10.1785/0220140092.

1976 Brantut, N., and R. C. Viesca (2014). Earthquake nucleation in intact or healed rocks. *Journal of Geophysical Research*, under review.

1793 Burks, L.S. and J.W. Baker (2014). Validation of ground motion simulations through simple proxies for the response of engineered systems. *Bulletin of the Seismological Society of America*, , p. , DOI: . (Awaiting Publication).

1964 Burks, L.S. and J.W. Baker (2014). A predictive model for ground motion fling step based on ground motion recordings and simulations. *Soil Dynamics and Earthquake Engineering*, under review.

1794 Burks, L.S., R.B. Zimmerman, and J.W. Baker (2014). Evaluation of Hybrid Broadband Ground Motion Simulations for Response History Analysis and Design. *Earthquake Spectra*, accepted.

1973 Chen, T., S. O. Akciz, K. W. Hudnut, D. Z. Zhang, and J. M. Stock (2014). Fault slip distribution of the 1999 Mw 7.1 Hector Mine Earthquake, California, estimated from post-earthquake airborne LiDAR data. *Bulletin of the Seismological Society of America*, under review.

1942 Coble, C. G., M. E. French, F. M. Chester, J. S. Chester, and H. Kitajima (2014). In situ frictional properties of San Andreas Fault gouge at SAFOD. *Geophysical Journal International*, DOI: 10.1093/gji/ggu306.

1980 Crempien, J. G. F. and R. J. Archuleta (2014). UCSB Method for Broadband Ground Motion for Kinematic Simulations of Earthquakes. *Seismological Research Letters*, accepted.
1932 Crowell B. W., D. Melgar, Y. Bock, J. S. Haase, and J. Geng (2013). Earthquake magnitude scaling using seismogeodetic data. *Geophysical Research Letters*, 40, p. 6089-6094, DOI: 10.1002/2013GL058391.
1898 Curren, I. S., and P. Bird (2014). Formation and suppression of strike-slip fault systems. *Pure and Applied Geophysics*, under review.
1743 DeBock, D.J., J.W. Garrison, K.Y. Kim, and A.B. Liel (2014). Incorporation of spatial correlations between building response parameters in regional seismic loss analysis. *Bulletin of the Seismological Society of America*, 104, DOI: 10.1785/0120130137.
1911 Deelman, E., K. Vahi, G. Juve, M. Rynge, S. Callaghan, P. Maechling, R. Mayani, W. Chen, R. da Silva, M. Livny, and K. Wenger (2014). Pegasus, a Workflow Management System for Large-Scale Science. *Future Generation Computer Systems*, under review.
1812 Denolle, M. A., E. M. Dunham, G. A. Prieto, and G. C. Beroza (2014). Strong Ground Motion Prediction using Virtual Earthquakes. *Science*, 343, p. 399-403, DOI: 10.1126/science.1245678.
1836 Denolle, M. A., H. Miyake, S. Nakagawa, N. Hirata, and G. C. Beroza (2014). Long-period seismic amplification in the Kanto Basin from the ambient seismic field. *Geophysical Research Letters*, 41, p. 2319-2325, DOI: 10.1002/2014GL059425.
1988 Dolan, James F., and Ben D. Haravitch (2014). How Well Do Surface Slip Measurements Track Slip at Depth in Large Strike-Slip Earthquakes? The Importance of Fault Structural Maturity in Controlling on-Fault Slip versus off-Fault Surface Deformation. *Earth and Planetary Science Letters*, 388, p. 38-47, DOI: 10.1016/j.epsl.2013.11.043.
1839 Dong, S., G. Ucarkus, S. Wesnousky, J. Maloney, G. Kent, N. Driscoll, and R. Baskin (2014). Strike-slip Faulting along the Wassuk Range of the northern Walker Lane, Nevada. *Geosphere*, 10, p. 40-48, DOI: 10.1130/GES00912.1.
1983 Dreger, D. S., G. C. Beroza, S. M. Day, C. A. Goulet, T. H. Jordan, P. A. Spudich, and J. P. Stewart (2014). Validation of the SCEC Broadband Platform V14.3 Simulation Methods Using Pseudo Spectral Acceleration Data. *Seismological Research Letters*, under review.
1791 Duputel, Z., P. S. Agram, M. Simons, S. E. Minson and J. L. Beck (2014). Accounting for prediction error when inferring subsurface fault slip. *Geophysical Journal International*, 197, p. 464-482, DOI: 10.1093/gji/ggt517.
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1796 Erickson, B. A., and E. M. Dunham (2014). An Efficient Numerical Method for Earthquake Cycles in Heterogeneous Media: Alternating Subbasin and Surface-rupturing Events on Faults Crossing a Sedimentary Basin. *Journal of Geophysical Research*, 119, DOI: 10.1002/2013JB010614.
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1989 Field, E. H., G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, T. Parsons, P. M. Powers, B. E. Shaw, W. R. Thatcher, R. J. Weldon, and Y. Zeng (2014). Long-Term, Time-Dependent Probabilities for the Third Uniform California Earthquake Rupture Forecast (UCERF3). *Bulletin of the Seismological Society of America*, submitted.
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1962 Fletcher, J.M., M.E. Oskin, O.J. Teran, and E. Hauksson (2014). Seismogenic Expression of Three Dimensional Strain within a Single Earthquake Sequence. *Nature*, in preparation.
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system: surface rupture kinematics of the April 4, 2010 El Mayor-Cucapah Mw7.2 earthquake . *Geosphere*, 10, p. 797-827.

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1767 Gabuchian, V., A.J. Rosakis, N. Lapusta, and D.D. Oglesby (2014). Experimental investigation of strong ground motion due to thrust-fault earthquakes. *Journal of Geophysical Research: Solid Earth*, 119, p. 1316-1336, DOI: 10.1002/2013JB010409.

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1921 Johnson, K., E. Nissen, S. Saripalli, J.R. Arrowsmith, P. McGarey, K. Scharer, P. Williams, and K. Blisniuk (2014). Rapid Mapping of Ultra-fine Fault Zone Topography with Structure from Motion. *Geosphere*, 10, p. 969-986, DOI: 10.1130/GES01017.1.

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1899 Jolivet, R., Z. Duputel, B. Riel, M. Simons, L. Rivera, S. E. Minson, H. Zhang, M. Aivazis, F. Ayoub, S. Leprince, S. Samsonov, M. Motagh, and E. Fielding (2014). The 2013 Mw 7.7 Balochistan earthquake: Seismic potential of an accretionary wedge. *Bulletin of the Seismological Society of America*, 104, p. 1020-1030, DOI: 10.1785/0120130313.

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1955 Kang, J., and B. Duan (2014). Elastic and Inelastic Responses of Compliant Fault Zones to Nearby Earthquakes in Three Dimensions: a parameter-space study. *Geophysical Journal International*, in preparation.

2029 Karaoglu, H., and J. Bielak (2014). Ground-motion simulation and validation of the 2004 Chuetsu, Japan, earthquake using different velocity models.. *Bulletin of the Seismological Society of America*, in preparation.

1993 Lee, E.-J., P. Chen, T. H. Jordan, P. B. Maechling, M. A. M. Denolle, and G. C. Beroza (2014). Full-3-D tomography for crustal structure in Southern California based on the scattering-integral and the adjoint-wavefield methods. *Journal of Geophysical Research: Solid Earth*, 119, p. 6421-6451, DOI: 10.1002/2014JB011346.

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VI. Appendices

A. Science Milestones

NSF has requested that we submit an annualized list of milestones as part of a revised SCEC4 plan for 2012-2017. According to NSF instructions, these milestones are based on the six fundamental problems in earthquake physics described in the SCEC4 proposal (see Table 1 of this supplement). Our response to the NSF request adopts the premise that milestones are to be used by SCEC and its sponsoring agencies as indicators of research progress along unknown conceptual pathways rather than, say, lists of working-group tasks, timelines for IT developments, or absolute measures of research volume from individual research groups.

We have therefore concentrated on targets for SCEC's interdisciplinary activities in earthquake system science, such as those related to the SCEC Community Models, which will include a new Community Geodetic Model (CGM) and a Community Stress Model (CSM); those related to a proposed new set of Special Fault Study Areas (SFSAs); and those coordinated through the Technical Activity Groups (TAGs), such as the newly established Ground Motion Simulation Validation TAG, which brings earthquake engineers together with ground motion modelers. Because SCEC interdisciplinary activities in some cases depend on ancillary support from special projects (e.g., IT developments, HPC resources), reaching some of the milestones will be contingent on receiving this ancillary support.

The milestones are organized by a numbered research topic or collaboration. The problems addressed by each numbered item are listed parenthetically at the end of each paragraph; e.g., [I-VI] indicates that the milestones for that topic or collaboration are relevant to all six problems. Owing to the unpredictable nature of basic research, the milestones for the first two years are more explicit than those for the out-years of the SCEC4 program.

