Southern California Earthquake Center

Annual Report: Year 4

November 15, 2014 – November 15, 2015

SC/EC
AN NSF+USGS CENTER

Funded by Cooperative Agreements with:

NSF Award 1033462 | USGS Award G12AC20038

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I. Introduction 2
A. Southern California as a Natural Laboratory 2
B. SCEC as a Virtual Organization 3
C. Earthquake System Science 5
II. Organization and Management 6
A. Board of Directors 6
B. Administration and Leadership Changes 6
C. External Advisory Council 7
D. Working Groups 7
E. Planning Committee 8
F. Communication, Education and Outreach 8
G. SCEC Participants and Diversity Plan 8
H. International Collaborations 11
III. SCEC Accomplishments 13
A. Research Accomplishments 13
B. Communication, Education and Outreach Accomplishments 56
IV. SCEC Goals and Objectives 70
A. 2016 Science Collaboration Plan 70
B. Communication, Education, and Outreach Milestones and Metrics 88
V. Publications 91
VI. Appendices 101
A. Science Milestones 101
B. Communication, Education, and Outreach Strategic Plan 106
C. 2015 Report of the SCEC Advisory Council 116

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 fourth 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.

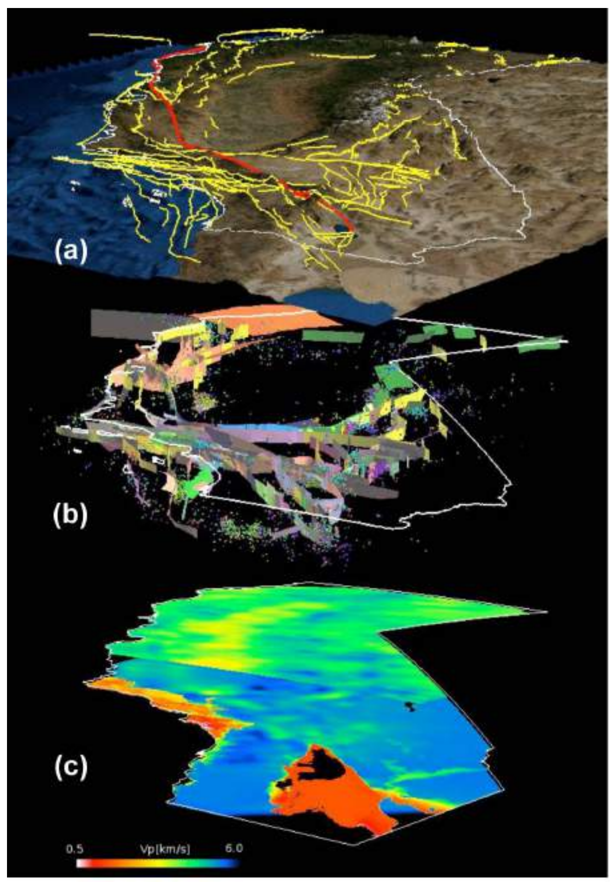


Figure 1.1. Perspective of California, looking northwest and showing elements of the Unified Structural Representation (USR): **(a)** traces of active faults (yellow lines) and the San Andreas master fault (red lines), **(b)** the statewide Community Fault Model (CFM), and **(c)** statewide Community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

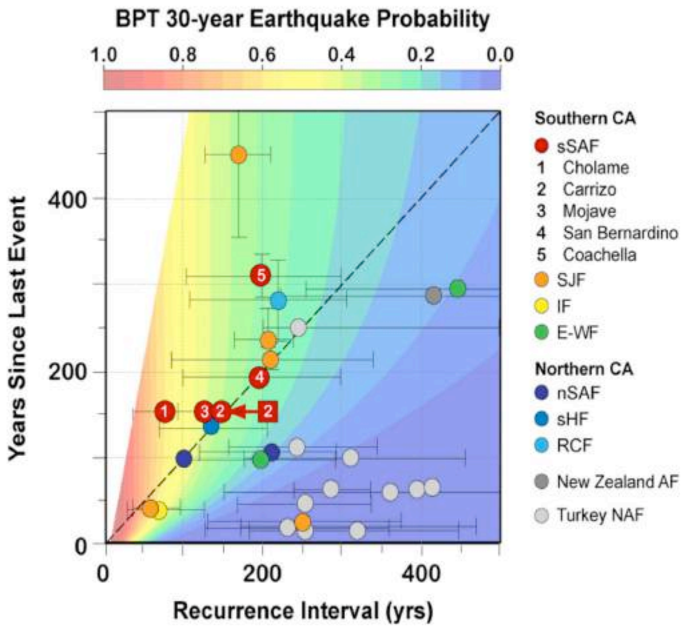


Figure 1.2. A plot of time since the last event vs. mean recurrence interval for sections of the southern San Andreas fault (red points) and other strike-slip faults in California and elsewhere. The arrow indicates the reduction in the mean recurrence interval for the Carrizo section implied by the new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

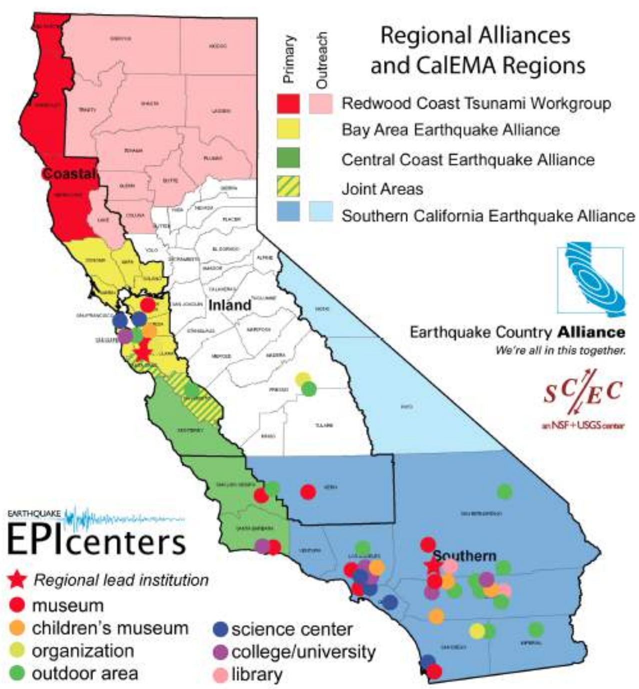


Figure 1.3. Four chapters of the Earthquake Country Alliance (colored areas) and locations of the EPIcenters (colored symbols), two key partnerships developed by the SCEC CEO program.

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 52 (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 (1960 as of November 2015) and the registrants at the SCEC Annual Meeting (568 in 2015). Annual Meeting registrations for SCEC's entire 25-year history and other demographic information are shown in Figure 1.4.

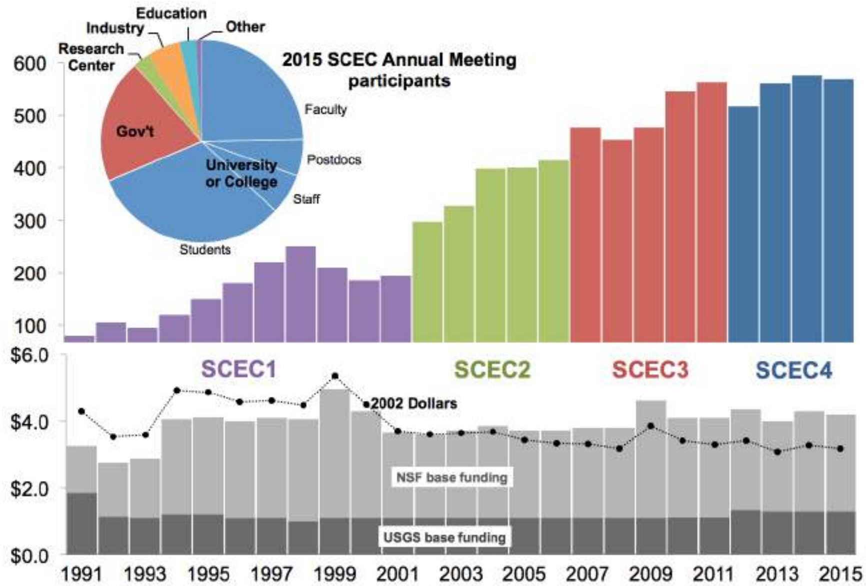


Figure 1.4. Colored bars show registrants at SCEC Annual Meetings, one measure of how the collaboration has grown during its 25-year history, 1991-2015. Pie chart shows the institutional profile for 2015 pre-registrants (568 total). The lower bar chart is the history of SCEC base funding in as-spent 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. SCEC4 Member Institutions (November, 2015)

Core Institutions (17)	Participating Institutions (52)
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)	Academia Sinica (Taiwan); Appalachian State University; Arizona State University; Brown University; CalPoly, Pomona; CalState, Fullerton; CalState, Long Beach; CalState, Northridge; CalState, San Bernardino; Carnegie Mellon University; Centro de Investigación Científica y de Educación Superior de Ensenada (Mexico); Colorado School of Mines; Cornell University; Disaster Prevention Research Institute (Japan); Earthquake Research Institute (Japan); ETH Zürich (Switzerland); Georgia Institute of Technology; GNS Science (New Zealand); Indiana University; Lawrence Livermore National Laboratory; Marquette University; National Aeronautics and Space Administration Jet Propulsion Laboratory; National Central University (Taiwan); National Chung Cheng University (Taiwan); National Taiwan University (Taiwan); Oregon State University; Pennsylvania State University; Purdue University; Smith College; State University of New York at Stony Brook; Texas A&M University; University of Alaska, Fairbanks; University of Bristol (UK); University of California, Berkeley; University of California, Davis; University of California, Irvine; University of Canterbury (New Zealand); University of Cincinnati; University of Illinois at Urbana-Champaign; University of Kentucky; University of Massachusetts, Amherst; University of Michigan; University of New Hampshire; University of Oregon; University of Texas at Austin; University of Texas at El Paso; University of Wisconsin, Madison; 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, nongovernmental organizations, and commercial enterprises. The CEO program has used SCEC research in developing effective new mechanisms to promote community preparedness and resilience, including the many publications that have branched from the original SCEC publication, Putting Down Roots in Earthquake Country.

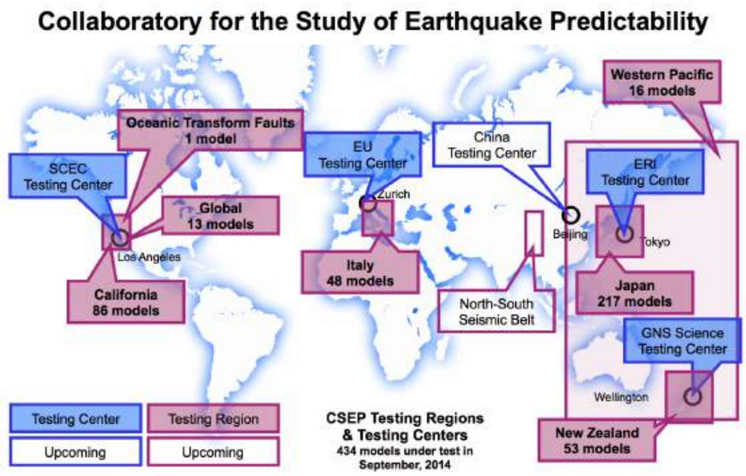


Figure 1.5. Map showing the worldwide distribution of activities developed under the Collaboratory for the Study of Earthquake Predictability (CSEP).

5. SCEC is an ***international leader*** that inspires interdisciplinary collaborations, and it involves many scientists from other countries. Currently, 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.

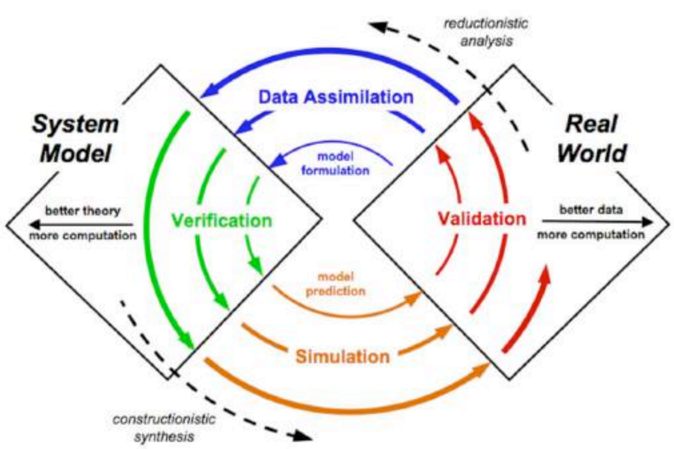


Figure 1.6. The inference spiral for system science, illustrating the improvement of system-level models through an iterated cycle of model formulation (blue), model verification (green), simulation-based prediction (orange), validation against observations (red), and data assimilation (blue). Verification 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 2015, the institutional membership stands at 69, comprising 17 core institutions and 52 participating institutions (Table 1.1). SCEC institutions are not limited to universities, nor to U.S. organizations. Three of the major USGS offices—Menlo Park, Pasadena, and Golden—are core institutions represented by liaison (non-voting) members on the SCEC Board. There are currently 12 foreign institutions recognized as partners with SCEC through a growing list of international cooperative agreements. SCEC currently involves more than 1000 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 Michele Cooke of UMass-Amherst and Roland Bürgmann of UC-Berkeley.

B. Administration and Leadership Changes

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 Center Director recommended and the Board approved of several changes in the SCEC leadership structure intended to redistribute some of the Director's responsibilities and workload. Greg Beroza of Stanford was promoted to a newly formed Center Co-Directorship; he will serve as the Co-PI on the SCEC5 core proposal and will retain his position as PC Chair. As Chair of the Planning Committee, he continues to serve as liaison to SCEC science partners, chairs of the annual meeting, oversees the development of the annual RFP, and recommends an annual collaboration plan to the Board based on the review process. The modified by-laws enable mechanisms for the Co-Director to act as the PI of SCEC special projects.

Two new science leadership positions have been created: a PC Vice-Chair (PC-VC), filled by Judi Chester of Texas A&M; and an Executive Director of Special Projects (ED-SP), filled by Christine Goulet of USC. Another new leadership position was also created within SCEC's Communication, Education and Outreach Program, the CEO Assistant Director for Strategic Partnership, which has been filled by Sharon Sandow of USC.

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).

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.

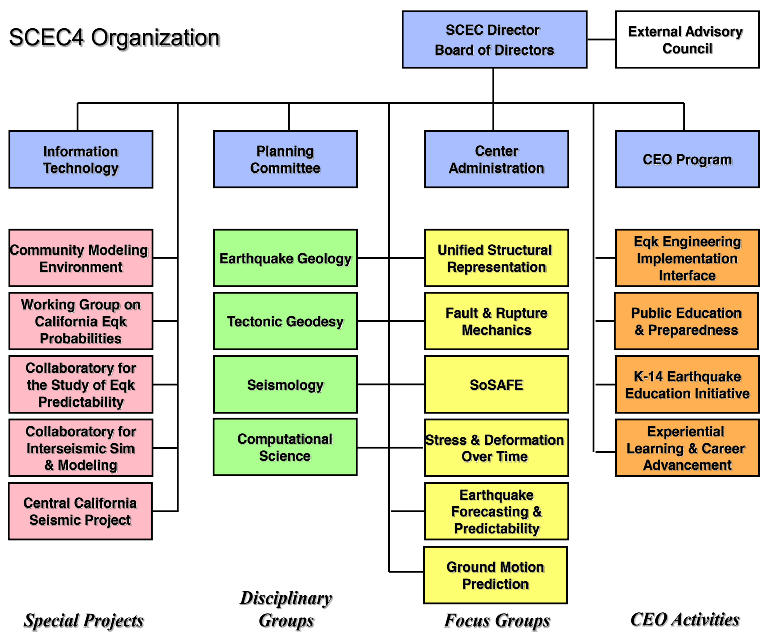


Figure 2.1. The SCEC4 organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects (pink), CEO activities (orange), management offices (blue), and the external advisory council (white).

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. Domniki Asimaki of Caltech is replacing Christine Goulet as the co-leader of GMP. David Sandwell of UCSD will take over for Jessica Murray (USGS) as leader of the Tectonic Geodesy Disciplinary Group. Gareth Funning of UCR will be joining the group as co-leader. Liz Hear of Capstone Geophysics will take over for Thorsten Becker of USC as SDOT 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 Jean-Paul Ampuero of Caltech will replace Martin Mai of KAUST as leader for SIV.

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 Sharon Sandow the new CEO Assistant Director for Strategic Partnership.

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, 18 of the 20 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 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 20), 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 2015.

	Race						Ethnicity		
	Native	Asian	Black	Pacific	White	NA	Latino	Not	NA
Faculty (Tenure-Track)	0	17	0	0	105	35	8	122	27
Faculty (Non-Tenure-Track)	0	0	0	0	4	2	0	2	4
Research Faculty (Tenure-Track)	0	2	0	0	12	4	0	13	5
Research Faculty (Non-Tenure-Track)	0	3	0	0	13	5	1	14	6
Postdoctoral Scholar or Fellow	0	12	0	0	17	19	3	28	17
Staff Scientist (Doctoral Level)	0	16	0	0	66	23	3	73	29
Staff (Research)	0	2	0	0	17	7	1	18	7
Staff (Management and Administration)	0	3	0	0	22	4	2	22	5
Staff (Communication, Outreach, PR)	0	1	0	0	4	0	0	5	0
Technician	0	0	0	0	1	1	0	1	1
Professional Geologist	0	1	0	0	14	5	4	9	7
Professional Engineer (Civil and Environmental)	0	1	0	0	6	1	1	5	2
Professional Engineer (Other)	0	0	0	0	3	0	0	2	1
Consultant (Engineering)	0	0	0	0	3	2	0	3	2
Consultant (Information Technology)	0	1	0	0	1	1	0	2	1
Consultant (Other)	0	0	0	0	3	0	0	3	0
Emergency Manager	0	0	0	0	0	1	0	0	1
Building Official	0	0	0	0	0	0	0	0	0
Self-Employed	0	0	0	0	0	0	0	0	0
Teacher (K-12)	0	1	0	0	7	6	3	6	5
Student (Graduate)	0	38	0	0	103	35	10	136	30
Student (Undergraduate)	0	1	0	0	14	8	7	11	5

Student (High School)	0	0	0	0	1	0	1	0	0
Retired	0	0	0	0	4	1	0	4	1
Unemployed	0	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	1	0	0	1
Unspecified	0	10	0	0	31	115	3	34	119

	Gender			**Citizenship**		
	Male	Female	NA	US	Other	NA
Faculty (Tenure-Track)	125	28	4	101	44	12
Faculty (Non-Tenure-Track)	4	2	0	5	1	0
Research Faculty (Tenure-Track)	14	4	0	11	7	0
Research Faculty (Non-Tenure-Track)	16	5	0	13	8	0
Postdoctoral Scholar or Fellow	28	15	5	16	30	2
Staff Scientist (Doctoral Level)	71	30	4	65	35	5
Staff (Research)	16	9	1	19	7	0
Staff (Management and Administration)	17	11	1	25	4	0
Staff (Communication, Outreach, PR)	4	1	0	5	0	0
Technician	0	1	1	1	1	0
Professional Geologist	14	5	1	17	3	0
Professional Engineer (Civil and Environmental)	5	2	1	7	1	0
Professional Engineer (Other)	2	1	0	1	2	0
Consultant (Engineering)	3	1	1	2	2	1
Consultant (Information Technology)	2	1	0	3	0	0
Consultant (Other)	1	2	0	3	0	0
Emergency Manager	0	1	0	1	0	0
Building Official	0	0	0	0	0	0
Self-Employed	0	0	0	0	0	0
Teacher (K-12)	6	8	0	13	1	0
Student (Graduate)	98	73	5	109	67	0
Student (Undergraduate)	8	13	2	20	2	1
Student (High School)	0	1	0	1	0	0
Retired	5	0	0	3	2	0
Unemployed	0	0	0	0	0	0
Other	0	0	1	0	0	1
Unspecified	40	16	100	31	121	4

	Disability							
	None	Hearing	Visual	Mobility	Learning	Speech	Emotional	NA
Faculty (Tenure-Track)	153	2	1	0	0	0	0	1
Faculty (Non-Tenure-Track)	6	0	0	0	0	0	0	0
Research Faculty (Tenure-Track)	18	0	0	0	0	0	0	0
Research Faculty (Non-Tenure-Track)	20	0	0	0	0	0	0	1
Postdoctoral Scholar or Fellow	46	0	0	0	0	0	0	2
Staff Scientist (Doctoral Level)	104	0	0	0	0	0	0	1
Staff (Research)	25	0	0	1	0	0	0	0
Staff (Management and Administration)	26	0	1	1	0	0	0	1
Staff (Communication, Outreach, PR)	5	0	0	0	0	0	0	0
Technician	2	0	0	0	0	0	0	0
Professional Geologist	20	0	0	0	0	0	0	0
Professional Engineer (Civil and Environmental)	8	0	0	0	0	0	0	0
Professional Engineer (Other)	2	0	0	0	0	0	0	1
Consultant (Engineering)	5	0	0	0	0	0	0	0
Consultant (Information Technology)	3	0	0	0	0	0	0	0
Consultant (Other)	3	0	0	0	0	0	0	0
Emergency Manager	1	0	0	0	0	0	0	0
Building Official	0	0	0	0	0	0	0	0
Self-Employed	0	0	0	0	0	0	0	0
Teacher (K-12)	13	0	0	0	0	0	0	1
Student (Graduate)	173	0	0	0	1	0	0	2
Student (Undergraduate)	23	0	0	0	0	0	0	0
Student (High School)	1	0	0	0	0	0	0	0
Retired	4	0	0	0	1	0	0	0
Unemployed	0	0	0	0	0	0	0	0
Other	1	0	0	0	0	0	0	0
Unspecified	155	0	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 partnerships with Afghanistan, Canada, Colombia, Greece, Iran, Mexico, New Zealand, India, Japan, Italy, Afghanistan, Pakistan, CNMI, and the Philippines on holding ShakeOut drills. SCEC hosts the websites for all ShakeOut drills worldwide. See *www.shakeout.org*.
- **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 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 Japan in September 2015 for students of both countries. There were 17 participants (2 senior faculty, 2 early career faculty, 1 postdoc, and 12 graduate students) from the U.S. and 30 from Japan. The summer school has become a major international activity beyond just the U.S. and Japan. Students from Brazil, Singapore, Turkey, Germany, the Netherlands, New Zealand, China, Korea, Thailand, France, and Mexico also participated. See http://www.eri.u-tokyo.ac.jp/iSSEs2015/index.html.
- **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, Annemarie Christopherson, and David Rhoades of the New Zealand testing center visited SCEC in 2015.

- **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 2015 ACES biennial workshop was held in Chengdu, China in August 2015. See http://www.csi.ac.cn/ACES2015/Home/index.html.
- **ETH Zurich/Switzerland**. Stefan Wiemar and Jeremy Zechar are participants in the SCEC/CSEP projects. Luis Dalguer participates in the rupture validation project.
- **Korea Institute of Geosciences**. Seok Goo Song participates in the rupture validation project.
- **KAUST/Saudi Arabia**. Martin Mai participates 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 2015 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, Western University/Canada, University of Bristol/UK, University of Canterbury/New Zealand, 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) Hokudan Symposium in January to mark the 20th anniversary of the 1995 Kobe earthquake, 2) the Lithosphere-Asthenosphere Boundary meeting in London in March, 3) the EGU assembly in Vienna, Austria in April, 4) the 7th International Conference on Seismology and Earthquake Engineering in Iran in May, 5) the Japan Geosciences Union meeting in Japan in May, 6) the 9th International Workshop on Statistical Seismology in Germany in June, 7) the IUGG meeting in Prague in June/July, and 8) and the ACES International Workshop in Chengdu, China in August.

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. Resources include 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.

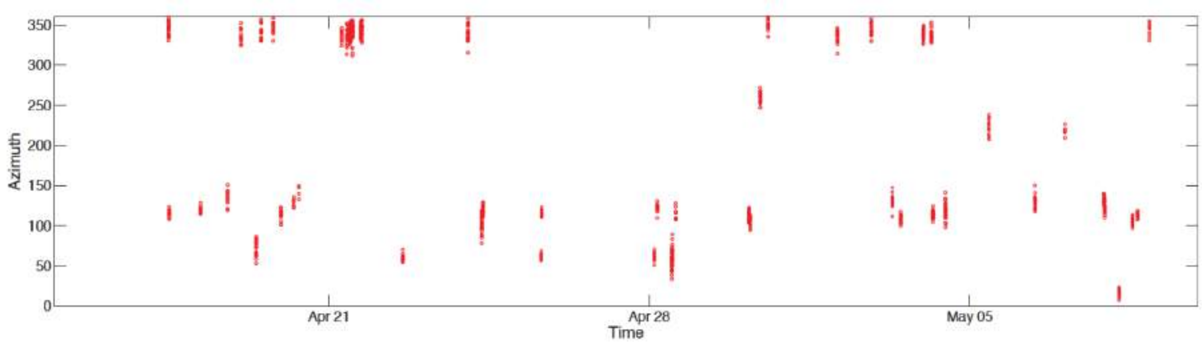


Figure 3.1. About 3 weeks of tremor activity along the San Andreas Fault as detected by the array analyses. Note the streaking nature of tremor propagation. Azimuth is with respect to the array center.

a. Tremor Detection Analysis: Deep fault slip can manifest in the form of tremor and has been observed on several faults in California, yet is far from ubiquitous. Several studies explore tremor along the select set of faults in California where it occurs, notably the San Andreas fault, San Jacinto fault. Tremor along the Parkfield segment of the San Andreas was the first to be identified outside of a subduction zone, but the factors that control tremor activity are still not well understood. Ghosh has been operating a temporary seismic array in the region and finds that tremor occurs almost daily. They use backprojection to locate the tremor and determine that it occurs in distinct patches along the fault (Figure 3.1). Additionally, they find that tremor rates increase dramatically in the hours following the South Napa earthquake. Peng and Yang conducted a systematic search for tremor in California, focusing on a region below the San Gabriel Mountains and along the San Jacinto fault. They find no evidence for tremor beneath the San Gabriel Mountains despite near lithostatic pore pressures (Yang and Peng, 2013). And, in an extensive search for tremor along the San Jacinto fault that utilized matched filter techniques they only find one instance of clear tremor; this tremor was previously reported and occurs during passing surface waves of the 2002 Denali earthquake (Figure 3.2). These results confirm that a unique set of conditions are needed for tremor to occur.

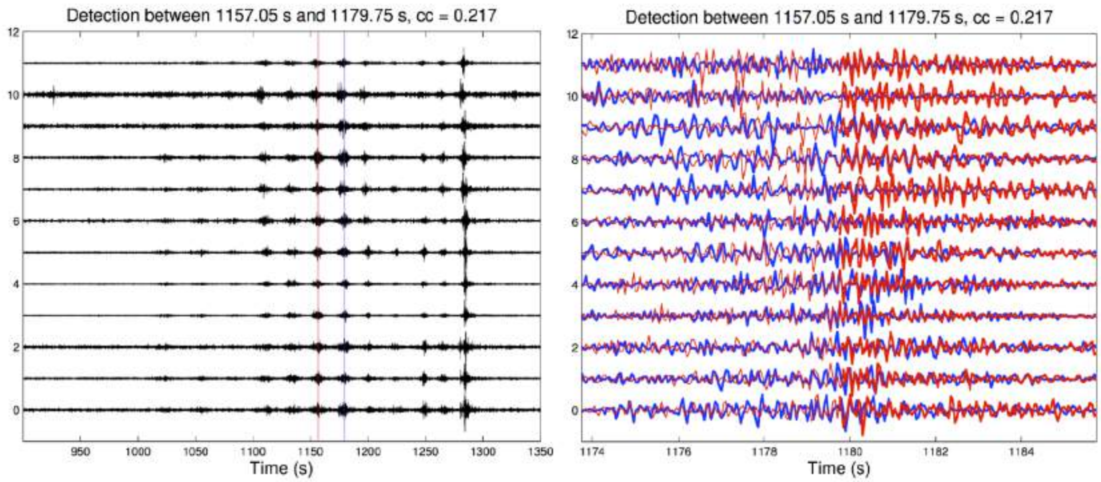


Figure 3.2. An example of tremor waveform detection along the San Jacinto Fault using a LFE template (red). In the left panel, continuous data is shown in black. Time is set in reference to the origin time of the 2002 Denali Fault earthquake. On the right panel, a zoom-in plot of the template (red) and detected event (blue).

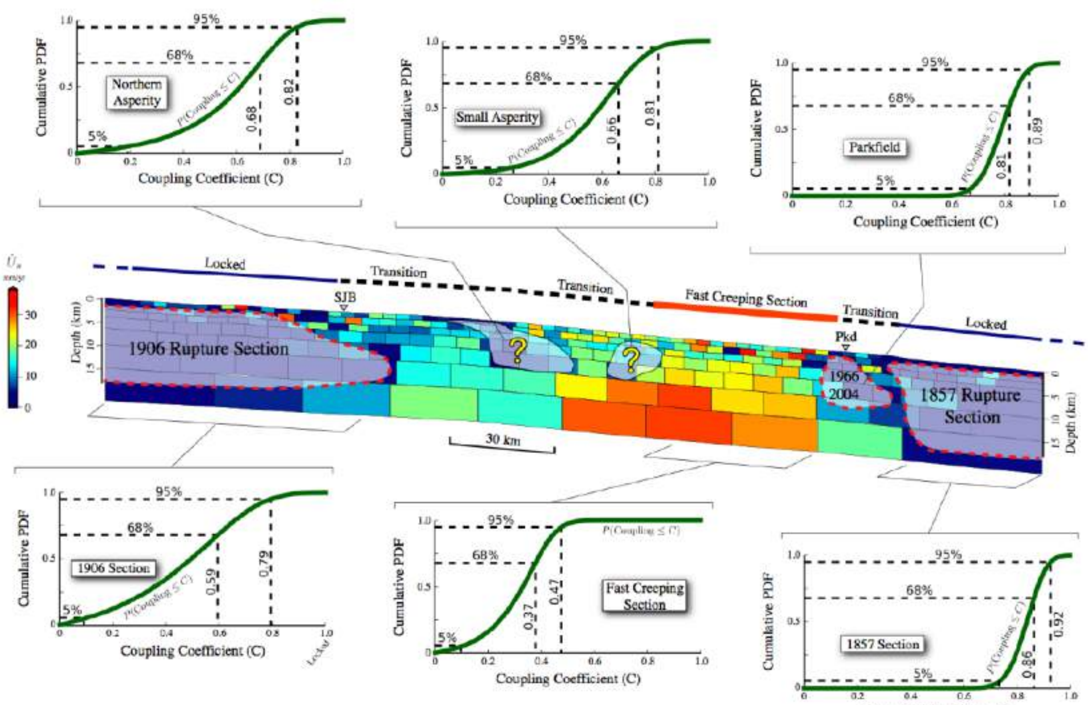


Figure 3.3. From Jolivet et al. (2015). Seismic and aseismic asperities along the central San Andreas Fault. Color represents the mode of the a posteriori PDF of slip in the along-strike direction. Semi-transparent areas marked with red dashed lines correspond to asperities where significant earthquakes are known to have occurred, including the 1857 M7.9 Fort Tejon, 1906 M7.9 San Francisco and 1966 and 2004 M6.0 Parkfield earthquakes. white transparent areas with question marks are zones that are inferred to be coupled and the potential source for future earthquakes.

b. Fault Coupling, Slip Behavior, and Source Properties: Both seismic and aseismic slip distribution and source properties can vary significantly along strike and with depth with changes in fault coupling, frictional properties, pore-fluid pressures, and/or fault structure. Ampuero conducted the first probabilistic estimate of of fault coupling along the Parkfield-Cholame section of the San Andreas fault. Fault coupling is estimated from high-resolution SAR- and GPS-derived observations of surface displacements. The results show that locked asperities are consistent with the inferred locations of M > 6 earthquakes, including patches possibly associated with two foreshocks of the 1857 M7.9 Fort Tejon earthquake (Figure 3.3). A study by Peng examined the variation in aftershock distributions for a set of 10 M>4 mainshocks along the San Jacinto fault (SJF) near Anza. They find that all aftershock distributions are extended in the along-strike direction. Additionally, deeper mainshocks have abnormally long aftershock zones suggesting that they are modulated by changes in fault frictional properties as depth increases (Figure 3.4). Further, Peng postulates that the deep aftershocks zones may be driven by deep creep along the SJF (Meng and Peng, 2015). McGuire and Ben-Zion explore rupture velocity and directivity for M>3 earthquakes along the SJF to determine how fault structure and damage zones can affect these source properties and use second moment estimates and measurements of peak ground motions to estimate the directivity. They observe a clear correlation between Peak Spectral Accelerations (PSAs) near the corner frequency and the expected directivity from second moment estimates for the 2013 M5.1 earthquake on the SJF (Figure 3.5).

c. Estimating Stress from Anisotropy: Anisotropy can be used to estimate crustal stress and mantle flow and provide a better understanding of tectonic forcing that drives deformation. Miller and Becker are collecting disparate anisotropy datasets to develop a 3D model of anisotropy for southern California. They conduct a number of comparisons between different inferences of crustal stress and strain-rates. For example, they compare coseismic stress estimates using a focal mechanism inversion and compare to Kostrov summed strain-rates. They find that throughout much of southern California these two estimates are closely aligned (Figure 3.6); however, they do find some deviation in the estimates near the Transverse Ranges and near the southern seg-

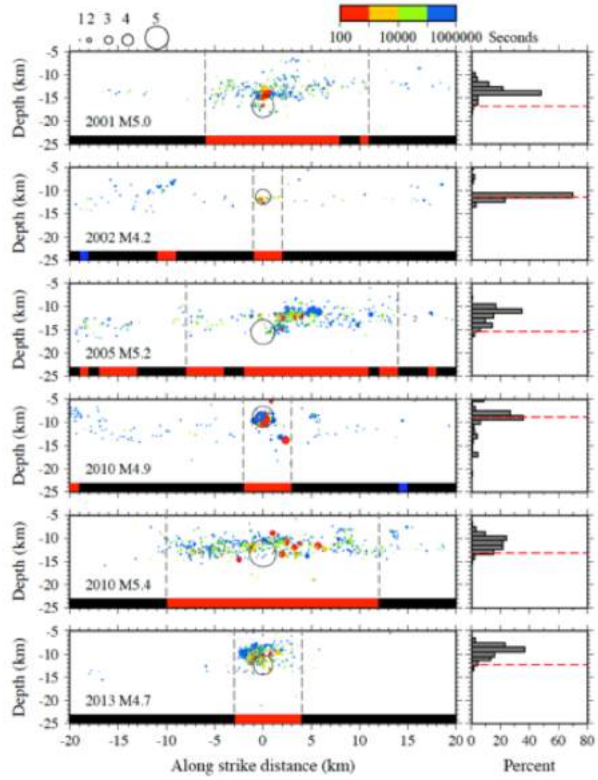


Figure 3.4. (Left) The cross-section view of the SJF around the hypocenters of moderate earthquakes. Dots denote aftershocks, which are color coded by their origin times and scaled by their magnitudes. The horizontal bars denote the β-values (black β<2; red β>2). The vertical grey lines denote the defined aftershock zone. (Right) The histogram of depth distribution of aftershocks. The horizontal red line denotes the depth of the mainshock.