Year 1 (2012-2013)

1. ***Improved Observations.*** Archive and make available at the SCEDC waveforms, refined catalogs of earthquake locations and focal mechanisms for the period 1981-2011. Begin cataloging validation earthquakes and associated source descriptions and strong ground motion observations for California for use in ground motion simulation validation. Implement automated access to EarthScope GPS data for transient detections. Initiate planning with IRIS and UNAVCO to improve the scientific response capabilities to California earthquakes. [I-VI]
2. ***Transient Geodetic Signals.*** Develop data-processing algorithms that can automatically detect geodetic transients localized within Southern California using continuously recorded GPS data. Provide access to authoritative GPS data streams through CSEP. Implement at least two detection algorithms as continuously operating procedures within CSEP. [V]
3. *Com**munity Modeling Environment.*** Implement, refine, and release software tools for accessing the SCEC CVMs. Define reference calculations and evaluation criteria for 3D velocity models. Conduct comparative evaluations among different CFMs and CVMs. Deliver statewide versions of CFMs for use by WGCEP in UCERF3. Develop dynamic rupture verification exercises that incorporate effects of large-scale branching fault geometry on dynamic rupture and ground motions.[II, III, IV, VI]
4. ***Community Geodetic Model.*** Obtain input from the SCEC community via a workshop in order to define the conceptual and geographic scope of the CGM, including the time-independent and time-dependent model components, the data to be assimilated into the model, and the type and spatial distribution of model output. [I, II, V]
5. ***Community Stress Model.*** Develop a strategy for archiving and curating observational and model-based constraints on the tectonic stress field in Southern California. Based on this strategy, begin developing components of the database that will underlie the CSM. Organize a SCEC collaboration to contribute existing observational and model-based constraints to this database. [I, II]
6. ***Special Fault Study Areas.*** Identify requirements for SFSA Science Plans. Solicit SFSA projects from the SCEC community, notify community of projects and post Science Plan(s) for 2013 RFP on

the website. Coordinate interdisciplinary activities, including workshops, to prototype at least one SFSA. [I-VI]

7. ***Ground Motion Simulation Validation.*** Develop a set of validation procedures suitable for the application of ground motion simulations in seismic hazard analysis and earthquake engineering. Identify a set of ground motions recorded in large California earthquakes to use for validation. Use codes available in the CME to simulate the ground motions. Compare these simulations with the observed recordings and other empirical models where they are well-constrained. [VI]
8. ***Source Modeling.*** Support WGCEP in the development and release of UCERF3. Reduce the updating interval of the short-term forecasting models being tested in CSEP. Improve methods for detecting, classifying, and analyzing various types of seismic clustering. [II, V]
9. ***Time-Dependent Earthquake Forecasting.*** Support WGCEP in the development and release of UCERF3. Reduce the updating interval of the short-term forecasting models being tested in CSEP. Improve methods for detecting, classifying, and analyzing various types of seismic clustering. [II, V]

<u>Year 2 (2013-2014)</u>

1. ***Improved Observations.*** Begin cataloging SCEC-supported geochronology analyses available for Southern California. Complete cataloging validation earthquakes and associated source descriptions and strong ground motion observations for California for use in ground motion simulation validation. Start comparing InSAR and GPS data to flag any suspect data as a first step to integrated use of GPS and InSAR in the CGM. Start developing plans for enhanced seismic instrument deployments in the SFSAs and elsewhere in Southern California. Update coordination of earthquake response capabilities of the SCEC community with partner organizations, including USGS, IRIS, and UNAVCO. [I-VI]
2. ***Transient Geodetic Signals.*** Increase the number of geodetic transient detection algorithms automated within CSEP that continuously operate on authoritative GPS data streams. Assess and refine detection thresholds through the use of synthetic data for a range of earthquake sizes for all operating detectors. [V]
3. ***Community Modeling Environment.*** Improve CVMs by applying full-3D waveform tomography to data from hundreds of earthquakes. Perform reference calculations and apply goodness-of-fit measures to evaluate CVMs against earthquake waveform data. Improve stochastic kinematic rupture models that incorporate source complexity observed in dynamic rupture simulations, including supershear rupture. Provide access to the UCERF3 statewide hazard model via the OpenSHA software platform. Develop methodology for calculating an extended ERFs based on UCERF3. [II, III, IV, VI]
4. ***Community Geodetic Model.*** Start generating a unified GPS time series dataset for secular and transient deformation and compiling LOS velocity maps from available SAR catalogs. Establish strategy for estimating secular rate as well as temporally variable signals (e.g., seasonal, postseismic). Assess the feasibility and the potential benefits of incorporating additional datasets (e.g., strainmeter, LiDAR) into CGM. Specify the CGM output needed for input to the CSM and transient detection and begin providing preliminary datasets as available. [I, II, V]
5. ***Community Stress Model.*** Populate the CSM data system with existing observational and model-based constraints. Begin coordination efforts with developers of the CGM and earthquake models. Investigate the variations in directions and magnitudes of the stresses and stressing rates predicted by different existing models. [I, II, IV]
6. ***Special Fault Study Areas.*** Solicit SFSA Science Plan(s) from the SCEC community and post Science Plan(s) for 2014 RFP on the website. Re-examine requirements for SFSA Science Plans. Evaluate whether SCEC should increase the number of SFSA-oriented studies in the SCEC base program. [I-VI]
7. ***Ground Motion Simulation Validation.*** Develop a list of metrics identified by earthquake scientists and engineers as needed to validate ground motion predictions for application to seismic hazard analysis and earthquake engineering. Use the observed ground motions of well-recorded California earthquakes to evaluate existing ground motion simulation methods and recommend improvements.

Establish the Broadband Simulation Platform as a high-performance cyberfacility for ground motion simulation by outside research communities, including earthquake engineers. [III, VI]

8. ***Source Modeling.*** Develop numerical methods that simultaneously resolve fault zone processes and large-scale rupture, including fault interaction, complex geometries, heterogeneites and multiple fault physics. Assess data available to distinguish source from path/site effects at high frequencies. Develop a methodology for uncertainty quantification in finite-fault source inversion and back-projection source imaging, tested on standardized data sets. [III, VI]
9. ***Time-Dependent Earthquake Forecasting.*** Assess the capabilities of UCERF3 for time-dependent forecasting through comparisons with earthquake catalogs or synthetic catalogs from earthquake models. Through CSEP and in collaboration with the USGS and CGS, test the suitability of deploying UCERF3 as an operational earthquake forecast. Couple UCERF3 to the Cybershake simulation suite for the Los Angeles region to prototype a time-dependent urban seismic hazard model. [II, VI]
10. ***Progress Report on SCEC4 Problems.*** Report to the SCEC4 community and Advisory Council on the progress made so far in formulating and testing hypotheses that address the six fundamental problem areas of earthquake physics.

Year 3 (2014-2015)

1. ***Improved Observations.*** Archive and make available at the SCEDC waveforms, refined catalogs of earthquake locations and focal mechanisms for the period 1981-2013. Continue cataloging SCEC-supported geochronology analyses available for Southern California. Submit a proposal to NSF/Earthscope that focuses on high-resolution imaging of SFSAs and elsewhere in Southern California. Begin developing catalogs of prehistoric surface rupturing events along major faults in the system. [I-VI]
2. ***Transient Geodetic Signals.*** Using the first two years of results from Southern California, assess the capability and consistency of the geodetic transient detection procedures. Develop ensemble-based detection procedures that combine the output of multiple detection algorithms. [II, V]
3. ***Community Modeling Environment.*** Incorporate stochastic descriptions of small-scale heterogeneities into the upper layers of the CVMs and evaluate the importance of these heterogeneities in ground motion models. Integrate and evaluate a statewide unified CVM suitable for 3D ground motion modeling. Incorporate new information on fault complexity from SFSA projects into the CFM. [II, III, IV, VI]
4. ***Community Geodetic Model.*** Assemble existing InSAR LOS velocity models and compile GPS solutions from multiple sources. Conduct comparisons among InSAR velocity models, among GPS solutions, and between InSAR and GPS LOS velocities to highlight areas of disagreement and determine likely sources of disagreement. Continue test exercise to identify best practices for InSAR time series analysis. [I, II, V]
5. ***Community Stress Model.*** Quantitatively assess discrepancies between various stress models. Begin the process of identifying classes of alternative stress models or branches for the CSM. [I, II, IV]
6. ***Special Fault Study Areas.*** Continue to execute coordinated plans for disciplinary fieldwork and interdisciplinary synthesis in SFSAs. Finalize the set of SFSAs to be investigated in SCEC4. [I-VI]
7. ***Ground Motion Simulation Validation.*** Develop scientific and engineering criteria for appropriate use of deterministic and stochastic ground motion simulations. Based on the Year-2 evaluation, assess how future SCEC simulation efforts can best assist seismic hazard analysis, risk analysis, and earthquake engineering. Implement in the Broadband Platform the capability to use more than one planar fault to describe an earthquake source's fault geometry. Examine SCEC4 research on dynamic weakening and the effect of geometrical heterogeneity on faulting and discuss if it is a sufficiently mature pathway to improve estimates of high-frequency wave excitation by seismic sources. [III, VI]
8. ***Source Modeling.*** Verify numerical methods and assess physical formulations of fault geometries. Develop and calibrate parameterization of resistance mechanisms that are suitable for large scale models of dynamic ruptures, including interaction with fault roughness and damage-zone properties. Develop improved source inversion approaches with enhanced information extraction from high frequencies, including by integration with back-projection imaging. [III, VI]

9. ***Time-Dependent Earthquake Forecasting.*** Develop approaches for using computational earthquake-cycle simulation models in forecasting. Employ these models for studying the predictability of large events and constraining seismic cycle parameters (maximum magnitude, inter-event time, etc.). Conduct prospective forecasting experiments in CSEP that test the key hypotheses that underlie time-dependent forecasting methods. [II]
10. ***Progress Report on SCEC4 Problems.*** Report to the SCEC4 Community and Advisory Council on the progress made so far in formulating and testing hypotheses that address the six fundamental problem areas of earthquake physics and report to SCEC4 community.