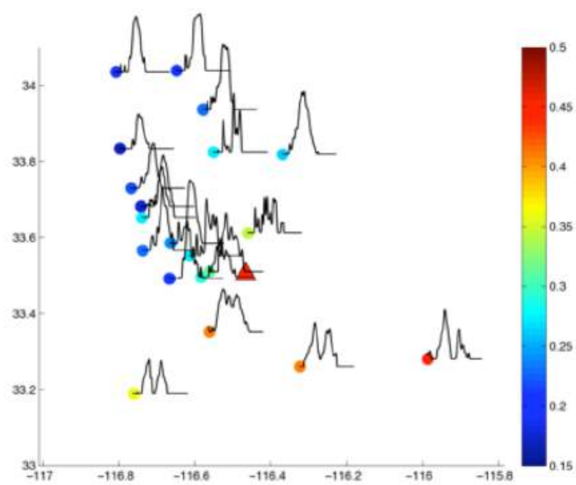


Figure 3.5. Apparent source time functions (ASTF) resulting from Empirical Green's Function deconvolutions at stations in the SJF array as a result of the March 2013 M5.1 earthquake (red triangle). Each ASTF is plotted at the location of the station denoted by the circle. The color scale of the circles denotes the characteristic duration of that moment-rate function, τc(s), in seconds. The earthquake lasted about 0.3 seconds but appears longer to the SE and shorter to the NW.

ment of the San Andreas. The origin of the differences is being investigated but may be caused by heterogeneous rock rheology or time-dependent alignment of stress and strain through the seismic cycle.

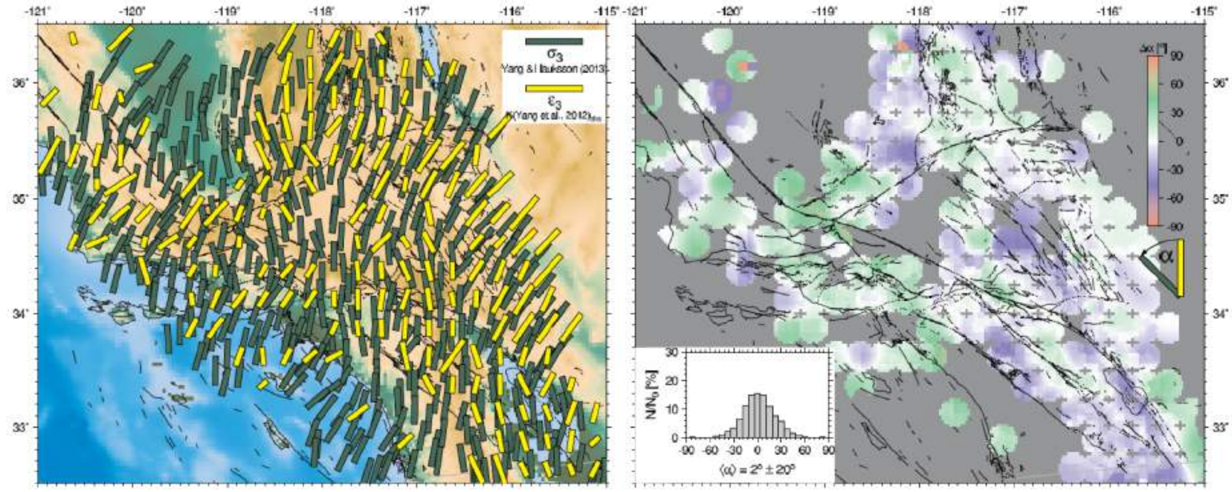


Figure 3.6. (Left) Comparison of coseismic "stress" from Michael (1984) type inversion (green, from Yang and Hauksson, 2013) and Kostrov summed strain-rates (yellow) based on the same focal mechanisms (Yang et al., 2012) (compressive axes show). (Right) Angular difference between the two axes, with sign determined as indicated in the legend, along with histogram (y axis showing frequency percent) over all sampled regions (sub plot), with legend stating the mean ± standard deviation of angular difference.

d. Induced Seismicity: The identification of induced seismicity and its impact on seismic hazard are of growing interest to scientists and the public alike. Chen and McGuire examine how earthquake source properties vary near geothermal operations in the Salton Sea region. They find that stress drops correlate with distance from geothermal wells, such that stress drops are lowest within 300 m of injection wells. Additionally, they also find low stress drops on a nearby fault that hosted a series of earthquake swarms in 2005, 2009, and 2010. Their results show that geothermal operations can locally change the source properties of earthquakes and provide new insights into the interaction between faults and fluids in a geothermal field. In 2014, a flurry of moderate earthquakes in the Los Angeles region raised concern as to whether some of the seismicity was of anthropogenic origin rather than tectonic origin. Hauksson et al. (2015) searched for evidence of induced earthquakes associated with oilfield operations in the seismically active Los Angeles basin (LA basin) (Figure 3.7). Such anthropogenic earthquakes can be caused by changes in loading on the adjacent crust as well as inflation or collapse of an oilfield reservoir when large volumes of fluids are injected or extracted. Overall, they found no obvious previously unidentified induced earthquakes, and that the management of balanced production and injection of fluids appears to reduce the risk of induced earthquake activity in the oilfields. To quantify the relationship between oil field activities and potential induced seismicity, Goebel et al. (2015) developed a novel method to

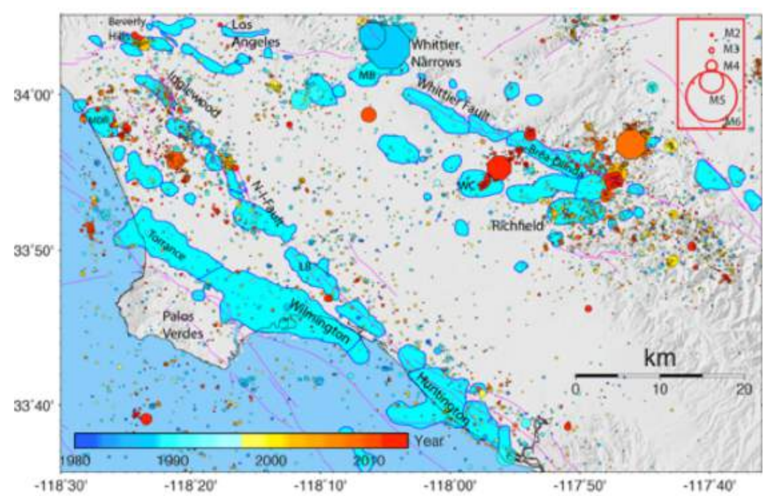


Figure 3.7. Relocated seismicity 1981-2014/06 recorded by SCSN and oilfields shown as irregular light blue areas (DOGGR web site). Symbol sizes are scaled with the earthquake magnitude with Mw≥5 shown as octagons (see scale in upper right corner), and color-coded by date. LB – Long Beach oilfield; MB – Montebello oilfield; MDR – Marina Del Rey; N-I-Fault: Newport-Inglewood Fault; WC – West-Coyote.

identify likely induced seismicity in tectonically active regions based on short-range spatio-temporal correlations between changes in fluid injection and seismicity rates. They applied this method to Kern County, central California, and found that most earthquakes within the region are tectonic in origin, except for four different possible cases of induced seismicity.

2. Tectonic Geodesy

Many of the SCEC Tectonic Geodesy (TG) activities this year have focused on development of the Community Geodetic Model (CGM), a crustal motion model consisting of velocities and time series for southern California that leverages the complementary nature of Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) observations. This project is coordinated by TG Leaders Murray and Sandwell and Transient Detection TAG Leader Lohman through in-person workshops (most recently in September 2014) and frequent video conferences. We have found this to be an effective method to organize the activities of the numerous participants and maintain momentum throughout the year. In addition to CGM-focused work, many other geodetic studies are producing exciting results.

a. Community Geodetic Model

Data collection and compilation. Funning, along with a graduate student and SCEC intern, carried out campaign GPS field work to obtain additional data at 23 benchmark sites in the Western Transverse Ranges, along the Elsinore fault, and in the northern Mojave desert. The additional data produced new velocity estimates for several sites with only one previous data point and resulted in more precise velocities for other sites. The data, which will be incorporated into the CGM, help to densify the secular velocity field for interseismic studies and establish a baseline of observations at more sites ahead of future significant earthquakes in the region.

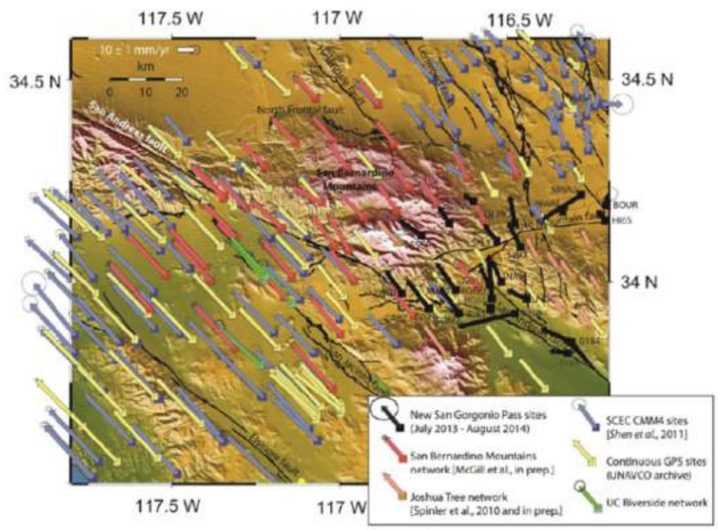


Figure 3.8. Example of SCEC-sponsored campaign GPS spatial densification: San Bernardino Mountains and San Gorgonio Pass. (Figure courtesy S. McGill).

McGill, Bennett, and Spinler continued campaign GPS data collection and modeling for the San Bernardino Mountains (SBM) and San Gorgonio Pass (SGP) area (Figure 3.8). This has resulted in the publication of velocities for 41 sites in the SBM and the establishment of 23 sites in the SGP. Additional data collection for the latter during 2015 will improve existing preliminary velocities. This project continues to involve SCEC interns, undergraduates, and teachers in fieldwork and data analysis.

Through a collaboration between CICESE and SIO, Sandwell and colleages conducted rapid-static GPS fieldwork in the Mexicali Valley along the Imperial and Cerro Prieto fault in order to improve estimates of shallow interseismic creep rates. Future CGM versions will aim to include these short-occupation, high spatial-density observations.

In support of the CGM and to ensure the maximum usage of SCEC-funded data in years to come, Floyd has taken the lead on transfer of legacy GPS data from the SCEC archive to the UNAVCO archive. This effort has involved identification of relevant datasets and verification of metadata. In addition, Floyd has interacted with PIs to facilitate the gathering of GPS data from recent SCEC-funded efforts and the provision of these data for inclusion in the CGM.

Drawing upon these and other data, Shen has produced an updated set of campaign GPS time series that incorporates data collected since the CMM4 (2004) and utilizes current, self-consistent processing strategies. This compilation features 130 new campaign sites, and 50 continuous sites have been included for the purpose of reference frame alignment. Metadata were thoroughly reviewed and corrected as needed to ensure the accuracy of processed results.

<u>Development and application of methods for model-based data synthesis and comparison of results</u>. Creating the CGM requires synthesis of existing results and development of new methodologies for analyzing and combining GPS and InSAR data via appropriate models to generate GPS station time series, spatially gridded InSAR time series, and a self-consistent integration of the two. A central aspect of this is the comparison of results obtained using different approaches. Both the GPS-focused and InSAR-focused CGM participants have been engaging in such comparisons.

To aid in this process, Herring and Floyd developed scripts for differencing, averaging, and computing comparison metrics for GPS time series and velocities that were produced by different processing centers. Application of these tools to GPS data has shown a good overall level of agreement. It has also highlighted the need to account for differences among processing strategies that influence position estimates and their reported uncertainties and, in turn, reference frame realization. Other factors such as inclusion of a scale term in reference frame adjustment and use of regional versus global reference frames are additional sources of significant variation in GPS time series and velocities produced by different groups.

GPS time series analysis strategies for estimating secular rates parameterize time-varying and constant signals and characterize noise sources in a variety of ways. McCaffrey has developed one approach that incorporates dislocation models to separate postseismic deformation from secular rates. The spatial coherence provided by the dislocation models is especially valuable when estimating velocities for GPS sites with little or no pre-earthquake data.

Integration and interpretation of GPS and InSAR observations requires accurate characterization of vertical deformation. Hammond et al. carried out a detailed analysis of vertical rates in the Ventura Basin by combined use of InSAR, GPS, leveling, and tide gauge data. The long-term vertical GPS velocities were obtained through application of a non-parametric median-based approach that is robust in the presence of steps and outliers. LOS velocities derived from the GPS rates, along with a regional deformation model, are used to constrain the InSAR LOS velocities and isolate the vertical motion. The resulting rates document basin subsidence due to groundwater level fluctuations and uplift consistent with contraction due to the Western Transverse Ranges and San Andreas Fault (SAF) systems. The four data sets span different time periods from the

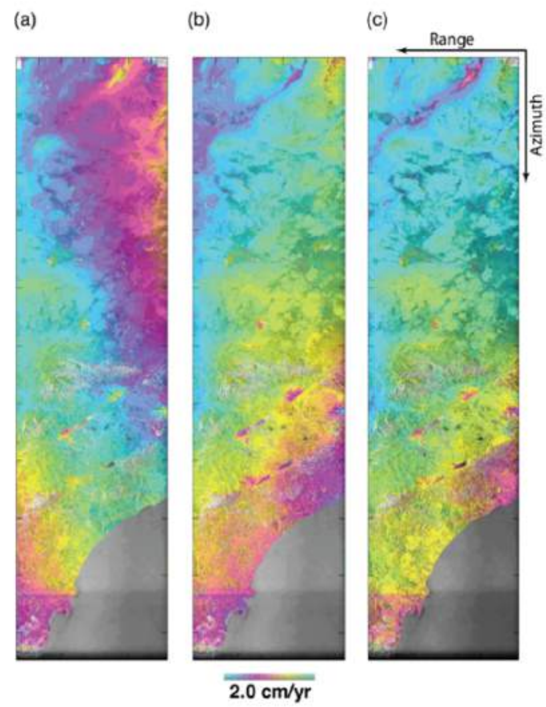


Figure 3.9a-c. (a) Average LOS velocity from Envisat data 2003 – 2010; LOD ramp error is visible across scene. (b) LOS velocity with application of empirical LOD correction. (c) LOS velocity with application of GPS-based correction. The two correction approaches show comparable results. (Figure courtesy Z. Liu)

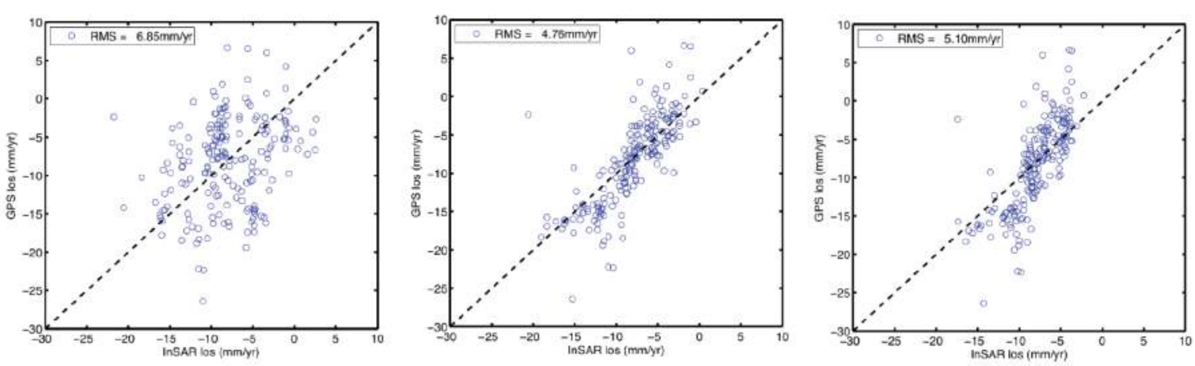


Figure 3.9d. Comparison of InSAR-based LOS velocities using different corrections (or no correction) to three-component GPS velocities projected into LOS direction. The empirical and GPS-based correction approaches show comparable results. (Figure courtesy Z. Liu)

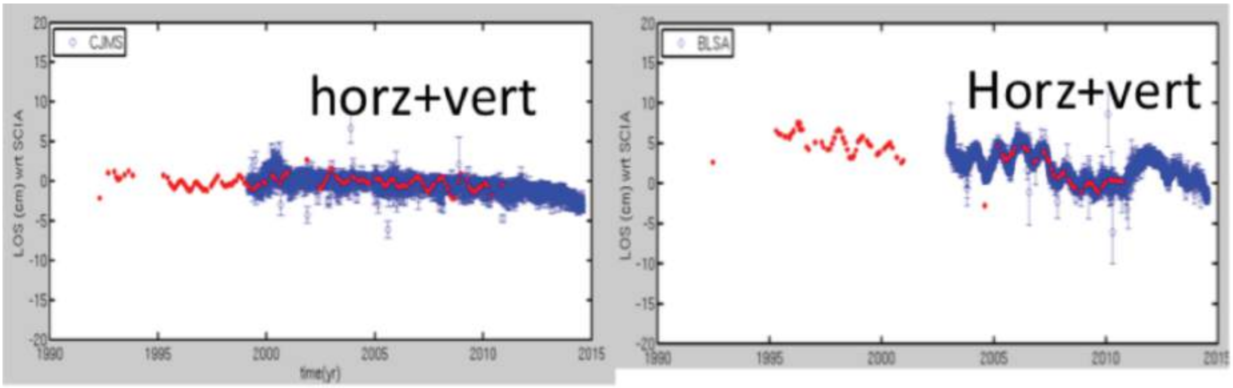


Figure 3.9e. Comparison of InSAR LOS time series obtained with empirical correction to projection of three-component GPS velocities into LOS direction. (Figure courtesy Z. Liu)

1930s to the present but suggest steady vertical rates except in areas of anthropogenic signals.