Year 4 (2015-2016)

1. ***Improved Observations.*** Refine catalogs of prehistoric surface rupturing events along major faults in the system and, if needed, document more events, including paleo-magnitudes, with more robust uncertainty measurements. Initiate the use of GPS data to better constrain 3D motion observed by InSAR, especially in the North/South direction. [I-VI]
2. *Transient Geodetic Signals.* Incorporate the CGM into the transient detection procedures as the reference model for time-dependent geodetic signals. Using the data collected in Southern California and elsewhere on geodetic transients, assess the observational constraints on the spectrum of deformation transients that might be associated with earthquake processes in San Andreas Fault system. [II, IV, V]
3. ***Community Modeling Environment.*** Develop a prototype CyberShake hazard model for the Los Angeles region based on extensions of UCERF3 and large suites of ground motion simulations up to 1 Hz calculated from improved CVMs. Provide interactive access to this layered seismic hazard model. [II, III, IV, VI]
4. ***Community Geodetic Model.*** Develop consensus approach for InSAR LOS time series analysis constrained by GPS data. Identify appropriate methods for characterizing noise in GPS time series, estimating derived quantities from GPS time series, and interpolating GPS-derived quantities for use in InSAR analysis. Apply these approaches to GPS time series product to provide necessary GPS constraints for InSAR component of CGM. [I, II, V]
5. ***Community Stress Model.*** Populate branches of the CSM that represent alternative approaches, assumptions, and data. Develop new models of stress and stressing rate in the southern California lithosphere to address identified gaps in the CSM. Validate CSM models using relevant data and physical constraints. Begin applying results to the problem of discriminating between competing models of fault system loading. [I, II]
6. ***Special Fault Study Areas.*** Through workshops and other collaborative mechanisms, begin to synthesize SFSA results for integration into SCEC products and activities and address SCEC science questions. [I-VI]
7. ***Ground Motion Simulation Validation.*** Extend validation studies to high-frequency ground motion simulations that incorporate improved representations of source physics, source complexity, attenuation, non-linear effects, and high-frequency scattering by small-scale heterogeneities. [VI]
8. ***Source Modeling.*** Validate implementation for more realistic models of fault resistance evolution through dynamic rupture code comparisons and work towards incorporating them into CFM-based simulations of earthquakes. Compare fault interaction patterns from dynamic rupture models to earthquake simulators. Generate a uniform database of kinematic source models of past earthquakes and extract constraints on mechanical fault properties. Develop fundamental insight into source inversion uncertainties. [III, VI]
9. ***Time-Dependent Earthquake Forecasting.*** Develop earthquake forecasting algorithms and evaluate their utility in deploying new versions of a Uniform California Earthquake Rupture Forecast. [II]
10. ***Progress Report on SCEC4 Problems.*** Report on the progress made so far by SCEC4 investigations of the six fundamental problem areas of earthquake physics. Synthesize the current state of interdisciplinary knowledge in each of these problem areas, and evaluate which among the alternate hypotheses described in the SCEC4 proposal are now favored by the observational data and model-based constraints. This report will be used as input to the SCEC5 proposal. [I-VI]

Year 5 (2016-2017)

1. ***Improved Observations.*** Archive and make available at the SCEDC waveforms, refined catalogs of earthquake locations and focal mechanisms for the period 1981-2015. Document results from significant earthquakes that occurred during SCEC4. Continue refinement of the catalog of prehistoric surface rupturing events along major faults in the system including realistic uncertainty estimates. Initiate new project for archiving and making available InSAR datasets from Sentinel and ALOS2 acquisitions, which pertain to geological problems being studied by SCEC investigators. Complete comparing InSAR and GPS data to flag any suspect anomalies in GPS data as a first step to resolving discrepancies between GPS and InSAR strain rates. [I-VI]
2. ***Transient Geodetic Signals.*** Using the data collected in Southern California and elsewhere on geodetic transients during SCEC4, assess the validated and potential utility of geodetic data in time-dependent earthquake forecasting. [II, IV, V]
3. ***Community Modeling Environment.*** Perform reference calculations and apply goodness-of-fit measures to evaluate a SCEC California statewide CVMs using earthquake waveform data. Calculate statewide CyberShake hazard model based on extensions of UCERF3, the California statewide CVM, and large suites of ground motion simulations up to 1 Hz. Provide interactive and programmable access to this layered seismic hazard model. [II, III, IV, VI]
4. ***Community Geodetic Model.*** Generate GPS-constrained InSAR LOS velocity product for all areas of southern California that are not decorrelated, GPS time series product comprised of southern California continuous and campaign data, GPS-derived quantities (e.g., secular rates, seasonal terms), and GPS and InSAR LOS velocities interpolated to common geographic grid. Demonstrate time series analysis best practices by producing combined InSAR-GPS LOS time series for geographic region used in test exercise. Document best practices and a framework for incorporating future observations. [I, II, V]
5. ***Community Stress Model.*** Release the final SCEC4 version of the CSM and assess its implications for earthquake physics. Recommend guidelines for future data collection and modeling studies to improve resolution of the CSM. [I, II]
6. ***Special Fault Study Areas.*** Publish synthesis studies of the SCEC4 SFSAs. Assess the utility of these syntheses in improving seismic hazard models for California. [I-VI]
7. ***Ground Motion Simulation Validation.*** Complete an evaluation of the simulated ground motions produced by the current versions of the Broadband Platform and the statewide CyberShake model. [VI]
8. ***Source Modeling.*** Develop realistic broadband kinematic source models of well-recorded earthquake in California that are consistent with source inversion and dynamic rupture modeling. Work with USGS/Golden to migrate improvements in source inversion into operational methods. [III, VI]
9. ***Time-Dependent Earthquake Forecasting.*** Use earthquake models, the CFM and CSM, and other modeling tools to quantify how fault-system complexities govern the probabilities of large earthquakes and rupture sequences. [II]
10. ***Progress Report on SCEC4 Problems.*** Conduct a final assessment of SCEC4 investigations of the six fundamental problem areas of earthquake physics, and evaluate the utility of new knowledge in time-independent and time-dependent seismic hazard analysis. [I-VI]

B. Communication, Education, and Outreach Strategic Plan

Creating an Earthquake and Tsunami Resilient California (2013-2017)

SCEC's Communication, Education, and Outreach (CEO) program complements the SCEC Science Plan, fostering new research opportunities and ensuring the delivery of research and educational products to the general public, government agencies, the broader geoscience community, engineers, students, businesses, and the media. SCEC CEO addresses the third element of SCEC's mission: *Communicate understanding of earthquake phenomena to the world at large as useful knowledge for reducing earthquake risk and improving community resilience.*

The theme of the CEO program during SCEC4 is *Creating an Earthquake and Tsunami Resilient California.* This includes: increased levels of preparedness and mitigation; expanded partnerships with research and practicing engineers, building officials, and others; routine training and drills; financial preparedness; and other ways to speed recovery and enhance future resilience. Each of these activities benefit from advances in earthquake science, by SCEC scientists and others (while tsunami research is not be a focus of SCEC, tsunami education and preparedness is an element of the CEO program and the ECA). The goal is to prepare individuals and organizations for making decisions (split-second through long-term) about how to respond appropriately to changing seismic and related hazards, including tsunami warnings and new technologies such as operational earthquake forecasts and earthquake early warning.

SCEC CEO is organized into four interconnected thrust areas:

- *Implementation Interface* connects SCEC scientists with partners in earthquake engineering research, and communicates with and trains practicing engineers and other professionals;
- *Public Education and Preparedness* thrust area educates people of all ages about earthquakes, and motivates them to become prepared;
- *K-14 Earthquake Education Initiative* seeks to improve earth science education and school earthquake safety;
- *Experiential Learning and Career Advancement* provides research opportunities, networking, and more to encourage and sustain careers in science and engineering.

The metrics listed below are a framework for assessing progress and effectiveness of SCEC CEO programs and activities as currently planned. New opportunities, partnerships, and funding, or reduction in funding levels, may result in modifications to these measures when reviewed annually. For example, at the beginning of SCEC3 the ShakeOut initiative did not exist and yet has become a major component of the SCEC CEO program extending our scope internationally. Milestones for each metric are tracked in the separate CEO_metrics_milestons_chart.xlsx file and are expressed (mostly) numerically, additional qualitative assessments for each focus area will be written for review each year. Additionally, some metrics will be reported without specific milestones (as explained for each metric), and some will be tracked for internal purposes but not reported annually.

1. The Implementation Interface

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

a. Research Engineering Partnerships

SCEC produces a large body of knowledge about the seismic hazard in California that enhance seismic hazard maps, datasets, and models used in building codes and engineering risk assessments. The Implementation Interface provides the organizational structure for creating and maintaining collaborations with research engineers, in order to ensure SCEC's research activities are aligned with their needs. These activities include rupture-to-rafters simulations of building response as well as the end-to-end analysis of large-scale, distributed risk (e.g., ShakeOut-type scenarios). Analysis of the performance of very tall buildings in Los Angeles using end-to-end simulation remains a continuing task that requires collaboration with both research and practicing engineers through PEER and other organizations. Our goal of impacting engineering practice and large-scale risk assessments require even broader partnerships with the engineering and risk-modeling communities, which motivates the activities described in 1.b.

Performance Metrics 1.a: **Implementation Interface – Research Engineering Partnerships**	
Metrics and Milestones to be reported annually	
1.a.001	Research engineers attending SCEC Annual Meeting and other SCEC research workshops.
Metrics to be reported annually (without specific targets)	
1.a.002	Documented uses (citations, reports) of SCEC simulation models and other SCEC products in engineering research and risk assessments. This needs to be assessed for a few years to understand current levels. We will also try to track diffusion time (from release of product or publication to incorporation into other work, especially signature projects).
1.a.003	SCEC projects and collaborations involving research engineers. Given uncertainties in funding and participation we cannot commit to milestones.
1.a.004	Partnerships with engineering and risk modeling organizations (with MOUs or other written partnership agreements). As such partnerships depend on interest of the other organizations we cannot forecast milestones but will report progress each year.
1.a.005	Jointly-funded projects with partner organizations. Given the uncertainty in funding we cannot commit to specific milestones, however this is a measure of the success of our Interface.

b. Activities with Technical Audiences

The Implementation Interface also develops mechanisms for interacting with technical audiences that make decisions based on understanding of earthquake hazards and risk, including practicing engineers, geotechnical consultants, building officials, emergency managers, financial institutions, and insurers. This will include expansion of the Earthquake Country Alliance to include members focused on mitigation, policy, and other technical issues. SCEC will develop training sessions and seminars for practicing engineers and building officials to introduce new technologies (including time-dependent earthquake forecasts), discuss interpretation and application of simulation records, and provide a forum for SCEC scientists to learn what professionals need to improve their practice. This is already happening annually with SEAOSC (*Buildings at Risk* Summits), and we may also collaborate with EERI, NEES, PEER, or others. These activities will increasingly be online, with frequent webinars and presentations and discussions videotaped and available for viewing online.