PIs focusing on InSAR time series analysis have made important advances in the past year. Tymofyeyeva and Fialko developed a technique that reduces InSAR time series scatter by averaging redundant interferograms that share a common scene in order to estimate and remove the ionospheric and tropospheric noise. Using the corrected interferograms in InSAR time series analysis, these authors documented time-varying interseismic deformation along the Blackwater Fault. They found little evidence for previously inferred deformation across the Hunter Mountain Fault and suggest that InSAR LOS velocities used in earlier studies may have been contaminated by seasonal variations.

In a second important development, Liu found that by correcting empirically for a temporally correlated local oscillator drift (LOD) error in Envisat data, it is possible to generate a deformation map based on InSAR data alone that is comparable to one obtained with a GPS-based correction (Figure 3.9). Agreement between InSAR-only motion estimates and GPS observations demonstrates the possibility of obtaining accurate velocity maps and time series from InSAR data even in regions with sparse GPS coverage. Application of the empirical correction to data from the Eastern California Shear Zone shows that transient deformation inferred from the InSAR data cannot be explained by the LOD error and is more likely due to long-term postseismic deformation.

Sandwell led software development to extend the capability of GMTSAR for use with ALOS-2, Sentinel 1, and ScanSAR data. These tools will enable SCEC scientists and the broader geodesy community to fully utilize the wealth of new SAR data that are becoming available. These data will allow vastly improved InSAR time series analysis, directly impacting future versions of the CGM.

b. Additional Tectonic Geodesy Activities

<u>Deformation modeling</u>. Tong, Sandwell, and others have developed a viscoelastic earthquake cycle model to investigate geologic/geodetic slip rate discrepancies along the Mojave segment of the SAF. McGill, Spinler, and Bennett used GPS data to infer a slip rate of 6.5 /- 3.6 mm/yr for the San Bernardino section of the SAF; this agrees with geologic estimates at 95% confidence. Avouac et al. developed a robust and efficient method for investigating combinations of simultaneous physical processes that best explain observed postseismic deformation. They apply this method to the El Mayor Cucapah (EMC) postseismic GPS data to study the roles of afterslip and viscoelastic relaxation, trade-offs between these processes, and their potential impact on nearby faults. Meanwhile, modeling of vertical velocities near the Cerro Prieto geothermal area by Sandwell and colleagues Trugman and Borsa suggests that stressing rates in the vicinity of the EMC hypocenter exceed the tectonic rate, perhaps due to extraction of water during geothermal production. Utilizing the UCERF3 horizontal GPS velocity field and the vertical rates of Hammond and Burgette (see above), which exhibit a gradient of 2 – 4 mm/yr over 100 km, Johnson inferred ~10 mm/yr of shortening across the Transverse Ranges. This may occur, in part, as 8-10 mm/yr reverse slip on faults of the Ventura Basin. In a parallel study, Marshall and colleagues incorporated the new CFM v5.0 geometry and used GPS and InSAR data to infer slip rates on the Ventura and Oak Ridge faults of the Ventura Basin. While they report little vertical deformation in this region, their slip rate estimates are in general agreement with those of Johnson.

Strain transient observation and technique development. Wyatt and Agnew continue to operate the Piñon Flat Observatory (PFO), despite budget constraints. The long history of laser strainmeter (LSM) observations have recorded repeated transient events in the days to weeks after moderate local and larger distant earthquakes as well as events not correlated with earthquakes. Motivated by their observations of swarm-like clustering of small earthquakes and swarm migration, Shearer et al. are using PFO LSM and PBO borehole strainmeter data to investigate possible causative processes including fluid flow and aseismic slip (Figure 3.10). This work has identified at least ten instances of strain anomalies correlated with peaks in the local seismicity rate. Some, but not all, of the anomalies correlate with M>3 earthquakes, however not all moderate earthquakes have associated strain transients and some transients occur without a M>3 earthquake. These observations may indicate that the strain anomalies associated with increased seismicity rate arise from slow slip at depth on the San Jacinto Fault just north of the 2006 M5.2 Anza earthquake. Agnew and colleagues are meanwhile testing the newly developed Trench Optical Fiber Strainmeter (TOFS) which may present an alternative to LSMs that is easier to install and operate. Two TOFSs have been installed at PFO, and a third is planned for 2015, to enable testing and calibration of the systems. While TOFS data are noisy at periods exceeding several hours, ongoing work is focused on noise reduction techniques.

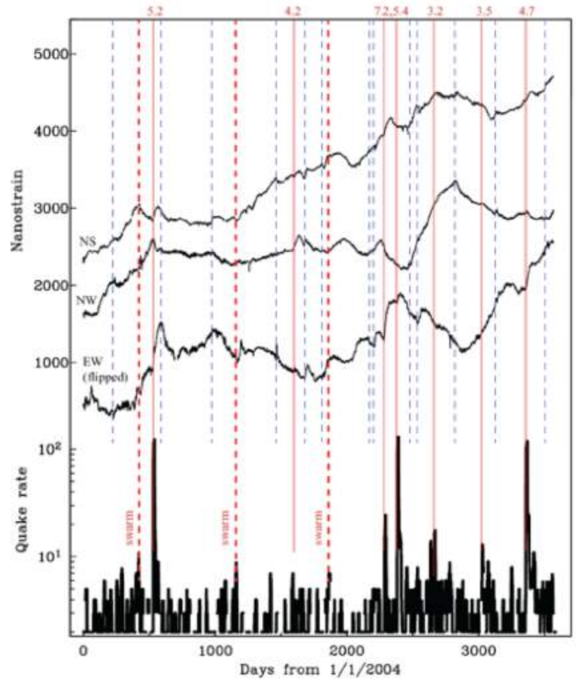


Figure 3.10. Strain events recorded on PFO LSM and temporally correlated increases in seismicity rate. Blue dashed lines: rainfall events. Solid red lines: M>3 earthquakes associated with seismicity rate peaks. Dashed red lines: seismicity rate peaks correlated with strain events but with no associated M>3 earthquake. (Figure courtesy P. Shearer).

Geodetic methods for improved earthquake early warning. Bock et al. continued development of seismogeodetic approaches for earthquake early warning. This work included shake-table testing of low-cost MEMS accelerometers and a geodetic module developed by his group and deployment at existing continuous GPS sites. This technology produces real-time 100 Hz position streams constrained by GPS and accelerometer data. Related work focused on further development of algorithms that use these data to improve real-time magnitude estimates via scaling relationships and finite fault modeling, the latter of which also provides additional source information useful for refining EEW alerts and tsunami modeling.

Surface offsets from LiDAR data. Nissen et al. have focused on further development of techniques for estimating 3D surface offsets from repeat-pass LiDAR data in areas with heavy vegetation. This work was done as part of the VISES collaboration and used two recent earthquakes in Japan as test cases. They have shown that this approach can be robust, not only in densely vegetated regions, but also for zones of steep displacement gradients and for imagery separated by long (e.g., 2 – 4 year) time intervals.

3. Earthquake Geology

Earthquake Geology 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.

a. Ventura Special Fault Study Area: A self-consistent picture has emerged from the Ventura SFSA project of large, tsunamigenic earthquakes spanning several faults of the Ventura-Santa Barbara basin. Slip events exceeding 5 meters, and perhaps as much as 10 meters, are required to explain geomorphic evidence for coseismic emergence of the coastline (Rockwell et al., in preparation) and formation of fold scarps east of Ventura (Grenader et al., this meeting). Because the western half of this fault system underlies the Santa Barbara channel, large slip events are expected to produce damaging tsunamis (Ward, 2014 SCEC report). The Oxnard Plain, located downthrown side of the fault, is expected to receive the worst inundation, while little runup occurs on the fault hanging wall near Ventura. Carpenteria Slough, located towards the western end of the Ventura Anticline, would undergo an intermediate level of subsidence, and appears to be well situated to record earthquake-induced subsidence and tsunami events. New results from Simms, Rockwell, et al. (2014 SCEC report, and this meeting) show evidence for three inundation events here since 4.1 ka — a result consistent with the record of emergence of the coastline near the anticline crest. Within the deep Santa Barbara basin, distinct layers of reworked marine sediment may indicate coseismic disturbance and submarine landslides (Berelson et al., 2014 SCEC report and this meeting), though not necessarily triggered by earthquakes on the Ventura-Pitas Point fault.

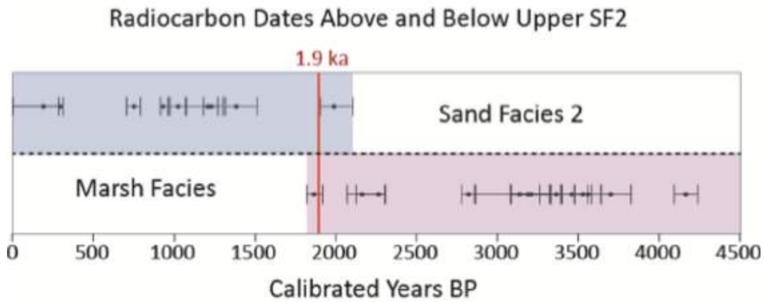


Figure 3.11. Carbon dating constrains transition from marsh facies to sand facies due to abrupt, likely coseismic inundation of Carpenteria Slough ca. 1,900 years before present.

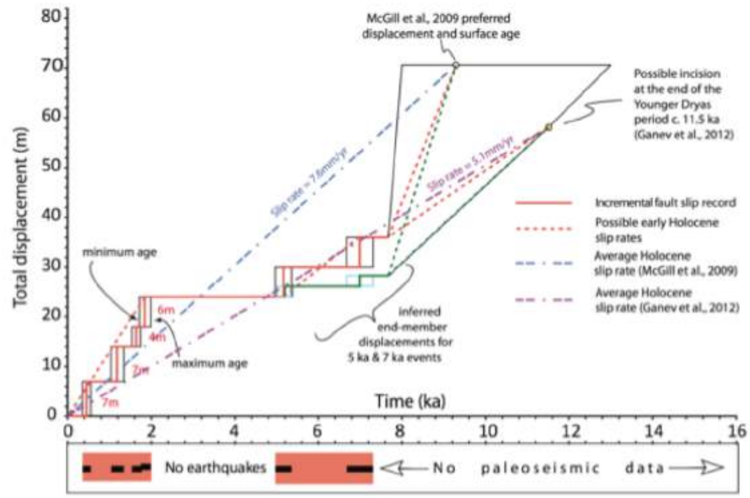


Figure 3.12. Slip rate and paleo-earthquake age data from the central Garlock Fault plotted versus time. Solid red line shows inferred incremental slip history of the central Garlock fault based on paleo-earthquake ages from Dawson et al. (2003), mapping of small geomorphic offsets by McGill and Sieh (1991), and Christmas Canyon West 1.9 ka slip rate (this study); thin, black vertical lines denote error ranges on paleo-earthquake ages. Suggested offsets in the ca. 5 ka and 7 ka earthquakes are based on range of possible offsets from 2 to 6 m based range of small offsets measured by McGill in Sieh (1991). Dashed purple line shows latest Pleistocene-Holocene slip rate of Ganev et al. (2012) based on their model of incision beginning at end of Younger Dryas period 11.5 ka. Dashed blue line shows preferred slip rate from McGill et al. (2009); solid horizontal black line shows possible age range of offset channel used in their rate calculation. Short-dashed green and red liens show possible early Holocene slip rates that would be required to explain both well-constrained the mid- to late Holocene incremental slip record and the longer-term rates of McGill et al. (2009) and Ganev et al. (2012). Lower panel shows age ranges of paleo-earthquakes from Dawson et al. (2003) El Paso Peaks trench site.

b. Geochronology and Fault Slip Rates: Geochronology advances supported under SCEC4 continue to yield new and more precise slip-rate data for the southern California fault system. A workshop convened in last October brought together geologists and geochronologists in a productive discussion of emerging techniques in exposure and luminescence dating. One of the highlights of SCEC geochronology has been the development of the pIR-IRSL technique on K-feldspar (Roder et al., 2012). Application of this technique to alluvial fan offsets along the Garlock fault yields a new, short term rate of 12.8 +/- 2.4 mm/yr that encompasses a cluster of four earthquakes between 500 and 1900 years ago (Dolan et al., in review). This is double the Holocene average rate of 6 mm/yr, and well in excess of the current loading rate of the Garlock fault inferred from geodesy. Overall, it appears that loading and strain release on the Garlock fault are temporally clustered, probably in alternation with right-lateral slip through the Eastern California Shear Zone. Newly collected lidar data from the Agua Blanca fault, northern Baja California, reveals several slip-rate sites in new detail (Behr et al., 2014 SCEC report). Pending geochronometry of these sites will reveal important information on how much plate-boundary strain is transferred to the California borderland, as well better understanding of seismic hazard for northern Baja California. Slip rate of the Sierra Madre fault, located on the margin of the Los Angeles basin, and the Wheeler Ridge blind thrust, southern San Joaquin Valley, are also being revisited with lidar data and modern geochronology approaches (Hanson et al., this meeting; Kleber et al., this meeting).

c. Fault Slip vs. Distributed Deformation: Results from the eastern California shear zone reveal new insight into the balance of fault slip and distributed deformation of the surrounding rock volume. Reanalysis of coseismic slip from the 1992 Lander earthquake (Milliner et al., this meeting) and the 1999 Hector Mine earthquake (Stock, et al., 2014 SCEC report; Witksoky et al., this meeting) confirm sharp, along-strike slip gradients near 10^-3 (1m in 0.5 km), and suggest that fault slip distributions could be fractal rather than smoothly elliptical. New fault slip rate data from the Calico fault and Harper Lake fault are consistent with slip transfer between these structures via linking reverse faults, as well as substantial off-fault deformation in zones of uplift and towards strike-slip fault terminations. Overall, as much as 40% of the deformation budget across the northern Mojave Desert may be absorbed in a distributed manner (Oskin, Cooke et al., 2014 SCEC report).

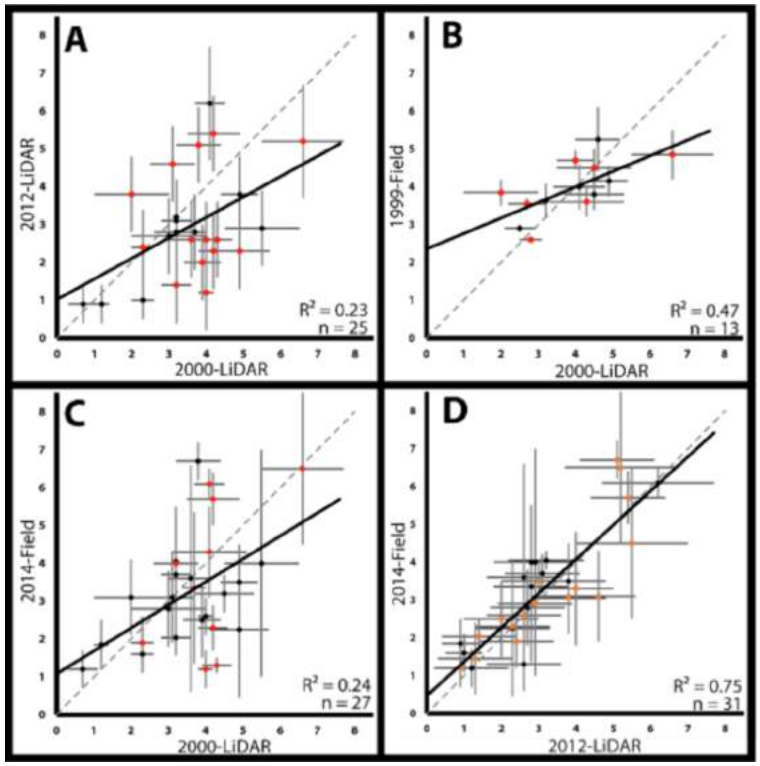


Figure 3.13. Comparison of four different datasets of co-located offset measurements within the maximum slip zone of the Hector Mine surface rupture. Of the six possible combinations only the four which yield n > 10 are plotted. A 1:1 line is plotted as dashed gray line, and a linear regression and associated R-squared is shown. Data is colored based on subjective quality rating (orange or red = poor or fair, black = good or very good) assigned during 2014 fieldwork (A,B,C) or to 2012-LiDAR measurement (D).