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

Performance Metrics 1.b: **Implementation Interface – Activities with Technical Audiences**	
Metrics and Milestones to be reported annually	
1.b.001	Practicing engineers, geotechnical consultants, building officials, emergency managers, insurers, etc. attending SCEC Annual Meeting and other SCEC research workshops (each year)
1.b.002	Practicing engineers, geotechnical consultants, building officials, emergency managers, financial institution representatives, and insurers in the ECA (statewide, cumulative)
1.b.003	Training sessions, seminars, and field trips for practicing engineers, building officials, etc. (organized by SCEC or co-sponsored) (each year)
1.b.004	Online activities such as webinars, online trainings, and filmed presentations (each year)
Metrics to be reported annually (without specific targets)	

1.b.005	SCEC researchers (including students) participating in engineering/building code/etc. workshops and other activities (hosted by SCEC or other organizations) (each year). This is an activity which we will promote however we have limited ability to require, so milestones cannot be specified (until a trend is determined)
1.b.006	Documented technical (not research) uses of our models and informational resources (downloads, citations, etc., cumulative). As our capacity builds for documenting such use (perhaps quite complicated) we will report results, however milestones cannot be specified initially.
1.b.007	Documented uses of SCEC tools/information in developing or conforming to building codes, guidelines, and standards (cumulative). This is something we will develop the capacity to track, however because this can be limited by the frequency of code updates and other external issues, we cannot estimate milestones.

2. Public Education and Preparedness

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

a. Earthquake Country Alliance

The ECA public-private partnership is the primary organizational structure within the Public Education and Preparedness thrust area. Due to the success of the ShakeOut, the ECA is now statewide and includes three established regional alliances. In September, 2011 the relationship between SCEC and the ECA (managed by SCEC since it's inception in Southern California in 2003) was cemented via a Memorandum of Understanding specifying SCEC as the administration headquarters of the statewide alliance and SCEC'S Associate Director for CEO as ECA's Executive Director. The MOU describes SCEC's roles and responsibilities in managing the ECA under the direction of a Steering Committee comprised of three representatives of the three regional alliances in Southern California, the Bay Area, and the North Coast. The Great California ShakeOut has been the primary collaborative activity so far, but additional activities with measurable outcomes are also managed or planned by the ECA. This planning builds on a California Office of Emergency Services earthquake communications plan developed in 2009 that emphasizes the value of a statewide collaboration.

As the administrative home of the ECA, USC/SCEC:

- Appoints the SCEC Associate Director for Communication, Education, and Outreach as ECA's Executive Director to implement ECA programs, manage budgets, supervise staff (including SCEC staff working on ECA activities), students, and contractors, at the direction of the ECA Steering Committee;
- Coordinates the *Great California ShakeOut* and other major activities of the ECA, as requested by the ECA Steering committee;
- Creates, updates, and maintains ECA-branded websites, including www.earthquakecountry.org, www.shakeout.org, www.dropcoverholdon.org, and www.terremotos.org;
- Provides financial and legal administrative services including contract administration, purchasing, payroll, and legal/government reporting aspects as required of non-profit organizations.

As a partnership program managed by SCEC, ECA:

- Maintains an ECA Steering Committee to establish priorities and objectives, and oversee funding and program decisions;
- Selects an Executive Committee (of the ECA Steering Committee) to advise and coordinate with the ECA Executive Director;
- Appoints a Strategic Organization Advisory Group with representatives of statewide and other strategic organizations; and
- Establishes and maintains statewide committees that provide coordination of sector-based outreach and projects in coordination with Executive Director and ECA Steering Committee.

Each ECA organization, including SCEC, independently determines the commitment of the their own resources, including human, technical, and financial resources, as they carry out the fundamental actions of this voluntary, non-binding Agreement. As the home of ECA, SCEC allocates appropriate staff and administrative resources (phones, mailing, etc.) and may seek additional funding for these resources in partnership with the ECA. SCEC provides mechanisms for managing ECA-specific funding and resources that are not co-mingled with other SCEC funding, and works with ECA leadership to ensure that such resources are allocated appropriately.

<u>ECA 5-year goals (2012-2017)</u>:

1. Further develop the awareness of, engagement in, and support for the ECA among internal audiences
2. Cultivate collaboration among stakeholder Alliance members
3. Build and maintain a community of earthquake / tsunami-ready Californians who, by demonstrating their readiness activities within their social circles, can help foster earthquake readiness as a social movement as well as all-hazard preparedness
4. Expand the community of earthquake / tsunami-ready Californians by reaching out to those who are not yet engaged in earthquake/tsunami readiness activities

These goals for building the ECA and its resources/activities will result in new products and programs for which metrics and milestones cannot yet be specified. For example, based on the work of the Redwood Coast Tsunami Workgroup, the other Alliances will expand their tsunami messaging and programming, and all ECA members will receive instructions on implementing and communicating preparedness and mitigation strategies for both earthquakes and tsunamis. However three primary initiatives of the ECA are well-established (ShakeOut, *Putting Down Roots in Earthquake Country* publications, and the EPIcenter network) and measures are listed below. As new initiatives are developed similar metrics and milestones will be developed.

Performance Metrics 2.a: **Public Education and Preparedness – Earthquake Country Alliance**	
Metrics and Milestones to be reported annually	
2.a.001	Registered ECA Associates (cumulative)
2.a.002	Participants of functional and sector committees (each year)
2.a.003	Strategic Organizational Partners with MOUs (cumulative)
2.a.004	Partner organizations (Associate or strategic orgs) that link to ShakeOut & ECA website (cumulative)
2.a.005	New resources/programs for cultural/sector communities that have not yet been engaged (each year)
2.a.006	ECA curricular resources for use by schools, colleges, and free-choice learning institutions to teach about earthquakes and preparedness (cumulative)
Metrics to be reported annually (without specific targets)	
2.a.007	Amount of funding (grants, donations) for ECA and its activities (each year). Because of funding uncertainties, this will be reported but milestones cannot be specified
2.a.008	Unique visitors to each of ECA's websites (including the California ShakeOut site) and social media followers (each year). Milestones will not be specified until trends can be forecasted.
Metrics to be tracked internally (not reported)	
2.a.009	Associates in each Alliance (cumulative) (initial totals need to be confirmed)
2.a.010	Active functional and sector-based committees (each year)
2.a.011	People/organizations showcased as "ECA heroes" or "Shakeout Spotlights", etc.) (each year)
2.a.012	New tsunami documents and programs (each year)

b. ShakeOut Earthquake Drills

In addition to its lead role in organizing the California ShakeOut, SCEC manages a growing network of ShakeOut Franchises across the country and around the world (see *www.shakeout.org*). In order to develop and maintain the ShakeOut brand and reduce potential confusion between the different drills, SCEC works with officials in these regions and for most hosts the website for their drill. This approach serves to standardize earthquake messaging nationally and internationally, and allow groups to share best practices for recruiting participation, such as the use of social networking sites. Some ShakeOuts rely more heavily on SCEC, while some are managing more of their content, reviewing registrations, and more actively communicating with participants. Manuals and guidelines for organizing ShakeOut drills will be developed in 2013.

The original California ShakeOut itself has expanded greatly, from 5.4 million in 2008 to more than 9.4 million participants in 2012, with 19.4 million total across 16 Official ShakeOut Regions. New materials and activities for additional communities and in multiple languages are developed each year (ShakeOut websites are now online in English, Spanish, French, Italian, and Japanese). In the future, operational earthquake forecasts should create additional interest for the ShakeOut drills and increase participation and preparedness in general (as well as interest in earthquake science). The ShakeOut drills are also an excellent structure to prepare Californians to respond to earthquake early warnings. For the warnings to be effective, individuals, organizations, and governments must be trained in how to respond appropriately given their situation. Also, the Shakeout drills continue to be an annual exercise of SCEC's post-earthquake response plan.

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

Note: The following metrics and milestones are basic aspects of ShakeOut participation. Extensive surveys have been done after each ShakeOut and will be reported on in 2013; the results of these surveys will provide additional indicators and metrics to monitor in order to assess the effectiveness of the ShakeOut drills in terms of what participants are learning, plans being improved, and mitigation being conducted.

Performance Metrics 2.a: **Public Education and Preparedness – Earthquake Country Alliance**	
Metrics and Milestones to be reported annually	
2.a.001	Registered ECA Associates (cumulative)
2.a.002	Participants of functional and sector committees (each year)
2.a.003	Strategic Organizational Partners with MOUs (cumulative)
2.a.004	Partner organizations (Associate or strategic orgs) that link to ShakeOut & ECA website (cumulative)
2.a.005	New resources/programs for cultural/sector communities that have not yet been engaged (each year)
2.a.006	ECA curricular resources for use by schools, colleges, and free-choice learning institutions to teach about earthquakes and preparedness (cumulative)
Metrics to be reported annually (without specific targets)	
2.a.007	Amount of funding (grants, donations) for ECA and its activities (each year). Because of funding uncertainties, this will be reported but milestones cannot be specified
2.a.008	Unique visitors to each of ECA's websites (including the California ShakeOut site) and social media followers (each year). Milestones will not be specified until trends can be forecasted.
Metrics to be tracked internally (not reported)	
2.a.009	Associates in each Alliance (cumulative) (initial totals need to be confirmed)
2.a.010	Active functional and sector-based committees (each year)
2.a.011	People/organizations showcased as "ECA heroes" or "Shakeout Spotlights", etc.) (each year)
2.a.012	New tsunami documents and programs (each year)

c. *Putting Down Roots in Earthquake Country* publication series

This print and online publication series remains very popular and likely will be replicated in additional regions during SCEC4, similar to new versions produced since 2005. The existing versions will continue to be updated and improved with new science and preparedness information. For example, tsunami content was added in 2011 to the Southern California version of the handbook, based on content created for the 2009 version of *Living on Shaky Ground.* This is a similar document published by the Redwood Coast Tsunami Workgroup that now also includes the SCEC/ECA *Seven Steps to Earthquake Safety.*
Research results related to earthquake forecasting are already included in the handbook, and this information will be updated as operational earthquake forecasts and earthquake early warning become a reality in California.

Beyond updates focusing on content, new versions or translations of the publication will expand the reach of *Roots* with particular emphasis on underserved communities. This will involve partners that specialize in communicating in multiple languages and via culturally appropriate channels. Additionally, versions for low-literate or visually impaired audiences, and perhaps for children and seniors will be pursued. These booklets, supported by the California Earthquake Authority and California Office of Emergency Services, have been written and customized for 10 regions plus a statewide version, and will be titled "*Staying Safe Where the Earth Shakes"*

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

Performance Metrics 2.c: **Public Education and Preparedness – Putting Down Roots in Earthquake Country**	
Metrics and Milestones to be reported annually	
2.c.001	Update and improve So Cal booklet with new science and preparedness information
2.c.002	Inclusion of updated earthquake forecasting information (UCERF3, etc.)
2.c.003	Area-specific versions in English (ShakeOut regions and Designated Media Areas
2.c.004	CA versions in different languages or for other audiences (statewide, cumulative)
Metrics to be reported annually (without specific targets)	
2.c.005	Booklets (*Roots,* supplements, multi-langage versions) distributed (each year) Due to uncertain funding for printing, quantities to be printed/distributed cannot be listed as milestones.
2.c.006	Evaluation activities (status will be reported, results may be in following year) 2013: Reviewed with statewide prep. Survey 2014: Assess business version 2015: Assess multi-language versions 2016: Reviewed with statewide prep. Survey
Metrics to be tracked internally (not reported)	
2.c.007	Inclusion of tsunami content in updated Bay area versions of the handbook (not SCEC managed, but ECA supported)
2.c.008	Funding raised (sponsors, agencies) for developing and printing materials

d. Earthquake Education and Public Information centers (EPIcenters)

This network of "free-choice" learning institutions within the ECA has grown rapidly, with over 68 participating institutions involved. Many more are expected to join as a result of outreach by SCEC and the participants, including new museums, parks, and other venues in California, but also in other states. National organizations such as the American Association of Museums and the Association of Science and Technology Centers will also be involved.

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

In addition to managing the EPIcenter network, SCEC continues to maintain its existing exhibits and interpretive trails, and create new venues with EPIcenter partners. For example, SCEC consulted with the California Science Center for its updated earthquake exhibit and has a close partnership with the San Bernardino County Museum with which it develops programming for its Hall of Geological Wonders and other venues. Also, SCEC's partnership with the Quake Catcher Network has already led to installation of QCN sensors at more than 25 EPIcenters.

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

Performance Metrics 2.d: Public Education and Preparedness – EPIcenter Network	
Metrics and Milestones to be reported annually	
2.d.001	Participating museums, parks, and other free-choice learning venues in California and in other states (cumulative)
2.d.002	Partner national organizations (e.g. research organizations, museum associations, etc.) (cumulative)
2.d.003	SCEC-developed exhibits, interpretive trails, or programs in use (cumulative)
2.d.004	EPIcenters and schools with QCN sensors
2.d.005	EPIcenter field trips or other professional development field experiences (each year)
2.d.006	EPIcenters using network materials (including materials from national organizations and the ShakeOut) (each year)
Metrics to be reported annually (without specific targets)	
2.d.007	Partner participation in EPIcenter surveys (%, each year) Participation is difficult to forecast initially
2.d.008	Results of surveys Once surveys are developed additional metrics may be added to this plan. Until then key results will be reported.

e. Media Relations

SCEC scientists are increasingly called upon for interviews by local, national, and international reporters and documentary producers. This is especially true after earthquakes, even those in other countries. As a result the demand on SCEC scientists after a large California earthquake will be even greater than in previous earthquakes. In 2014 SCEC staff developed new procedures for post-earthquake media coordination. In addition, the breadth of SCEC's research, including its information technology programs and the development of time-dependent earthquake forecasting, is also increasing the need for expanded media relations. New strategies and technologies are being developed to meet these demands.

For example, SCEC is implementing use of a media relations service for identifying and connecting with reporters nationwide. The service maintains current contact information for reporters and assignment editors and allows us to distribute and track news releases (rather than relying on USC or other partners). SCEC has used a companion service from the same provider for tracking coverage of SCEC and ShakeOut news.

Social media capabilities have also being expanded in SCEC4 under the management of SCEC's new Communciation Specialist Jason Ballmann (whose hiring is the result of increased support from FEMA). The SCEC Youtube Channel (*youtube.com/scec)* is now regularly supplemented with new content. will soon include the use of podcasts, webinars and other virtual news conferences, and other technologies. SCEC and the ECA are increasing the availability of multi-lingual resources (materials, news releases, experts, etc.) to more effectively engage all media, including foreign media. Summer and school-year internships for journalism or communications students assist CEO staff in developing these technologies and resources.

An important component to our media relations strategy will be media and risk communication training for the SCEC Community. Training will likely be held each year at the SCEC Annual Meeting (the first was in 2012). New content management software for SCEC's web pages will allow members of the community to create online summaries of their research, along with video recordings of presentations, as part of a new experts directory. SCEC will partner with USGS, Caltech, and other partners to offer annual programs that educate the media on how to report earthquake science, including available resources, appropriate experts, etc. The first two were held in January 2014 as part of the 20th Anniversary of the Northridge Earthquake (a media training workshop at Caltech and a press conference at USC).

Performance Metrics 2.e: **Public Education and Preparedness – Media Relations** (NOTE: Each milestone is split between SCEC Research and CEO-ECA topics, each year)	
Metrics and Milestones to be reported annually	
2.e.001	Traditional news advisories and releases
2.e.002	Podcasts or online interviews (audio and/or video)
2.e.003	Virtual news conferences / webinars
2.e.004	People in SCEC Experts directory (with summaries/videos/etc.)
2.e.005	Experts identified, trained (if necessary) and available for interviews in non-English languages
Metrics to be reported annually (without specific targets)	
2.e.006	Traditional news stories (online, print, radio, tv) (SCEC, ECA, ShakeOut)
2.e.007	Social media posts/followers/etc. (SCEC) As this is determined by factors beyond our influence (earthquakes in particular) cannot provide targets until trends are tracked
2.e.008	Non-English news advisories/releases (by language) This will depend on the number of news stories and our capacity for translation (ideally through partner organizations, as fees can be high)
2.e.009	Media and risk communication training seminars for SCEC community (and # of participants) Not clear yet how many will be needed and how many people need to participate.
2.e.010	Programs to educate the media on how to report earthquake science (and number of participants) These may be best as small workshops, or might be offered as online webinars. Our SCEC institutions and ECA partners will likely co-present.

3. K-14 Earthquake Education Initiative

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

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

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

Performance Metrics 3: **K-14 Earthquake Education Initiative** (all categories include materials developed in collaboration with SCEC partners)	
Metrics and Milestones to be reported annually	
3.001	Event-based or “place-based” local/regional education opportunities (each year)
3.002	Educational materials improved or created to provide information about local earthquake hazards and relevance for learning about earthquakes (per year)
3.003	Educator workshops offered to introduce these resources to educators (each year)
3.004	Educators participating in all programs
3.005	Participating educational and research organizations in the initiative (cumulative)
Metrics to be reported annually (without specific targets)	
3.006	New learning experiences and materials for use after large earthquakes (each year) Specific milestones cannot be projected as this depends on the number of large earthquakes each year

4. Experiential Learning and Career Advancement

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

The ELCA program in SCEC4 is built on the foundation of our long-established USEIT and SURE internship programs that challenge undergraduates with real-world problems that require collaborative, interdisciplinary solutions. Each summer they involve over 30 students (including students at minority-serving colleges and universities and local community colleges). The interns experience how their skills can be applied to societal issues, and benefit from interactions with professionals in earth science, engineering, computer science, and policy. Some interns continue their research during the academic year (especially USC students).

These undergraduate internship programs will be the centerpiece of a high school to graduate school career pathway for recruiting the best students, providing them with high-quality research, education, and outreach experiences, and offering career mentoring and networking opportunities.

At the high school level, this effort will be closely linked with SCEC’s K-14 Earthquake Initiative and based on programs that expose high school students to earthquake research, inquiry-based curricula, and visits by SCEC scientists. This may identify students that could participate in USEIT or a SURE project at a local SCEC institution, perhaps even in the summer prior to their first year in college.

For graduate students, we will identify funding for master’s level (including new Ph.D. students) internships that provide unique opportunities. This will include support for cross-disciplinary computer science research by master's students similar to the ACCESS program (which completed in 2010). Students may participate in the USEIT program as mentors, conduct research with scientists at other SCEC institutions than their own school, and participate in CEO activities such as media relations, curricula development, and program evaluation.

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

In addition to research and education/outreach opportunities, mentoring will be offered to help ELCA participants consider career possibilities, and longitudinal tracking of alumni will provide data on how students are progressing.