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. This past year's accomplishments include:

- Both static and adaptive mesh refinement have been used to efficiently obtain highly accurate solutions to rupture dynamics problems. An initial FD discontinuous mesh implementation is being tested for stability.
- Several GPU-based codes have accelerated High-F, CyberShake, and high-order DG simulations, which helped generate CyberShake 15.4.
- Both scattering and intrinsic attenuation reduce seismic wave amplitudes.
- Inelastic material response, in both the near-fault and near-surface regions, is demonstrated to substantially decrease ground motion.
- A rotationally invariant, 3D version of the stress relaxation equations is developed based on the rate-state evolution equation for earthquake simulator RSQSim.
- A new finite difference method was introduced to study earthquake sequences in heterogenous media, accounting for both viscoelastic and plastic off-fault material response.
- Multi-HPC systems are used for user-driven validation studies, which brings predicted ground motions into closer agreement with observations.
- Data-intensive HPC techniques were applied for earthquake detection in continuous waveform data.

a. Dynamic Rupture Simulations: Advances in HPC center around source physics, in particular fault geometric complexity as the origin of variability in slip and rupture velocity that contribute toward the generation of incoherent high-frequency radiation from earthquakes. Ensemble dynamic rupture simulations, involving thousands of realizations of the stochastic fault geometry, were introduced to quantify the range of stress levels at which earthquakes will occur, with contributions to resistance coming from both friction and from fault geometric complexity. Correlations between fluctuations in slip and rupture velocity were linked to the local fault geometry, offering a new procedure for generating pseudo-dynamic rupture histories (Trugman and Dunham, 2014) for use in more efficient reciprocity-based ground motion simulations. Additionally, the short spatial and temporal scales over which fault strength and slip rate vary near the rupture front motivates the introduction of a highly refined mesh that tracks the rupture front (and other sharp features like wavefronts). Both static and adaptive mesh refinement were first applied to rupture dynamics problems during SCEC4 (Kozdon and Wilcox, 2014; Pelties et al., 2014; Kozdon and Dunham, 2015), and show great potential for future high-resolution modeling studies. The Dynamic Rupture Code Comparison Group has tested several codes participating against benchmark exercises that incorporate a range of features, including single and multiple planar faults, single rough faults, slip-weakening, rate-state, and thermal pressurization friction, elastic and visco-plastic off-fault behavior, complete stress drops that lead to extreme ground motion, heterogeneous initial stresses, and heterogeneous material (rock) structure. The group's goals are to make sure that when our earthquake-simulation codes simulate these types of earthquake scenarios along with the resulting simulated strong ground shaking, that the codes are operating as expected. This year's benchmarks focused on ruptures in layered and depth-dependent material structures, and ruptures on nonplanar faults with and without off-fault plasticity.

b. OpenSHA/UCERF3 Development: Kevin Milner and Thomas Jordan continue to develop OpenSHA, an open-source, Java-based platform for conducting SHA. This development transform the results of SCEC science into practical products like UCERF3. Recently, supercycles and synchronization signatures are analyzed in synthetic seismic sequences. Synchronization is a key concept in nonlinear dynamics. UCERF3 does not explicitly model supercycles, but they emerge from long runs of physics-based rupture simulators, such as the RSQSim model and the ALLCAL model. In these models, the synchronization of large events on different fault sections leads to variations in seismic energy release of ± 50% on time scales of about 200 years. Spectral analysis of a million-year RSQSim catalog shows synchronization harmonics with a fundamental period of 200 years and a corresponding depletion at longer event periods. This synchronization signature is absent in UCERF3 and randomized versions of the RSQSim catalog. Further investigation of synchronization and its time dependence using two-dimensional "recurrence plots" have been conducted to map the temporal recurrence of proximate RSQSim states. The results are used to speculate on the hazard implications of the supercycle hypothesis.

c. Accelerating dynamic rupture and wave propagation simulations: Progress has been made in accelerating dynamic rupture and wave propagation simulations using GPUs. Hercules-GPU is a CUDA-based implementation, the stiffness contributions, attenuation contributions of the BKT model, and the displacement updates are implemented entirely on the accelerator using the CUDA SDK. This GPU code was used for La Habra validation exercise on OLCF Titan and achieved a factor of about 2.5x speedup with respect to the CPU code. The GPU version of AWP-ODC is used in recent CyberShake 15.4, the first 1-Hz seismic hazard map for LA region, which saved nearly 80% of SGT calculation time. Jeremy Kozdon and his team have developed a GPU-enabled high-order discontinuous Galerkin FE code for earthquake rupture dynamics based on quadrilateral and hexahedral elements. This approach is capable of handling both adaptivity in order (known as p-adaptivity) and well as adaptivity in element size (known as h-adaptivity). The extension of the numerical approach is enabled through the use of the OCCA library, an abstraction of several offloading paradigms for fine-grained, on-node parallelism. The CPU+GPU+MPI implementation currently includes elastodynamics with slip weakening friction and has shown almost-ideal weak-scaling across 32 NVIDIA Titan Black GPUs. This implementation is being validated including adding dynamic mesh adaptivity.

d. Computational Developments of Earthquake Simulators: A form of off-fault stress relaxation, based on rate-state seismicity equations, has been developed by James Dieterich's team at UCR to resolve several problems associated with geometrically complex faults in elastic media. Slip on geometrically complex faults in elastic media produces fault interaction stresses that non-physically grow without limit. These stresses in turn suppress fault slip, break the linear slip vs. length scaling for ruptures, and result in non-convergent solutions as model resolution increases. They developed a rotationally invariant, 3D version of the stress relaxation equations based on the rate-state evolution equation. This involves calculating the inner product of 3D stress tensors with reference stress tensors (set by steady-state stability conditions), and employing the scalar results in the stress relaxation equations. This generates results similar to, but more general than, previous work that used shear and normal stresses resolved onto a reference plane for the equations. Earthquake simulators typically use the boundary element method to compute static elastic stress changes due to slip on faults. Faults can be discretized using either rectangular or triangular elements, and there was previously a widespread view that triangular elements, which can cover a fault surface without gaps, would be more accurate. However, an extensive set of quantitative tests by Barall and Tullis has demonstrated that this is not always true; there are many cases, depending on fault curvature, where rectangular elements are more accurate. Their work will help guide the development of more accurate earthquake simulation tools.

e. FD Discontinuous Mesh Implementation: Finite-difference discontinuous grid implementations suffer inherently from stability problems due to the nature of exchange of wavefield information between the fine and coarse grids. In particular, staggered grids, where analytical stability conditions are less tractable, provide a challenge. The cause of instability is likely related to down-sampling of the wavefield from the fine grid into the coarse grid, and possibly the interpolation to obtain the wave field when transferring the wave field from coarse to fine grids. The preliminary analysis by Kim Olsen and his group at SDSU suggests that stability is affected by several factors, including media properties, spatial dimension, the presence of absorbing boundaries, and anelastic attenuation.

f. SEISM Tools: SEIMS-IO is designed with highly condensed, easy-to-understand APIs for users to choose. This library simplifies the programming of parallel I/O, with an interface hiding complex low-level operations. To accommodate the generalized interface, the earlier SEISM-IO library is modified to integrate different initialization/open/write processes in MPI-IO, HDF5, PnetCDF and ADIOS. The generalized interface has been tested using the wave propagation AWP-ODC solver on the NSF TACC Stampede

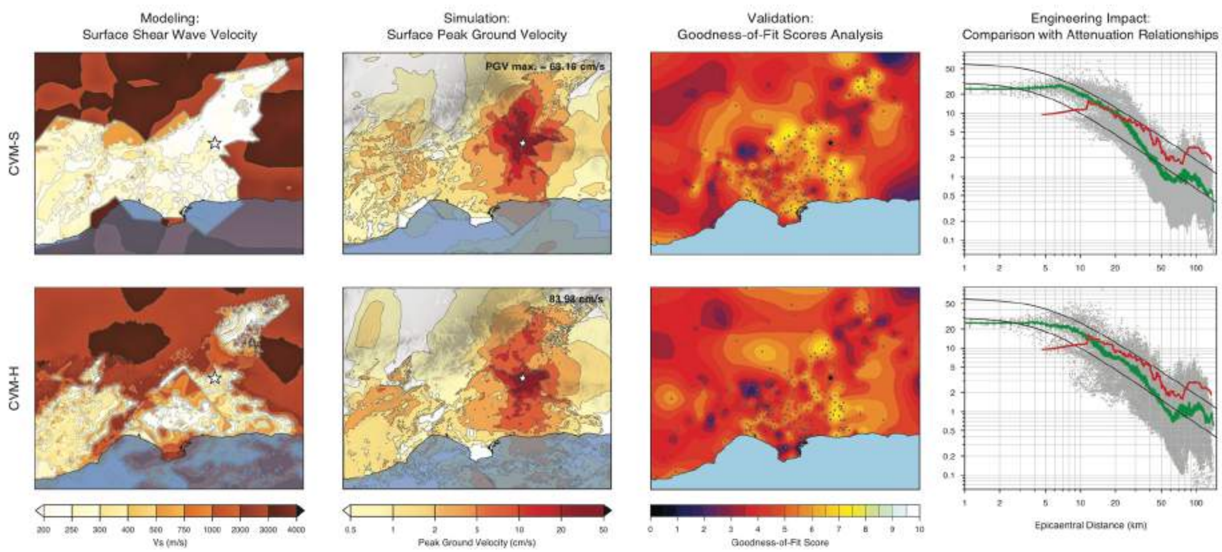


Figure 3.14. Summary results and analysis of simulations for the Mw 5.4 2008 Chino Hills earthquake using different velocity models (CVM-S and CVM-H) and showcasing the connection from geoscience modeling to engineering applications. The top row shows results corresponding to the simulation done using CVM-S, while the bottom row shows those corresponding to CVM-H. Each column from left to right shows: (1) The surface shear wave velocity for each model. 3D meshes built for these simulations consist of up to 15 billion finite elements. (2) The simulation results for the surface horizontal peak ground velocity. The star indicates the epicenter location. (3) Validation results using goodness-of-fit metrics to compare synthetics to data. In this study we used over 300 recording stations. GOF scores closer to 10 (lighter colors) indicate a better fit with the data. (4) Comparison with attenuation relationships used in engineering to estimate peak ground velocity. The red line corresponds to the actual trend from earthquake data, the two black lines indicate an upper and lower bound based on empirical relationships, and the green line shows the trend of the surface results from the simulation, which are shown as a gray cloud of points on the background. Simulations were done using Hercules by Taborda and Bielak (2013, 2014).

system, the library has been used in the latest ShakeOut simulations by Daniel Roten. Scott Callaghan et al. have optimized CyberShake workflow, which automates and manages I/O and enable remote job execution on HPC systems. The enhanced workflow execution is efficiently split across multiple HPC systems, and previous heavy I/O workload from/to HPC parallel file systems is significantly reduced to achieve optimal performance. Charles Williams and Laura Wallace have developed a workflow for using PyLith-Generated Green's Functions with the Defnode Geodetic Inversion Code. The workflow allows to perform the necessary tasks for both SSE inversions and interseismic coupling inversions in a semi-automated way.

f. Efficient Similarity Search for Continuous Waveform Data: Continuous seismic waveform data offers a wealth of information, but many events go undetected with current methods. Template matching requires prior selection of event waveforms, and alternative cross-correlation methods are extremely computationally expensive. Yoon et al. (2015) have applied similarity search techniques developed by computational scientists to massive earthquake data sets for the first time. The method distills waveforms into sparse, binary fingerprints, enabling a hierarchical search across these fingerprints. In most cases, the method has detection capabilities comparable to cross-correlation, but with vastly smaller computational cost. This new approach will enable study of data sets that are simply impossible to analyze with current methods, opening a new era of seismic monitoring.

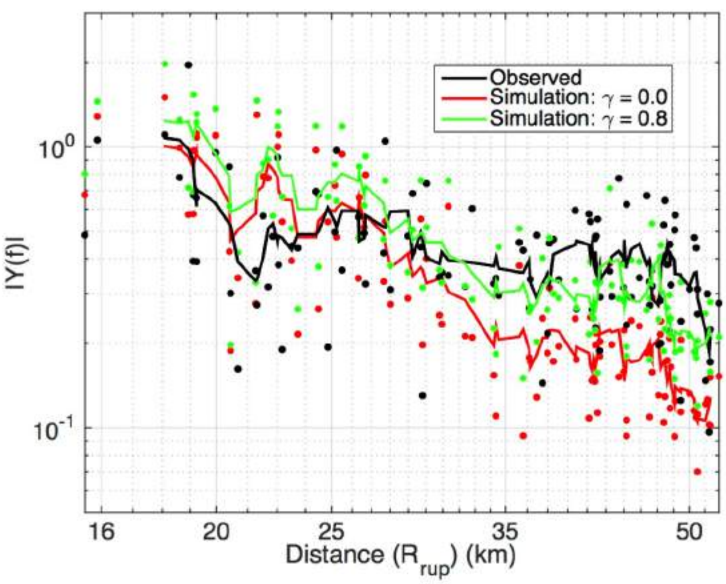


Figure 3.15. Fourier amplitude as a function of distance centered at 2.25 Hz using 100+ strong motion stations for the 2008 Mw5.4 Chino Hills, CA, earthquake. Dots depict values for individual stations and lines depict a 5-point moving average. Rrup indicates the closest distance to the ruptured surface of the fault plane. From Withers et al., 2015

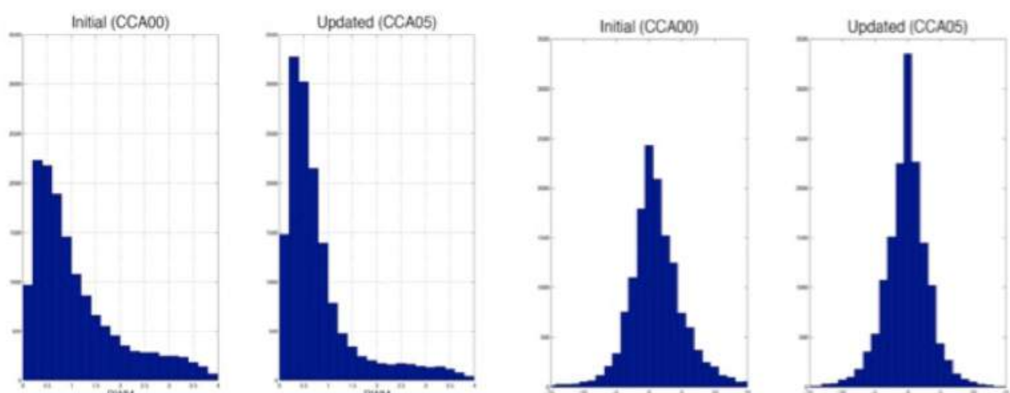
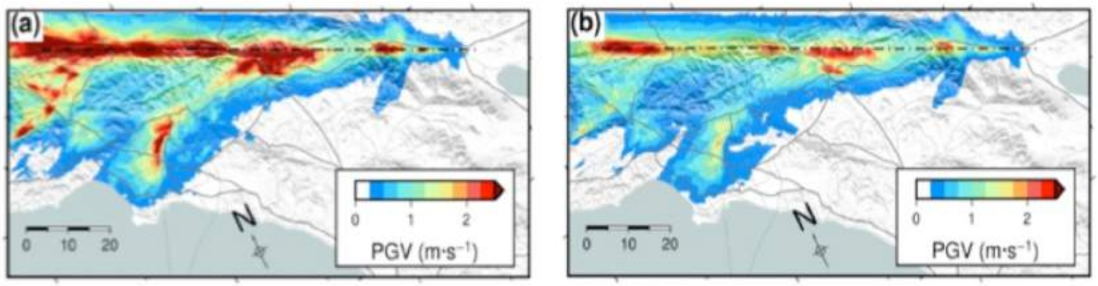


Figure 3.16. (left) The histograms of RWMs for ambient noise Green's functions for the initial model (CCA00) and the updated model (CCA05). (right) The histograms of frequency dependent group delay measurements (dtg) for ambient noise Green's functions for the initial model (CCA00) and the updated model (CCA05).



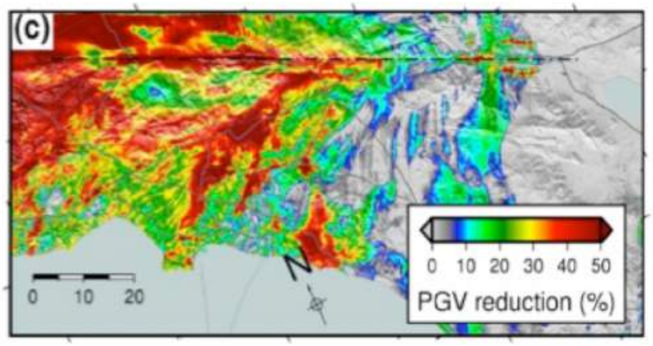


Figure 3.17. Peak ground velocities for the Los Angeles region obtained from dynamic simulations of the M7.8 earthquake rupturing the southern San Andreas fault from SE to NW. Simulation were done on OLCF Titan for (a) a visco-elastic medium and (b) an elasto-plastic (nonlinear) medium. As shown in the ration map(c), the reduction in peak ground velocity by nonlinearity is up to 50% for the ShakeOut scenario (Roten et al., 2014, 2015).

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, including strong ground motion prediction, earthquake hazards assessment, and fault systems analysis. These efforts include the development of Community Velocity Models (CVM's) and Community Fault Models (CFM's), which together comprise a USR. In partnership with other working groups in SCEC, the USR Focus Area also helps support the evaluation and improvement of these models through ground motions simulations, 3D waveform tomography, earthquake relocations, and fault systems modeling. This past year's accomplishments include:

- Refinement of the SCEC Community Fault Model (CFM) for southern California based on relocated seismicity catalogs and detailed fault traces in the USGS Quaternary Fault and Fold database. The latest updates include significant refinement to fault representations in the Peninsular Ranges, Mohave region, Santa Barbara Channel, and Western Transverse Ranges. These refinements include the faults systems that are the focus of the SCEC Special Fault Study Areas, and will be released in a forthcoming new model version.
- Completion of the first fully-evaluated Statewide Community Fault Model (SCFM v. 3.0), which involved peer review of the northern California fault representations. These faults were combined with the latest iteration of the southern California Fault model (CFM 5.0) to comprise the new statewide model.
- Development of new sets of regularly gridded representations for the fault included in the southern California CFM, to facilitate their use in earthquake simulators and other modeling applications.
- Release of a new version of the SCEC southern California USR, which includes the aforementioned CFM's and an updated version of the SCEC Community Velocity Model (CVM-H 15.1.0).
- Development of a first iteration Central California USR, including new representations of the Central Valley and Santa Maria basin structures that are compatible with fault representations in the SCEC SCFM. This new model is intended to support SCEC's Central California Seismic Project (CCSP), which will use these new structural representations to facilitate 3D waveform inversion studies.

a. Community Fault Models (CFM's): SCEC has engaged in a major effort to refine systematically the Community Fault Model (CFM) using detailed fault traces from the USGS Quaternary Fault & Fold Database, precisely relocated earthquake hypocenters, and new focal mechanism catalogs. This results in fault representations that are more precise, and often more highly segmented than in previous model versions (Figure 3.18). The first new model version incorporating these updates (CFM 5.0) was released at the 2014 Annual meeting, and this past year further refinements have been made with an emphasis on the Peninsular Ranges, Santa Barbara Channel, Transverse Ranges, and Mojave Desert regions. As part of this process, we have also developed detailed sets of fault representations in the Ventura Basin and San Gorgonio Pass regions, which are the focus of the SCEC Special fault Study Areas (SFSA's). These new updates will be made available in a forthcoming model release.

In addition, we facilitated a formal evaluation of the northern California fault model, which together with CFM 5.0 comprises the SCEC Statewide Community Fault Model (SCFM). The northern California models consists of more than 150 fault representations, many of which include sets of alternative representations (Figure 3.19). To facilitate the review, we provided the fault representations along with a spreadsheet with fault metadata to the evaluation group, which is comprised of scientists from SCEC, the USGS, and CGS. Evaluators were instructed to use SCEC VDO software to view and assess the fault representations. To coordinate this activity, we held a kick-off evaluation meeting at the USGS in Menlo Park (May 2015). Participants provided rankings for alternative fault representations, which are used to define the set of faults that define the preferred model version (SCFM v. 3.0).

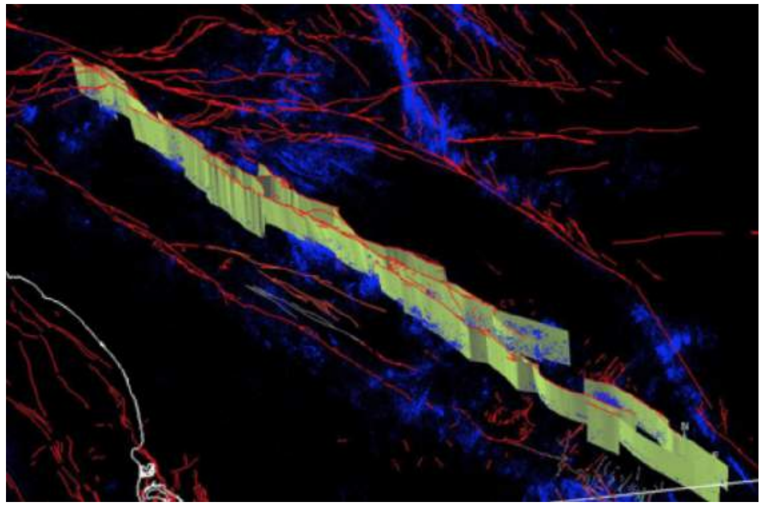


Figure 3.18. Perspective view of the San Jacinto Fault system in CFM 5.0. The San Jacinto and many other fault representations in the model have been made more compatible with detailed surface traces from the USGS Quaternary Fault & Fold Database (red traces) and relocated seismicity (blue) (Lin et al., 2007; Yang et al., 2012; Hauksson et al., 2012). As a result, these fault representations are more precise and – as shown here for the San Jacinto Fault – are more highly segmented.

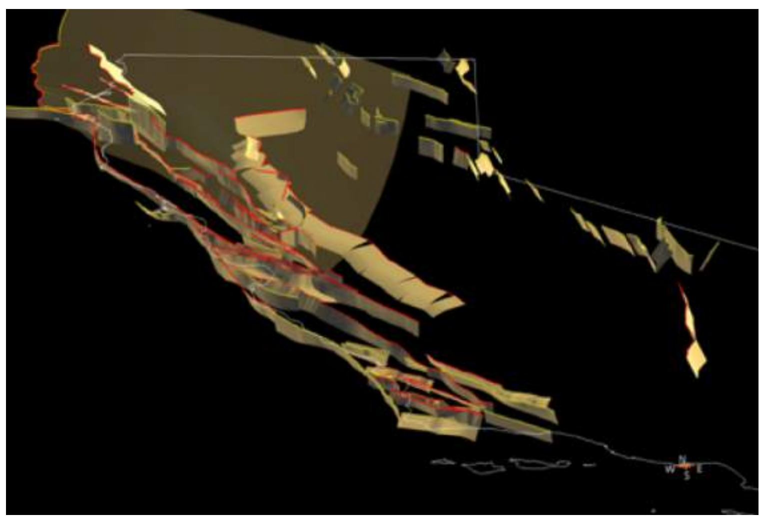


Figure 3.19. Perspective view of the SCEC northern California fault model, which together with the CFM comprises the Statewide Community Fault Model (SCFM). Fault traces in red have one or more alternative representations.

T-surfaces (Tsurfs) were chosen as the native format for CFM and SCFM faults because they provide for more accurate representations of complex, curviplanar surfaces that vary their geometries in depth or along strike. However, many fault system modeling tools, including most earthquake simulators, require either rectangular dislocations or more regularly gridded Tsurfs. Thus, through a coordinated effort involving several SCEC investigators we have developed sets of regularly meshed tsurfs. As a result of this process, we also developed a set of refined fault map traces.

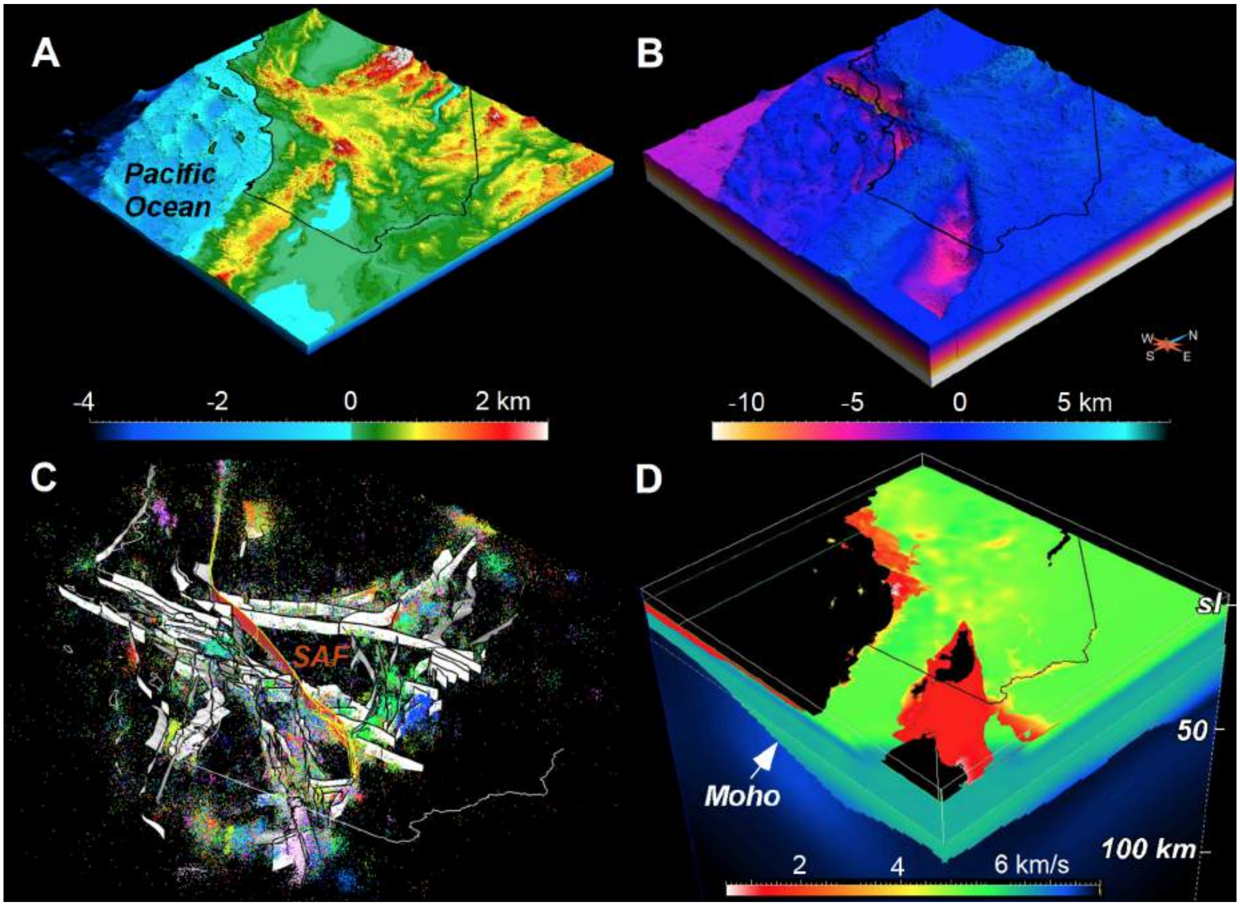


Figure 3.20. Perspective view of components of the Unified Structural Representation (USR). A) Topography and bathymetry; B) top basement surface; C) Community Fault Model (CFM) (Plesch et al., 2007); and D) USR showing Vp. SAF is the San Andreas Fault. Topographic and bathymetric surfaces are derived from USGS 3″ digital elevation model data and a National Oceanic and Atmospheric Administration 30″ grid (TerrainBase).

b. Building Unified Structural Representations (USR's): The concept of a Unified Structural Representation (USR) has been pioneered by the SCEC Community to support a wide range of earthquake science and hazard assessment efforts. The SCEC USR for southern California is a three-dimensional description of crust and upper mantle structure consisting of interrelated Community Fault (CFM) and Velocity (CVM) models (Figure 3.20). The development of these models has been inspired by recent advances in numerical methods and parallel computing technology that have enabled large-scale 3D simulations of seismic wavefields in realistic earth models. SCEC released its first formal USR version this year (Shaw et al., 2015), consisting of CFM 5.0 and CVM-H 15.1.0. The CVM component of this model includes a series of updates to the basin representations in the model, which are compatible with the locations and displacements of major faults in the CFM. The USR also includes a Geotechnical layer (GTL) that describes near surface velocities, and has been iterated using 3D adjoint waveform tomography. This model, as well as alternative velocity representations supported by SCEC, are actively being tested by comparison of observed and synthetic waveforms for earthquakes in southern California. Another related, current effort is focused on the implementation of statistical representations of small-scale velocity heterogeneity in these models, which offers the prospect of accurately simulating seismic waveforms to higher frequencies.

As a natural extension of these efforts, we also began development of a new USR for Central California in support of the newly established Central California Seismic Project (CCSP). The CCSP study area extends from the Transverse Ranges in southern California north to the Santa Cruz Mountains in the Pacific Coast Ranges, and from the Pacific plate east across the Great Valley and Sierra Nevada Ranges. This area effectively lies north of the current SCEC USR for southern California. Thus, development of the central California USR involved building a new model of the Central Valley, including the San Joaquin and southernmost Sacramento Valley basins. These basin structures were constrained using tens of thousands of direct velocity measurements from wells and seismic surveys, and incorporate the latest fault representations from the southern and northern California Community fault models. In the coming months, these new fault and velocity representations will be used to facilitate 3D waveform tomographic inversions that will help to improve our understanding of regional velocity structure and reduce uncertainties due to path effects in calculated strong ground motions.

6. Fault and Rupture Mechanics (FARM)

The Fault and Rupture Mechanics (FARM) interdisciplinary group focuses on understanding earthquake rupture mechanics through a combination of theoretical modeling, laboratory experiments and field observations. The results from research in FARM are closely linked to efforts in the SDOT, UCERF, and CSM programs (among others) in SCEC4. Improvements in computational capabilities are making it possible to more properly 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 earthquake deformation processes during quasi-static and dynamic conditions in both laboratory and natural fault samples. Progress in this area remains diverse and projects are numerous; however, several themes remain at the forefront as we look forward to SCEC5.

a. Heterogeneous Fault Stress and Structure: Considerable effort has remained focused on how heterogeneous fault stress and fault structure (e.g., roughness, larger scale fault segmentation and geology) influence seismicity and rupture propagation. Several studies have explored the role of fault roughness on earthquake processes. For example, new suites of calculations provide further insight into how fault roughness on non-planar faults actually promotes supershear rupture (Figure 3.21; Bruhat et al., 2015), an effect opposite of conventional wisdom. The role of local variations in fault orientation (i.e. fault roughness) has also been exploited to constrain the width of surface creep zones of the Southern San Andreas fault (Fialko et al.); application of coulomb plasticity (accounting for variations in normal stress arising from fault strike) provides a good explanation for the variations in the creeping width determined from geodetic studies. Further, Fialko et al. note that distributed interseismic creep needs to be accounted for to prevent systematic bias in paleoseismic slip rate estimates, especially where coseismic slip is distributed near the surface (owing to low normal stress and/or stable frictional properties). These studies highlight the need for improved geologic constraints on processes that promote strain localization within evolving faults - a focus of structural studies of exhumed faults (Figure 3.22; Shervais and Kirkpatrick).

The level of background stress, stress heterogeneity, and heterogeneity of fault zone properties influence both rupture propagation and the distribution of aftershocks. Shi

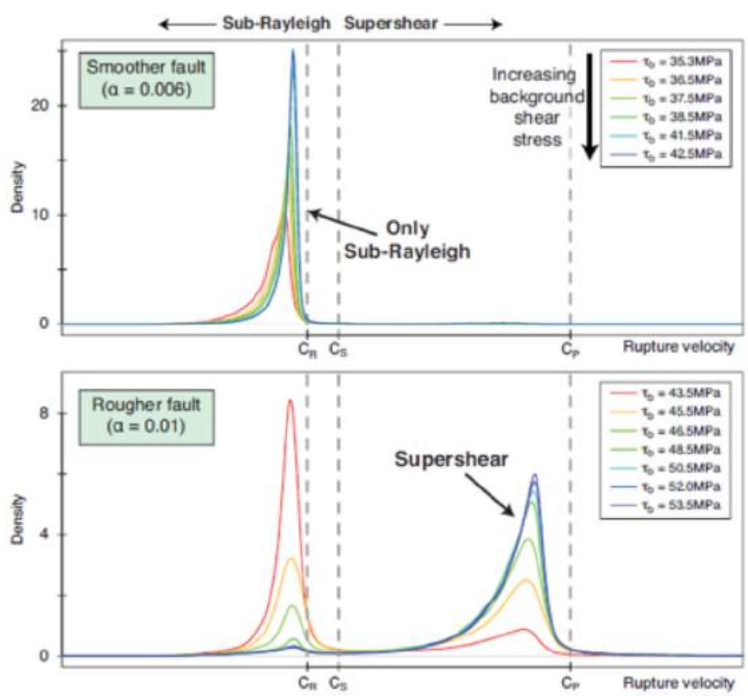


Figure 3.21. Bruhat et al. (2015) examined an ensemble of over 1000 dynamic rupture simulations on fractally rough faults with strong rate-weakening friction to identify conditions for supershear rupture speed. In contrast to prior thinking that supershear was favored on smooth, straight fault segments, supershear propagation was found to be most common on the roughest faults. Probability density function of rupture velocity from ensemble dynamic rupture simulations on non-planar, rough faults. (top) On a smooth fault, rupture velocities remain sub-Rayleigh, even for pule-like ruptures at high background stresses. (bottom) On a rougher fault, supershear ruptures appear, particularly at high background stress.

and Day investigate the role of fault geometry and initial stress on the likelihood of through-going ruptures across the San Gorgonio Pass Section of the San Andreas fault (Figure 3.23). They developed dynamic rupture simulations integrating information from SCEC CFM and CSM and found that the three different stress models available in the SCEC CSM lead to different answers regarding ruptures across the SGP, highlighting the need for reliable and self-consistent stress inputs in fault systems with complex geometry. The role of fault heterogeneity has also been explored in earthquake cycle models that include realistic frictional properties (Jiang and Lapusta). Models with different large-scale fault properties and the same heterogeneity produce microseismicity with different b-values in the G-R relation, reflecting variations in stress gradient and fault coupling. Such studies illustrate how observations of microseismicity can be used to constrain the frictional properties of faults, which can in turn be included into integrative earthquake cycle and rupture models and relationships between seismicity and geodetic data.