The final element of the ELCA program is career advancement opportunities for early-career researchers, including post-docs, young faculty, and research staff. We will highlight employment opportunities via SCEC's email list and on the SCEC website, and perhaps also post CVs of early career researchers seeking positions. We may also provide travel support for early career researchers to give presentations at conferences and department lectures nationwide, and provide presentation materials so that they can highlight their role in SCEC. Also, SCEC leadership positions, especially the planning committee, provide opportunities for exposure and career advancement.

Performance Metrics 4: **Experiential Learning and Career Advancement**	
Metrics and Milestones to be reported annually	
4.001	Participants (each summer) in SCEC undergraduate internship programs, based on current funding levels and potential leveraging (see note in text above)
4.002	Students involved in academic-year research or outreach projects (SCEC/ShakeOut/etc.) (each year)
4.003	% of undergraduate interns who are women / % under-represented minorities (each year)
4.004	High school students provided research, education or outreach experiences, (each year)
4.005	Master's level opportunities (see text above) (each year)
4.006	Early career researcher presentations supported (each year)
Metrics to be reported annually (without specific targets)	
4.007	# of intern alumni in graduate school or having graduate degrees Participation in SCEC is only one factor that may contribute to these metrics, so specific milestones are not appropriate
4.008	# of intern alumni in STEM professions or internships (cumulative) Participation in SCEC is only one factor that may contribute to these metrics, so specific milestones are not appropriate
4.009	# of employment or internship opportunities that are shared via SCEC email or website (each year). This depends on external partners and other factors beyond SCEC's control
4.010	# of early career researchers active in SCEC (criteria: anyone within 12 years of their highest post-secondary degree. Will be revised to 10 years in 2014. Hiring at SCEC institutions is beyond SCEC control, however knowing the total number and having communication with them will allow us to monitor and support progress
4.012	% of women/ underrepresented minorities in SCEC leadership positions

C. 2014 Report of the SCEC Advisory Council

1. Introduction

The SCEC Advisory Committee (AC) met at the Annual SCEC meeting in Palm Springs from Sept. 7 to 10, 2014 to review SCEC activities and offer advice to the SCEC leadership. The SCEC AC comprises the following members (names indicated with * are members who were present at the meeting):

- Gail Atkinson*, *Chair* (University of Western Ontario) gmatkinson@aol.com
- Norm Abrahamson* (Pacific Gas & Electric)
- Roger Bilham* (University of Colorado)
- Donna Eberhart-Phillips* (UC Davis)
- Kate Long* (California Office of Emergency Services)
- Warner Marzocchi* (INGV, Rome)
- M. Meghan Miller* (UNAVCO)
- Farzad Naeim (John A. Martin and Associates – through Aug. 2014)
- Tim Sellnow* (University of Kentucky)
- John Vidale* (University of Washington)
- Andrew Whittaker (University of Buffalo; Director, MCEER)

The AC met initially on Sept. 7 and was briefed by the SCEC leadership. Director Jordan provided the AC with a summary of the state of SCEC, and posed a list of issues on which they solicited AC feedback. Following the leadership briefing, the AC discussed the agenda for the next few days and shared initial thoughts. Over the following two days the AC attended scientific sessions and solicited impressions and feedback from attendees. A session with the SCEC CEO team under Associate Director Benthien was held Monday afternoon. The AC also reviewed a comprehensive workbook prepared for us by the SCEC leadership. The AC reconvened Tues. mid-day and Tues. evening to compile their report and recommendations, which was presented to the SCEC community on Wed. morning.

Our overall impression is that SCEC continues to maintain a unique position in the Earth Sciences on an international level. It is the pre-eminent organization in the world where a community of informed scientists are focused with razor sharp acuity on the physical issues of earthquake nucleation and seismic wave propagation, and their impacts on infrastructure and society. It maintains this enviable position through a combination of interdisciplinary strength and synergy that simultaneously encourages advancement across disciplines. SCEC represents the confluence of a stunning breadth of expertise and imagination. The results are consistently cutting edge: the SCEC meeting is a hotbed of stimulating new ideas that question many former assumptions in earthquake science. Some of these novel ideas will undoubtedly form the nucleus of future improvements in our understanding of earthquakes. It is also highly noteworthy that over the last several years the SCEC approach to technology transfer has matured markedly. This is a major SCEC4 accomplishment that provides a compelling rationale for support of SCEC5.

We discussed most of the specific issues and questions posed to us by SCEC Director Jordan, and offer the following observations.

2. Changes in leadership structure

SCEC has faced well-known challenges in finding a new SCEC Director, in the wake of Director Jordan's stated desire to retire from this role. A vigorous search process has taken place over the last few years, which for various reasons has not been successful. Consequently it is now not feasible to have a new Director in place in time to work with the SCEC community in preparation of the SCEC5 proposal, due Oct. 1, 2015. Director Jordan outlined the changes that SCEC has made to the leadership structure in order to accommodate this situation.

The AC view is that the proposed leadership plan effectively addresses the immediate challenges and sets the stage for a successful leadership succession. The AC welcomes the well-deserved appointment of the SCEC co-Director and co-PI, the Planning Committee Vice-Chair, and the addition of the USC-funded Executive Science Director – these are tangible and important changes that will enable SCEC5 and subsequently facilitate a successful search. In particular, it will become a much more tractable proposition for an internationally-based leadership candidate to step in near the beginning of SCEC5, with the

SCEC5 structure and plan in place, and a lead time of several years to work with the rest of the SCEC team before the need to consider SCEC6 is upon him or her. We feel that this plan, as well as the new pool of candidates that may well be available in a year or two, will be of great benefit in the search. We recommend that although the search is now officially paused, that SCEC use this pause to good advantage in discussing and broadcasting this upcoming opportunity with potential leaders, so that the search may be “primed” with top-level candidates when it resumes.

On balance, although the difficulty in securing a new SCEC Director has been frustrating for SCEC's leadership, it may ultimately prove to be positive for the future growth and development of SCEC. The situation has driven an important and healthy change in leadership structure that spreads leadership responsibilities more widely amongst the highly-capable scientific leaders that SCEC is so fortunate to count among its members. At the risk of stating the obvious, we would like to stress that SCEC as a whole is bigger than its Director, and this is a fact that can be highlighted in a positive way in the SCEC5 proposal.

3. Highlights of SCEC4

In the 2013 AC report, we provided a mid-term assessment on how SCEC4 is doing in achieving its goals in advancing our understanding in six fundamental areas of science that formed the SCEC4 proposal:

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

We felt it would not be particularly meaningful to try to update this assessment on a line-item basis - one year is too short a time to expect comprehensive and measurable progress across all areas. Rather, we take a slightly different approach and instead choose to highlight one specific area related to the themes, in which we noticed particularly exciting progress. We stress that of course this is only a small subset of the breadth of SCEC science achievements over the last year, which were highlighted in Co-Director Beroza's impressive summary presented to the SCEC membership during the meeting (and provided to the AC in a written report as part of the workbook).

We noted the following advances:

a. Plastic Deformation in Fault Zones

Fault zone numerical modeling is increasingly incorporating plastic and viscous deformation, as well as more nuanced friction and complex geometries in fault zones. It particular, plasticity leads to significantly reduced predicted ground motions. The implication of these modeling improvements is that it will be necessary to reassess source models derived without consideration of these complexities, which include nearly all of the work done in the past. This represents both a significant advance, and a significant challenge in interpretation of previous work.

b. Role of San Gorgonio Pass

The San Gorgonio Pass Special Study Focus Area (SFSA) has succeeded in focusing SCEC integrated research collaboration in a timely manner. Partitioning of large Southern California ruptures among the several strands of the San Andreas fault through the San Gorgonio restraining bend is growing clearer. Geological studies have identified details of the complex fault geometry of major strands and numerous smaller faults that provide a suite of rupture surfaces. These provide several scenario rupture paths that have previously released tectonic strain as seismic slip, and presumably will do so again. They show that through-going rupture during very large earthquakes occurs during some seismic cycles, but not all - a process anticipated by theoretical models involving weak surface sediments with differing rheological properties from those at depth. The SCEC SFSA approach is enabling San Gorgonio fault segment properties to be incorporated into sophisticated dynamic rupture models. The modeling will give more insight into the types of SAF earthquakes that would be able to break across the San Gorgonio Pass. This work will be an excellent example of collaborative SCEC4 accomplishments.

c. CSEP, Canterbury

The *Collaboratory for the Studies of Earthquake Predictability* (CSEP) is one of the successful ongoing SCEC initiatives. The main purpose of CSEP is to provide an infrastructure for a rigorous evaluation of the earthquake forecasting/predictions performance of different models. Despite the fact that the gold standard for robust model evaluation is through prospective experiments, significant insights can also be obtained from retrospective experiments. The most recent CSEP initiative in this field is focused on evaluating forecasting models performance during the Canterbury sequence in New Zealand. The results show, for the first time, that physics-based models outperform statistical models in 1-year forecasts, whenever detailed information about the source is available in near-real-time. This result is potentially transformative in the evolution of earthquake forecasting.

d. Seismology-Engineering Interface

Work on the seismology-engineering interface is bringing physics-based ground-motion simulations using SCEC products into engineering practice. This is evident through the active work on the broadband simulation platform over the last year as highlighted at the SCEC2014 workshop, and also by the broader activities of the technical simulation validation team led by Nico Luco. Progress in this area has been enhanced by the Earthquake Engineering Interface group led by Jack Baker and Jacobo Bielak and the impressive accomplishments of the group in rupture-to-rafters simulations and end-to-end analyses of large-scale distributed risk. The development of the SEISM framework is an important step to generate and ultimately apply the large suites of earthquake simulations needed for physics-based seismic hazard analysis. A key step in moving simulations to engineering applications has been the evaluation of the current state of simulations, including an evaluation of which methods are ready for application and the limits on those applications. Version control of the software for the simulation methods is also critical to allow repeatability of the results. As the use of the BBP increases, the issue of long-term archiving of simulations will become an important issue for SCEC to address. Finally, the preparation of a proposal that is a joint initiative between SCEC and PEER is also a notable milestone which, if funded, will further work on the seismology-engineering interface.

e. Time Scales in UCERF3

Uniform California Rupture Earthquake Forecast (UCERF) is a well-established SCEC initiative with important practical implications. The first UCERF models provided the long-term seismicity rates that have been embedded into the national seismic hazard map, and provided time-dependent earthquake forecasts on a time interval of few decades. UCERF3 has made substantial advances with respect to previous UCERF versions in terms of methodological procedures and scientific information, and also considers a wider range of forecasting time windows. In particular, UCERF3 incorporates ETAS-type modeling into the long-term forecasting model, solving some of the physical inconsistencies that are inherent to pure ETAS modeling. More importantly, UCERF3 provides an infrastructure that may become fundamental for a full development of the *Operational Earthquake Forecasting* (OEF) in California and an attractive tool for re-insurance companies.

f. ShakeOut and CEO

The *Communication, Education, & Outreach* (CEO) program continues to be a major success story for SCEC, and indeed serves as a model for other organizations. The flagship ShakeOut program has been both a national and international success, expecting to exceed 25 million participants in 2014. Using USC government relations student interns, CEO developed lists of local, state, federal, and international potential participants or partners, and created government participation guidelines to assist these groups, including custom information for Italy and Iran. CEO is also coordinating closely with FEMA's new America's PrepareAthon initiative, which is modeled after ShakeOut so that people and organizations can register drills for other hazards. The "Putting Down Roots" booklet series is going through a transition to a simpler format; the revamped "Staying Safe Where the Earth Shakes" will become the main booklet distributed in large quantities, in cooperation with the Cal OES and the California Earthquake Authority (CEA). CEA will be contracting with SCEC to host the 10 regional versions of these booklets on the ECA website and provide a logo/name customization service to organizations who wish to print large quantities for their own distribution.

CEO's exceptional coordination of the EPIcenters Network has expanded well beyond California in 2014 via EarthScope partnership and other activities. SCEC's Media Relations activities have also expanded in 2014, with SCEC's social media presence being greatly improved and regularly managed. CEO's K-14 Education Initiatives in 2014 included many useful components: InSight Vital Signs of the Earth summer institute, providing professional development to educators and students; new lessons based on field research that will be incorporated within other SCEC activities (such as the "Heroes of Earthquake Country" educator kit); teacher workshops in Oregon, Washington, and Alaska (with EarthScope); and a network of QCN sensors at schools of participating teachers. CEO's intern programs are as vibrant as ever, with 38 UseIT and SURE students in 2014 (and several more students working on ShakeOut recruitment- this may be considered a third intern program in 2015). A notable statistic this year is that 49% of the interns are underrepresented minority students, and 56% are women. CEO self-assessment notes that the long-term tracking of our alumni continues to be a challenging effort (true for most similar programs); plans for Masters level and early career opportunities also need to be better developed. More than half of the active participants of SCEC are considered early career, and CEO needs an effective strategy for supporting their career advancement.

CEO continues to expand SCEC's national and international visibility, and to bridge understanding of the physical science of earthquakes and social science of behavior change, spurring preparedness action. With its vigorous cross-sector partnerships, CEO is increasingly sought out as the source for expertise in development of earthquake education. An essential component of CEO's value continues to be its assemblage of broad partnerships, ensuring consistency of messaging among an expanded breadth of organizations which see themselves as earthquake education stakeholders: SCEC is at the table not only as a science education organization, but as a leader in public safety. In California specifically, the CEO Director is also the Director of the statewide Earthquake Country Alliance, maintaining a central role in California's ongoing national leadership in earthquake education and outreach.

The successes of CEO has challenged the available resources of the SCEC CEO group over the last year. To manage the demands of their successes in view of limited resources, a new plan to give helpful structure to the CEO activities has been formulated, and is discussed further in the following.

4. CEO Advisory Structure and Goals

Associate Director Mark Benthien has developed a sound plan for CEO structure, which was presented to the AC in a CEO session on Sept. 8, and also in a written brief to the AC. The plan aims to make best use of limited resources in furthering this critical and highly-successful area of activity. The essence of the plan is that a CEO planning committee to be formed, which will engage in regular communications through teleconferences to be held every few months. By focusing on activities and goals on a regular and structured basis, it will be feasible and attractive for stakeholders to participate. The formation of a planning committee also allows participants from a variety of organizations to have a more formal role.

Working CEO as a component into proposals directly, rather than as a percentage of a broader budget, may help to align CEO and science activities more closely. This would also provide a vehicle for CEO to potentially obtain new resources by helping other PIs with CEO components of their new projects, provided they are aligned with SCEC CEO mission-critical activities such as ShakeOut.

Two members of the AC (Long and Sellnow) will sit in on the teleconferences of this committee and offer advice as requested. These members will also report back to the AC on CEO issues and outcomes.

The AC recommended that Associate Director Benthien review the charters and charges of similar committees within other Earth Science organizations and facilities, to inform a draft charter and nominations for a CEO PC. Associate Director Benthien will then bring these back to the SCEC AC for review, suggestions, and nominations, with the goal of holding the first CEO PC teleconference late October, with bimonthly calls thereafter. The full committee should be populated by about February, with the first formal meeting late in January 2015.

An additional function of the CEO planning committee will be to prepare assessment materials on the CEO activities of SCEC4, and advise on integration of CEO activities throughout the projects of SCEC5.

5. Major SCEC Initiatives

The SCEC AC is aware that there are a number of major initiatives, above and beyond the core NSF-USGS-funded program, that are integral to the scientific and financial well-being of the SCEC mission. Moreover, the SCEC major initiatives align well with SCEC priorities and offer opportunities to further enhance SCEC accomplishments in strategic areas. Some comments on the current major SCEC initiatives follow.

a. High Performance Computing

There were three HPC initiatives proposed in the past year, each of which was a major proposal and planning effort: Community models of Earth structure (Phase II); Physics-based PSHA; and SI2. The first two are already funded, while a decision on the third is pending. The HPC initiatives continue the ongoing string of SCEC's success in physical modeling of earthquakes in parallel with the highly-recognized use of very large computers. SCEC activities have become a major platform for the showcasing of cutting-edge computational capabilities. In this regard, the SI2 plan is a natural extension of this tradition, while standing out as audacious and visionary in undertaking parallel development of hardware and software through a co-design center.

b. Central California Experiment

The proposed Central California experiment, aimed at reducing epistemic uncertainty in seismic hazard analysis by development of path-specific ground motion models, will be conducted with the support of PG&E. This program is a good model of a science research/industry partnership that is well aligned with the SCEC mission. It also provides a framework for integrating numerical simulations using 3-D crustal models into ground motion models for engineering applications, including the key aspect of empirical calibration of 3-D path effects. Although the study area is actually central California for this project (due to the area of interest of the sponsor), it will form a template for future similar studies in other areas including southern California.

c. CISM

The proposed new *Collaboratory for Interseismic Simulation and Modeling* (CISM) extends the concepts of CSEP, incorporating it into a common platform for the development of physics-based earthquake simulators and forecasting models. This extension offers a unique opportunity to directly link the development of models of increasing complexity with a robust testing phase; this allows researchers to understand which part of the modeling is the most relevant to reduce uncertainties in earthquake forecasting. The advantageous cycle between model development and testing may pave the way to better understand the physics of the earthquake occurrence process and to improve significantly the earthquake forecasting models. A side note, of considerable practical importance but difficult to place, is that the role of various partnering organizations in the implementation of earthquake forecasting tools into practice needs to be clarified, and understood by all parties.

6. Annual Meeting Format

The SCEC2014 meeting was the largest ever, and a great success in terms of its science content, as well as being extremely well organized and run, from beginning to end. The pre-meeting workshops were well-attended and effective.

During the regular SCEC meeting, attendees and the AC have consistently remarked that it is good to have only one talk at a time, as opposed to most other meetings that feature multiple parallel sessions. The single-session format leads to a common experience among attendees and promotes both interdisciplinarity and collaboration. However, a drawback is that it is sometimes hard for early career scientists to participate effectively during such a big session – even though SCEC does very well in featuring early career scientists as speakers. The AC wonders whether the SCEC meeting audience has grown too large for effective interaction and engagement.

To ensure the ongoing success of its flagship meeting SCEC leadership may wish to discuss how best to balance the size of the annual meeting and its inclusiveness – should there be some kind of limit on the number of registrants, or a cut-off date for registration? To promote early-career scientist participation in the discussions, should a new tradition be to have part of the discussion/question period devoted to comments from early-career scientists? One of the session convenors tried this tactic during the meeting, when she asked for questions from “someone who doesn’t already have a PhD”. The result was a partial success, and we think the success of this approach could grow if it was known in advance that such an invitation would arise consistently.

7. Plan for SCEC5

A major task for SCEC over the next year is planning and preparation of the SCEC5 proposal. The AC discussed the six major themes that have been elucidated to date by the SCEC “Tiger Teams”, each of which was a session at the meeting. An overall impression is that the naming of these themes will be important, as some of the initial words do not seem to us to be representative of the likely focus of the theme. The overall thrust of the themes is appropriate, reflecting SCEC’s breadth of experience and sharpening focus on issues of practical importance in applications, but the committee discussion stressed the importance of accuracy in naming the themes.

a. Understanding and Reducing Uncertainty

A provocative plenary by Norm Abrahamson set the tone for discussions on the importance of reducing uncertainties, by showing how uncertainties in hazard estimation lead to unmanageably-large uncertainties in the assessment of risk. Reduction of such uncertainty is a key objective for SCEC5. Further model development aiming at reducing uncertainties has to be strictly linked to a rigorous testing protocol. The latter is important to establish to what extent uncertainty is actually reduced by the addition of modeling detail and complexity. The attitude described by ‘the more detailed the model the better’ may not always apply, while a cycling between model development and testing can outline a pathway towards a real reduction of uncertainties.