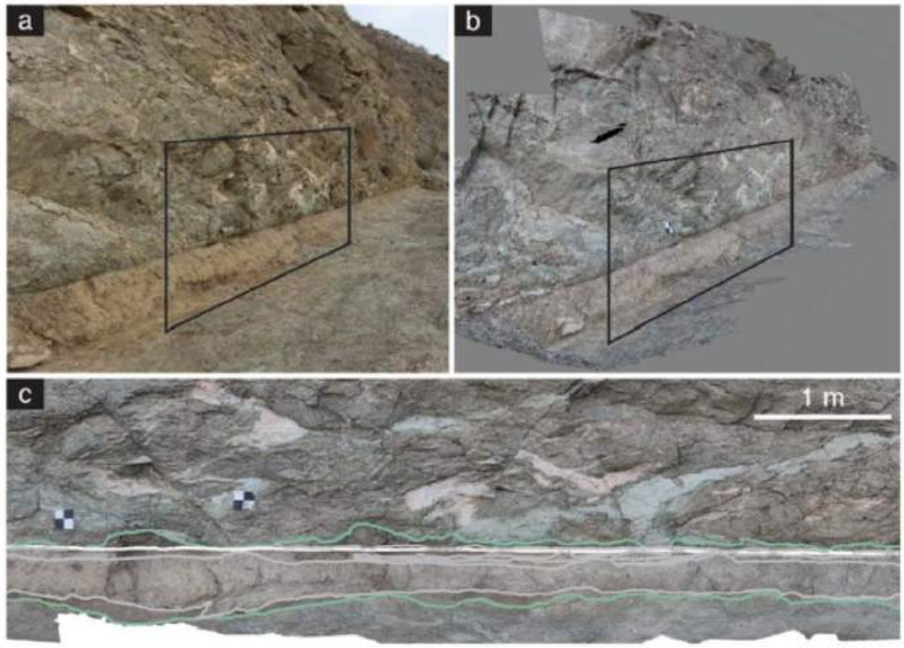


Figure 3.22. Kirkpatrick and Shervais mapped the internal structure of the Boyd fault, Southern California, using the structure-from motion methodology, to establish the dimension of contact asperities and how the fault roughness evolves with displacement. Example of the field workflow: a.) Photograph of an exposure of the Boyd fault. Around 150 photos similar to this were used to construct the outcrop model. b.) Model generated with Agisoft's PhotoscanPro shown from the same perspective as a. Boxes in a and b show the extent of c. c.) Rectified image exported from PhotoscanPro after the model was rotated to view the exposure down the slip vector. Lines show traces mapped in the field that were used to calculate roughness. White lines are the edges of the principal slip zone and green lines define the extent of the fault core.

b. Dynamic weakening and fault slip at the base of the seismogenic zone: Understanding rupture processes at the base of the seismogenic zone remains critical for evaluating the potential for large events in Southern California. New modeling studies on this topic focus on how realistic depth-dependent fault properties affect the spatio-temporal complexity of earthquake slip and the variability of arresting depth (Figure 3.24; Jiang and Lapusta). With reasonable depth-dependent parameters, thermal pressurization (TP) allows large earthquakes to penetrate deeper into creeping fault extensions, even when the shear zone width increases with depth below the seismogenic layer. An issue that remains potentially problematic is that incorporation of TP and flash heating (FH) into such models generally leads to rapid and near-total (and perhaps unrealistic) coseismic stress drops. Future work will be directed towards identifying fault properties that allow for reasonable stress drops for large events. Ma and colleagues hypothesize that dynamic compaction of fault gouge may provide a solution to this issue. They show that large dynamic stresses during rupture propagation cause the gouge layer to compact ahead of the rupture front, leading to rapidly elevated pore pressure in the effectively undrained fault zone - and significant dynamic weakening of the principal fault surface. Compared to other dynamic weakening mechanisms such as flash heating and thermal pressurization, this mechanism does not require slip to initiate. After the passing of the rupture front, dilatancy of undrained fault gouge reduces the pore pressure and restrengthens the fault, promoting a more pulse-like rupture. Thus dynamic gouge compaction and dilatancy provides a simple mechanical explanation for weak mature faults and pulse-like earthquake ruptures on these faults.

Analysis of dynamic weakening mechanisms also remains a focus of experimental and geological studies. New laboratory experiments have been performed to characterize the processes responsible for flash weakening in gouge (Griffiths and Prakash; studying dynamic weakening in samples from the SAFOD drill hole) and thermal pressurization (Tullis; who developed protocols to constrain competing effects of thermal and hydraulic diffusivity by controlling the permeability of the experimental samples). Theoretical studies provide new insights into the physical processes responsible for dynamic weakening, and rationale for their inclusion into earthquake cycle and rupture models. The role of thermally-activated contact processes have now been included into STZ models of gouge deformation (Carlson and colleagues); these PIs have also combined the STZ theory with fracture mechanics to model grain fragmentation. These analyses show that grain splitting dominates at small

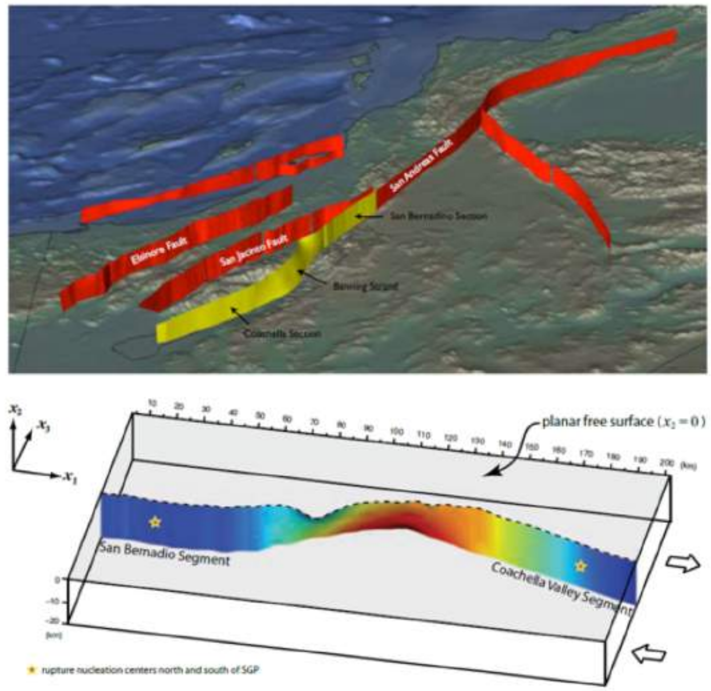


Figure 3.23. Shi and Day developed dynamic rupture simulations to investigate the role of initial stresses and fault geometry on the likelihood of a San Andreas rupture through the San Gorgonio Pass. The study integrates fault geometry from SCEC CFM-v4 (top) and initial stress constraints from the SCEC CSM (bottom). The results highlight the critical sensitivity of dynamic rupture to initial stress assumptions in geometrically complex faults.

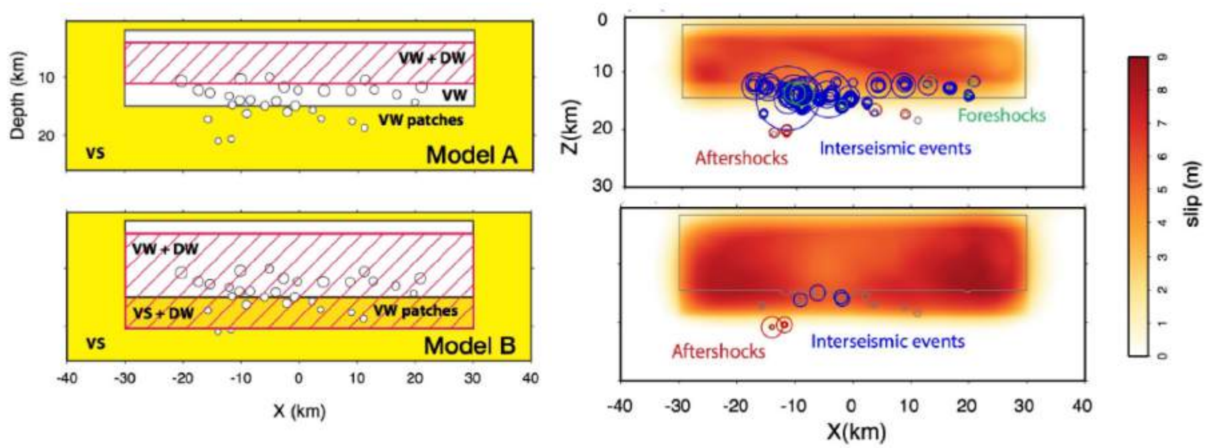


Figure 3.24. Jiang and Lapusta studied the effect of the depth limit of dynamic weakening on microseismicity patterns over several cycles. They compared fault models with down-dip limit of dynamic weakening being shallower (top row, Model A) and deeper (bottom row, Model B) than the transition between velocity-weakening (VW) and velocity-strengthening (VS). (Left) Schematic illustrations of the two models. Regions with the VW and VS low-rate properties are shown in white and yellow, respectively. Regions with enhanced dynamic weakening are shown as red hashed rectangles. Nucleation-promoting spots with altered friction properties are shown as open grey circles. (Right) The resulting microseismicity is illustrated as circles using the circular crack model with 3 MPa stress drop. Colors indicate typical final slip in a large event. The intensity and locations of microseismicity differ in the two models due to different stress distribution with depth and its evolution with time.

shear strains and grain abrasion dominates at larger displacements. A feedback between strain localization and grain fragmentation provides an explanation for the formation of a thin gouge layer with a characteristic particle size several orders of magnitude smaller than those outside the shear band. Further observations on the role of dynamic weakening on natural faults are being compiled using novel new techniques to date and constrain peak temperatures during past earthquakes on exposed faults in Mecca Hills (Evans).

c. Tectonic tremor and fault rheology: The observation (or lack thereof) of tectonic tremor provides a potentially powerful constraint on the mechanical properties of faults deep in the lower crust. Ampuero et al. developed a novel phase coherence method to identify localized sources of tremor-like activity (continuous radiation over extended durations) and systematically applied it to seismic waveforms to search for precursory tremor in the 5 minutes preceding 10,000 earthquakes in Southern California. They found no evidence for fore-tremor activity, but several un-catalogued foreshocks in events outside the SCSN footprint. Similarly, Peng et al. continued a systematic search for tectonic tremors in California. They found no additional triggered tremor beneath the San Gabriel Mountain in Southern California, suggesting that near-lithostatic fluid pressure is necessary, but not sufficient, for tremor to occur. They found no clear evidence of repeated LFE activity on the San Jacinto fault (SJF) triggered by the 2002 Denali Fault earthquake, or during other times where ambient tremors were suggested. Thus, the tremor along the SJF is rare and the source depth is not well constrained. Ghosh improved resolution of Parkfield tremor with data from a small-aperture array installed near Cholame; the improved resolution reveals that migrating swarms are the general mode of tremor occurrence in this area. Ghosh et al. also show delayed acceleration of tremor activity (lasting a few days) after the 2014 M6 South Napa earthquake. This observation can provide constraints on models of dynamic triggering of tremor and slow slip. Segall and colleagues modeled dynamic rupture triggering by slow slip events, focusing on how the spatial dependence of effective normal stress and slip weakening distance (dc) influence this behavior. They analyze how far a stable creeping zone can penetrate into a velocity weakening region before going unstable; for the aging law this distance is close to the size of the longest fault that never generates dynamic slip, but for the slip law it can be considerably greater. New experimental programs on viscous creep behavior at conditions appropriate for the base of the seismogenic zone also provide new insights into the possible mechanisms responsible for strain localization and slow earthquake instability (Sammis et al.).

7. Southern San Andreas Fault Evaluation (SoSAFE)

The SoSAFE special project focuses on geologic slip rate studies, paleoseismic investigations, and geodetic and modeling advances along the San Andreas and San Jacinto Fault systems. Recent accomplishments within this group include new data and analysis of the San Gorgonio Pass Special Fault Study Area, a workshop on geochronological methods used in the SoSAFE and Earthquake Geology community, and continued examination of the timing and size of earthquakes along the major plate boundary faults of southern California.

a. San Gorgonio Pass Special Fault Study Area: Recent work by several independent geologic slip rate investigators have called into question slip models developed in UCERF2 which held that slip along the Coachella strand of the San Andreas fault was largely transferred westward onto the San Gorgonio Pass thrust and northward into the Eastern California Shear Zone, with no slip continuing northwest through other SAF strands in the San

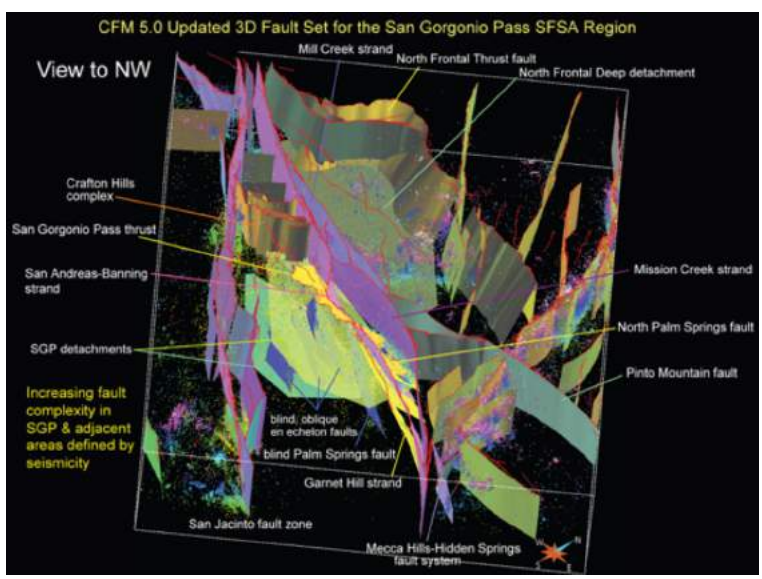


Figure 3.25. Key fault surfaces in CFM Version 5.0 in San Gorgonio Pass (Nicholson et al., 2015)

Gorgonio Mountains. At the eastern end of the Indio Hills, on-going work by Blisniuk et al. (2014) is consistent with a previous study by Behr et al. (2010) that indicates ~20 mm/yr is carried by the Mission Creek strand and that this rate has been constant since ~90ka. New studies were initiated along the northern strands of the San Andreas fault through the San Bernardino Mountains, where offset of Quaternary gravels on the Mission Creek and Garnet Peak strands indicate some slip continues to these latitudes, ultimately transferring slip onto the Mill Creek and San Bernardino strands of the San Andreas (Kendrick et al., 2015; Oskin et al. 2015). These results are compatible with strain observed in new geodetic results across the San Bernardino Mountains (McGill et al., 2015). To the south, Holocene rates along both ends of the Banning strand indicate slip remains low (2-6 mm/yr) along its entire length (Gold et al., 2015; Scharer et al., 2014). Within the Pass itself, studies by Yule and Heermance report Holocene dip slip rates on the San Gorgonio Pass thrust fault zone of 4-6 mm/yr, consistent with a paleoearthquake record that indicates ruptures are less frequent in the Pass than on the main San Andreas fault strands to the northwest and southeast (Yule et al., 2014). The emerging pattern suggests slip is accommodated along all of the mapped strands of the SAF.

Examination of seismicity patterns and new geophysical data contributed to revised understanding of each of SAF strands within the latest CFM. Significant revisions include the Mission Creek, Banning, and Garnet Hill fault surfaces, which are steeply north dipping, and the San Gorgonio Pass thrust as a low angle oblique fault (Nicholson et al., 2014). Investigation of historical seismicity underneath the Pass reveals patterns of stress drop that are spatially clustered; large stress drops are concentrated in deep earthquakes below the high peaks of SGP (Goebel et al., 2015). Given the new slip rate, seismicity, and fault geometries, examination of the potential for thoroughgoing rupture on the San

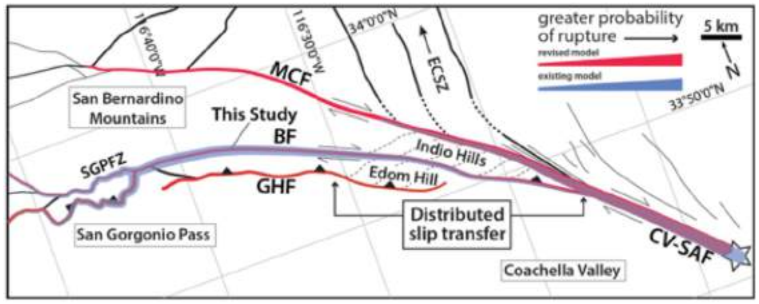


Figure 3.26. New models of slip transfer from the southernmost San Andreas Fault onto the Mission Creek (MCF), Banning (BF) and Garnet Hill (GHF) strands based on slip rate studies stemming from the San Gorgonio Pass SFSA, from Gold et al. (2015).

Figure 3.27. Paleochannels excavated for slip rate study at the Quincy site by Onderdonk et al. (2015) reveal variable strain release rates on the San Jacinto Fault over the last 2000 years.

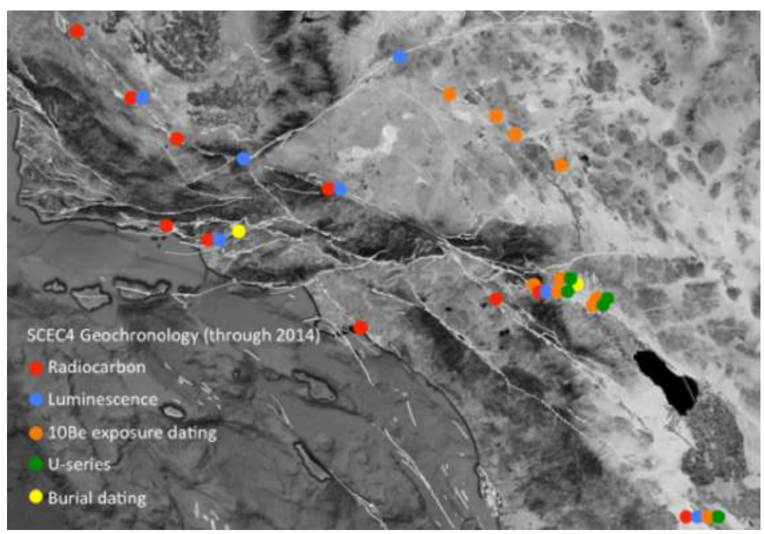


Figure 3.28. Summary of geochronological investigations and methods used in SCEC4 (Scharer et al., 2014).

Gorgonio Pass thrust using dynamic rupture models is now focused on the influence of stress heterogeneities using different regional stress models (Shi and Day, 2014) and on the details of fault geometry (Oglesby et al. 2014).

b. Paleoseismic studies on the San Andreas and San Jacinto Faults: Paleoearthquake investigations at the Elizabeth Lake site were conducted to test the frequency of thoroughgoing rupture on the Mojave section of the San Andreas fault. The Elizabeth Lake record covers the last 800 years and includes 4-5 earthquakes; when compared to the rupture history proposed by Scharer et al. (2015) from the neighboring Frazier Mountain and Pallett Creek sites, it is consistent with one 300 km long rupture similar to the 1857 earthquake in the last 800 years (Bemis et al., 2015). On the San Jacinto fault, Onderdonk et al. (2015) published a new slip rate and slip-per-event data for two time periods on the Claremont strand. They show that while the average slip rate in the last 1500-2000 years was 12-18 mm/yr, rates were faster (21-30 mm/yr) for the last 500 years, the result of a short period of larger than average slip during more frequent than average earthquakes. Fault rupture models on the San Jacinto fault were examined with new data from the Mystic Lake site on the Claremont strand, where Onderdonk et al. (2014) show evidence of 11-12 ground-rupturing earthquakes in the last 2000 years at the Mystic Lake site. New dating of these events correlates less than half of the Mystic Lake events with earthquakes at the neighboring Hog Lake site (Rockwell et al., 2015), indicating some, but not all, San Jacinto ruptures may rupture the 4 km step onto to the Clark fault (Onderdonk et al., 2014). In the Salton Trough, Rockwell and Weldon are developing novel approaches develop a chronology of the lake levels of Lake Cahuilla using stable isotope ratios from gastropod shells and dating of in place stumps buried by lake sediment that will be used to more precisely correlate paleoearthquakes on the San Jacinto, San Andreas, and Imperial faults. An important new constraint from this work is the date of the last Lake highstand, now restricted to about 1720 to 1726 A.D. Paleoearthquake records from several sites in the Salton Trough indicate the most recent event occurred during a lake highstand, indicating the most recent event on the southernmost San Andreas fault occurred several decades later than previously estimated.