One of the largest sources of uncertainty in hazard estimation is due to uncertainty in ground motions. Better observations of ground motions are a critical element, which may offer very useful reduction of uncertainty in hazard. The potential of improved observations of path and site effects to reduce uncertainty is likely of greater impact than the next generation of improvements from refined estimates of earthquake source processes.

Any significant reduction of epistemic uncertainty in ground motions may require a substantial (orders of magnitude) increase in the availability of high quality data. SCEC should find a way to facilitate meaningful expansion of instrumental network capacities, despite the fact that data collection and management is not considered a primary SCEC mission.

Reducing other sources of uncertainty may increase understanding of earthquake likelihood. One among many examples is the role of long-term time dependency of the seismicity rate. A long-term clustering has been found in some of the first versions of earthquake simulators; this clustering may offer an explanation of the so-called 'open interval' conundrum – looking at the paleoseismic data of all sites considered in UCERF3 project, it is surprising that none of them has produced another large earthquake in the last century. This could reflect time-dependency in earthquake rates that may have an impact on the assessment of hazard and risk; alternatively it may result from the relatively short period of observations relative to the earthquake cycle.

During Q&A, one observer noted that this theme (uncertainty) should not be the “lead” theme in SCEC5 – and also that the words aleatory and epistemic should not appear in the theme title. Tackling uncertainty on a heterogeneous and interdisciplinary set of problems is central to SCEC’s purpose. However, the title and scope of this theme, and its ordering within the SCEC5 proposal, should be further investigated and nuanced by SCEC leadership during the near-term planning for SCEC5. For example, a potential focus for this theme could be understanding and reducing uncertainty in the key areas of: (i) hazard assessment; and (ii) earthquake forecasting.

b. *Earth/Fault Properties - What Properties of Earth/Faults Are Important to Understand System Behavior?*

This theme encourages integration of dynamic rupture models, earthquake simulations, and geodetic modelling across a range of scale. The state-of-stress in the crust needs to be better understood, including stress concentration over numerous earthquake cycles, and factors that control stress levels during dynamic rupture. Extending fault models "beyond elasticity" is a goal, which necessitates the development of a Community Rheology Model (CRM). Many of the studies in individual SCEC disciplines are describing rheology, including types of non-linear rheology at various scales. The community rheology model could integrate these parameters in useful ways that would bring cross-disciplinary insight. Temporal variability may be included, as fault zone properties and the degree of strain localization may vary throughout earthquake cycles.

This theme will also investigate alternative mechanisms to load southern California faults, to go beyond backslip models. It may determine the roles and ranges of significant factors that control fault system behavior, including viscoelasticity, the presence of fluids, heat flow, and geothermal gradient. This will increase understanding of the range of feasible slip rates on mapped faults. Non-planar fault structure may also be a crucial factor in fault behavior. Dynamic weakening shows extreme sensitivity to local conditions including geometry and roughness. Both geology and modelling of faults in recent SCEC4 results are showing significant off-fault deformation. Such results are showing that there is no shallow slip deficit because of off-fault yielding. Characterizing multi-scale fault structure in an integrated manner is an important task for SCEC5.

c. *Simulated Earthquake Motions to Assess Hazard*

This theme was not well named. Its title should reflect that this theme is aimed at reducing uncertainty in hazard assessment - it is not actually aimed at reducing risk, though it may be considered a prerequisite for reducing risk. To be useable in engineering practice, the hazard assessment process must be well documented and reproducible. The broadband platform (BBP) is a good example of the type of prospective approach to evaluating model performance that is required. The management of simulation products will be an important issue – to enhance their usefulness, the archiving and format of these simulations needs to be carefully considered. As the BBP moves from a research topic to an application tool, the demand for use of the BBP for engineering projects will grow. SCEC will need to determine what role it will play in facilitating the application of the BBP and how it will charge for the use of the BBP. A promising avenue lies in establishing a firmer link between hazard estimates and felt observations/effects – perhaps using simple systems that might be readily tied to ground motion parameters, such as toppling of rocks, ringing of churchbells, toppling of chimneys, DYFI indicators, etc.). Although there is high uncertainty in estimating ground motion levels from such data, they do provide the spatially dense observations that are needed to constrain path effects and which are missing from the current seismic stations.

d. *To What Extent is Earthquake Behavior Predictable?*

This theme was not well named. Aspects of the problems associated with trying to understand and ultimately predict (or forecast?) earthquake behavior touch on many of the themes and working groups in SCEC. We've chosen to focus here on the timeliness of understanding and evaluating the risk of anthropogenic earthquakes. Induced seismicity affords new opportunities in both basic science and its funding. The physical mechanisms of induced seismicity and many important issues are not yet well understood, such as the determination of the maximum magnitude of induced events and the maximum distance (if any) from the anthropogenic source. Fluid pressure fluctuations, volume changes, fluid movement, thermal perturbations, and evolution of permeability all may be factors. The potential impact of induced seismicity on hazard assessment is large. Basic underlying questions include: What data do we require to understand the processes? Are there observable differences between anthropogenic and other earthquakes? The huge uncertainty about the most relevant processes behind induced seismicity provides fertile ground for pioneering studies.

Reflecting more broadly on earthquake predictability, the area of Operational Earthquake Forecasting (OEF) is an important scientific target that has a potential large impact on society and, at the same time, it offers a framework to evaluate what seismologists really know about earthquake predictability. OEF is a challenge for seismologists, pushing them from the development of conceptual models based on past observations to models that can be applied in a prospective way. The actual OEF models are mostly based on earthquake clustering and their skill is usually bounded in a low-probability environment. Significant improvements are expected, for instance modeling a wide range of potential precursors (geodetic, seismic, etc.), and/or exploring the potentialities of earthquake simulators. It is difficult to foresee all the scientific domains that may yield new insights on increasing earthquake predictability.

e. *Preparing for and Responding to Future Earthquakes*

A key area of research in SCEC5 will be in the area of early detection and rapid characterization of earthquakes and the role of detection in informing Earthquake Early Warning (EEW), which will rely on both physical and social science. Some questions were raised at the SCEC session as to whether the title EEW is optimal, and whether it is already too late to change. Heightened attention to rigor in vocabulary that distinguishes between early detection and early warning would be helpful in this regard. But regardless of the selected title, research under this topic will be furthered by SCEC contributions in a number of areas: (i) earthquake statistics and Bayesian analysis; (ii) merging geodetic and seismic signal information; (iii) recognizing large earthquakes from early observations; (iv) emergency planning to support issuing a timely, clear and actionable warning, (v) public education around how to respond to EEW messages; and (vi) tracking the efficacy of earthquake early detection, rapid characterization, and EEW (e.g. by CSEP activities).

Shakeout has attracted global recognition and influenced large numbers of citizens, planners, responders, and others. The research on actionable messaging adds great value to these efforts, and is clearly of great interest as early warning moves forward.

In terms of responding to an unfolding earthquake, SCEC leadership should focus on defining SCEC's critical role. The collaboration within SCEC provides a basis for rapid team organization. We view the SCEC role as acting as somewhat of a clearinghouse, bringing together the various stakeholders, players and emerging datasets. SCEC research could also focus on identifying crucial transient effects that may be important to characterizing earthquake processes, ones that may be missed in the post-earthquake response plans of other organizations. This could include pre-developed plans for types of arrays that would address earthquake rupture issues. SCEC has not had a role in the past as an instrument maintenance facility, and taking on that role would require a different focus for staff. Instead, SCEC could encourage the USGS to have available instruments and work with them to establish plans for academic and USGS staff to join in aftershock deployments. SCEC could play a role in providing logistical support.

f. *Communicating What We Know and Don't Know – Placeholder, More Input Needed.*

A primary recommendation is that SCEC needs to identify its audience, because a communication plan needs to establish relevance for that audience and communicate on a level commensurate with their science literacy. Communicating what is known should ultimately be expressed in terms of the contributions SCEC can make toward informing those at risk of how they can take meaningful action to protect themselves. This remains an area of strength for SCEC. The ongoing work to promote Shakeout Earthquake Drills and other education efforts continue to bring favorable attention to SCEC. Thus, continuing to dedicate time and other resources to communicating what is known is essential. SCEC's success in communicating what is known must, however, be tempered with a clear emphasis of what is unknown. Assumptions that earthquakes can be predicted, for example, create unrealistic expectation and unwarranted criticism when an earthquake occurs. Communicating what is unknown should be expressed as part of an ongoing effort to reduce uncertainty in the contexts within which it is estimated. Expressing the unknown in a simple and transparent way is important, as it precludes unrealistic expectations. Given the fact that SCEC has already generated an attentive audience with its current educational efforts, adding or continuing to provide messages that accept uncertainty and describe the ongoing efforts to reduce this uncertainty is warranted.

g. *Closing Remarks on SCEC5 Rationale*

In thinking about SCEC5, the proposal will need to answer the question: why does NSF/USGS need SCEC to continue? We think the answer should stress the cross-disciplinary focus with a large group of participants at all stages of research that is the strength and uniqueness of SCEC. We believe that NSF and USGS recognize the demonstrable momentum and value-added collaboration within SCEC. A strong case can be made that SCEC can guarantee world-class results and outreach with great return on investment. By contrast, there is recognizable competition in panel meeting evaluations of individual PI projects, with typically weak or informal outreach plans, and sometimes no guarantee of successful or documentable outcomes.