8. 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. This past year's accomplishments include:

- Continued development of the Community Stress Model (CSM) including the development of geodynamic model estimates of crustal stress state.
- Development of deformation models of the southern California crust that examine the extent to which deformation is accommodated by slip on faults versus distributed, plastic deformation off of the main faults.
- Contributions of model estimates of fault slip rates in the Ventura Special Fault Study area.
- Shear wave splitting inferences of mantle anisotropy across the San Andreas Fault.

a. Community Stress Model: SCEC4 has committed to the development of the Community Stress Model (CSM) to provide the SCEC community with better constraints on the stress field and provide a means to formally test physical connections between observations and stress models. A web site has been developed where the community can find information about the CSM, join the mailing list, view and download many of the submitted models, view comparisons between submitted models, and obtain information about how to submit models and data (http://sceczero.usc.edu/projects/CSM). A number of crustal models derived from focal mechanism and geodetic data are currently available, and several geodynamic models are now being developed. Observations needed to contain and or validate the stress models are either available on the web site or are currently being compiled. This includes borehole measurements from the World Stress Map, industry borehole data, and compilations of seismic anisotropy.

Becker and Parsons began their effort to impose mantle tractions from global mantle circulation computations with regional resolution of ~20 km on a California-scale crustal model with lateral heterogeneities and ~5 km resolution. The goal is to understand the effects of heterogeneous rheology on vertical force transmission and the likely background stress state in southern California. Preliminary results suggest that the topographic and crustal contribution to the total differential stress field are dominant and mantle contributions are minor.

Luttrell, Smith-Konter and Sandwell have investigated three different models for the CSM, each estimating a different component of stress due to a different set of physical processes with a different set of physical assumptions acting over different spatial and temporal scales. They estimate the minimum differential stress magnitude throughout southern California based on a force balance analysis between the stress state indicated by topography and gravity data and that observed in focal mechanism data. They estimate the stress field across southern California must have a differential stress magnitude of at least 60 MPa at seismogentic depth in order to maintain the stress orientation inferred from focal mechanism observations in the presence of the observed rugged topography. Using a simple homogeneous driving stress field, calculated stress due to rugged topography, and models of stress accumulation rate due to locked fault segments throughout southern California, they have identified the fault loading time on each modeled segment that best brings the simple forward model in line with the stress orientation indicated by focal mechanisms. Along the main San Andreas fault segments, this loading time is estimated to be ~4000 years, an order of magnitude larger than either the time since last rupture or the expected recurrence interval, possibly indicating incomplete crustal stress release over the timescale of a single earthquake cycle.

b. Deformation Models: Liz Hearn is developing a finite element (FE) deformation model of the southern California lithosphere to estimate stresses and stressing rates for the SCEC Community Stress Model, to reconcile geological and geodetic slip rates, and better understand how strain is accommodated away from known, major faults. Initial calculations have made it clear that plasticity and an alternative to the “split node” technique for modeling stress-driven slip along faults are required. These features have been implemented, and are being evaluated with test models.

Fialko and Lindsey are investigating the spatial pattern of surface creep and off-fault deformation along the southern segment of the San Andreas fault using a combination of multiple interferometric synthetic aperture radar viewing geometries, survey-mode GPS occupations of a dense array crossing the fault, and numerical models. The data reveal pervasive shallow creep along the southernmost 50 km of the fault. Creep is localized on a well-defined fault trace only in the Mecca Hills and Durmid Hill areas, while elsewhere creep appears to be distributed over a 1–2 km wide zone surrounding the fault. The degree of strain localization is correlated with variations in the local fault strike. Using a two-dimensional boundary element model, Fialko and Lindsey show that stresses resulting from slip on a curved fault can promote or inhibit inelastic failure within the fault zone in a pattern matching the observations. The occurrence of shallow, localized interseismic fault creep within mature fault zones may thus be partly controlled by the local fault geometry and normal stress, with implications for models of fault zone evolution, shallow coseismic slip deficit, and geologic estimates of long-term slip rates.

c. Shear Wave Splitting: Miller and Becker are working to collect disparate anisotropy data to jointly integrate them into a 3D model of anisotropy for the southern California lithosphere. SKS splitting measurements across the San Andreas fault do not show a strong signature associated with a deep extension of San Andreas fault shear into the mantle. The "fast azimuth" of SKS splits across the San Andreas fault does not show a clear deviation in orientation from the broad-wavelength mantle flow

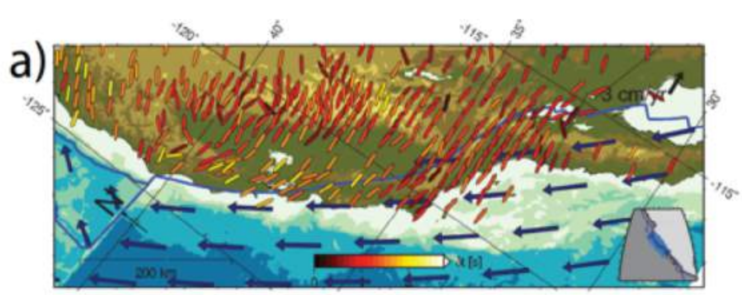


Figure 3.29. Shear wave splitting results for the San Andreas fault from Miller and Becker. SKS splits are station-averaged and shown with constant length sticks, aligned with the “fast azimuth” and colored by delay time (see color bar, yellow colors corresponding to ~2 s). Blue vectors are platemotions from Argus et al. (2011) in top plate fixed reference frames. Oblique Mercator projections aligned as indicated in the small inset overview maps. Blue lines are plate boundaries from Bird (2003).

alignment. This is in contrast to the Alpine fault in New Zealand, for example, which does show a clear rotation of the SKS fast direction into alignment with the orientation of the Alpine fault. The tentative conclusion is that mantle flow does not localize in the mantle under the San Andreas fault.

c. Ventura Special Fault Study Area: Marshall investigated mechanical boundary element models of slip rates across faults in the Ventura Basin/Western Transverse Range region. Large coseismic offsets have been identified in the geologic record near the Ventura fault and the associated Ventura Avenue anticline, implying a local source for ~M8 earthquakes in the past. Such large magnitude events are difficult to reconcile with the previous SCEC Community Fault Model (CFM) v4.0 discontinuous fault geometry. Recent work by Hubbard et al. [2014] provides evidence for a previously unrecognized ~80 km long and continuous fault surface extending from the San Cayetano fault through the Ventura fault and ~30 km offshore. Because of different subsurface interpretations of the fault geometry at depth [e.g. Hubbard et al., 2014; Kammerling et al., 2003], two potential Ventura fault geometries were tested by Marshall et al. Both models share the same surface trace but differ in that the Hubbard et al. [2014] or "Ramp" model contains a nearly horizontal ramp section at depth. The Kammerling et al. [2003] representation (or "No Ramp" model) utilizes a constant dip angle and merges with the Red Mountain fault at a depth of 10 km. They find that the constant dip, or "No Ramp" model, fits the geologic slip rate data best, however the differences between the slip rates from the two sets of models are small.

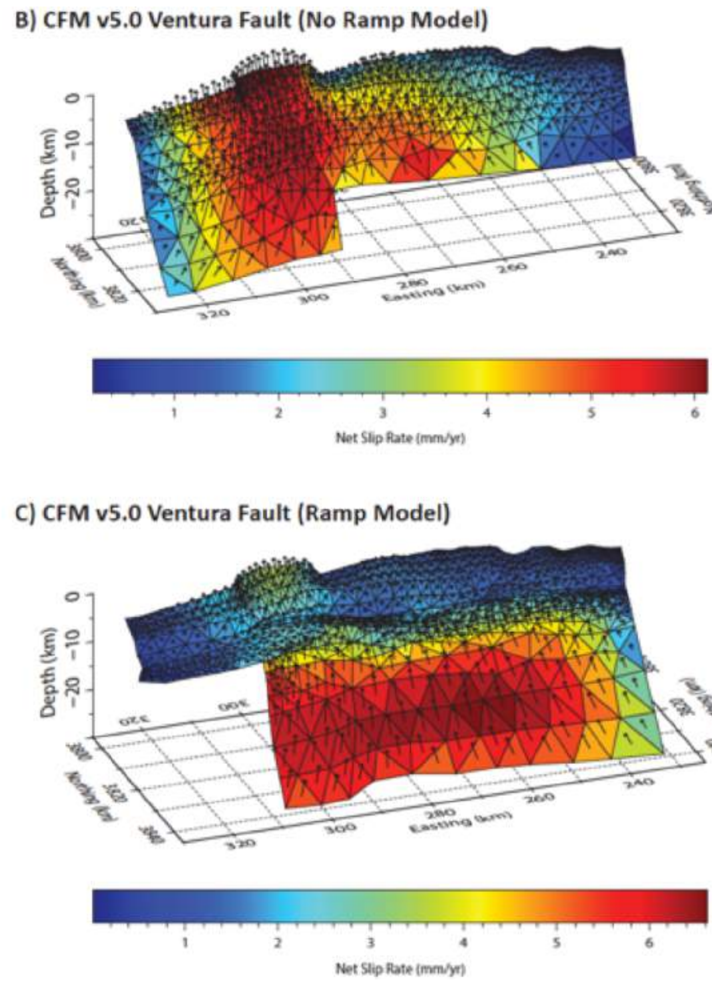


Figure 3.30. Mechanical model-predicted three dimensional slip distributions on the Ventura fault by Marshall et al. A) Not shown. B) The CFM v5.0 no ramp model. C) The CFM v5.0 ramp model.

Johnson, Hammond, and Bur-

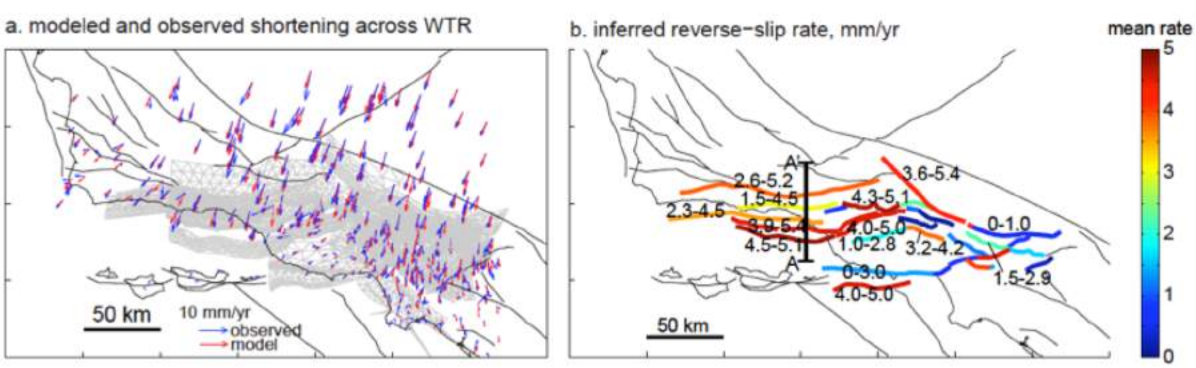


Figure 3.31. Results of inverting geodetic velocity field for fault slip rates in the Western Transverse Ranges by Johnson, Hammond and Burgette. a. Modeled and observed shortening rates across the region. b. Inferred reverse-slip rates on faults. Model mean and 99% confidence limit of reverse sense of slip rate is shown.

gette have incorporated existing and newly acquired geodetic data from the western Transverse Ranges into a regional kinematic model of present-day deformation rates across the Ventura Basin. They use a kinematic method in which a long-term horizontal and vertical velocity field is constructed assuming slip on faults in elastic plate over an inviscid fluid. The interseismic deformation field is modeled with backslip on the faults in an elastic halfspace. Using Monte Carlo Metropolis methods, they invert the geodetic data for slip rates and coupling, constrained by the upper and lower slip rate bounds in the UCERF3 geologic model. They find significant shortening across the Transverse Ranges of ~10 mm/yr. This is shortening attributed only to motion along faults in the western Transverse Ranges, after removing contributions from the San Andreas and other large strike-slip faults as well as far-field loading. The summed reverse-slip rate across the Transverse Ranges along a profile through Ventura is >15 mm/yr with 8-10 mm/yr across the Ventura Basin (Oak Ridge and Ventura Faults).

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. This past year's accomplishments include

- Developing and testing forecast models based on Coulomb stress changes
- Developing focal mechanism forecast methods
- Continuing development of OpenSHA and significant improvements in UCERF3
- Revealing new properties of small-magnitude earthquake clusters in relation to large events, human-induced earthquakes, and aseismic transients
- Further improvement of automatic processing of the SCSN waveform archive and producing an updated version of the high-quality earthquake catalog for southern California
- Progress in constraining the minimum level of background stress, and the amplitude and length-scale of stress heterogeneity, to inform physical models of earthquake triggering

a. Earthquake forecasting development and testing: Traditionally, this is the principal activity of the SCEC EFP community. This year, Jackson and Strader explored prospective earthquake forecasts based on Coulomb stress changes. It has been shown that instantaneous Coulomb stress or shear stress changes apparently influence the locations (but not the magnitudes) of future earthquakes. In particular, it has been shown that with 95% confidence, M ≥ 2.8 earthquakes preferentially nucleate where shear or Coulomb stress increased; and on average, 59% of earthquakes occurred within stress-enhanced zones, regardless of the choice of rupture plane or type of stress change (Strader and Jackson, 2014, 2015). These conclusions are corroborated by the studies of Werner, Marzocchi, Gerstenberger, and Liukis. The team conducted a retrospective evaluation of short-term forecasting models for the Darfield M7.1 sequence. It has been reported that Coulomb/rate-state models and hybrid Coulomb/statistical models provided more informative forecasts during the sequence than statistical models over all tested forecast horizons (1-year, 1-month and 1-day). The team also tested how well the information gains of medium-term forecasting models can be explained by short term earthquake clustering conforming to the Omori-Utsu law, and the optimization and testing hybrid models and exploration of their potential

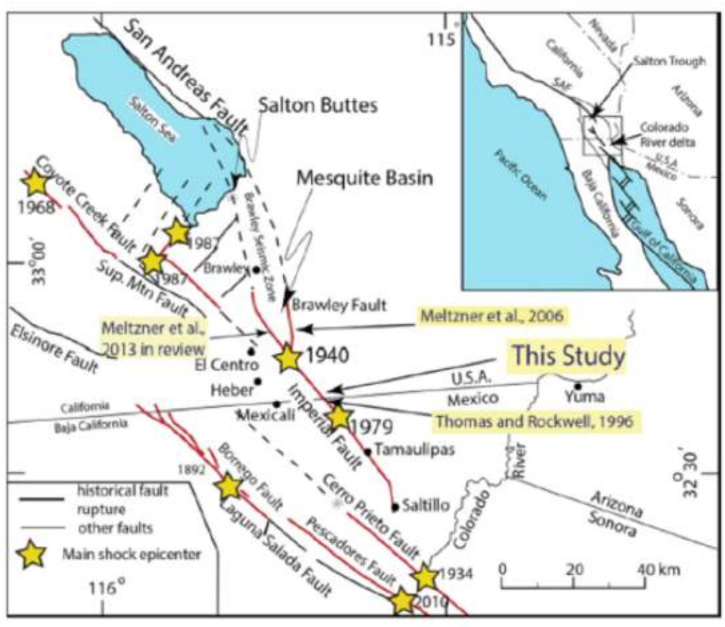


Figure 3.32. Map of major structural elements of the plate boundary fault system in and around the US/Mexico border region.

as a powerful testing tool within CSEP for the future (Gerstenberger et al., 2014, Helmstetter and Werner, 2014, and Steacy et al., 2014).

Based on the above results, it has been concluded that an optimized combination of smoothed seismicity and Coulomb stress may show improved success in prospective forecasts experiments. The results provide support for the Coulomb/rate-state earthquake triggering hypothesis and may eventually guide the model development for Operational Earthquake Forecasting (OEF) systems.

Forecasts of the focal mechanisms of future earthquakes are important for seismic hazard estimates and other models of earthquake occurrence. Kagan and Jackson (2014, 2015) approached this problem by performing a high-resolution global forecast of earthquake rate density as a function of location, magnitude, and focal mechanism. In these forecasts they have improved the spatial resolution to 0.1 degrees and the latitude range from pole to pole. The focal mechanism estimates require distance-weighted combinations of observed focal mechanisms within 1000 km of each grid point. Simultaneously they calculated an average rotation angle between the forecast mechanism and all the surrounding mechanisms.

A topic of continuing interest in EFP is testing recurrence models for plate boundary faults. The project by Rockwell, Jerrett, Wessel, and Klinger addressed this problem at the Imperial fault in the Salton Trough. It is the main plate boundary fault that transfers most of the displacement across the international border. It also has the distinction of being the only fault in southern California that has sustained two well-documented surface ruptures in the historical period (1940 and 1979). The project tested basic recurrence models for the Imperial fault. In particular, it suggests that the region of large 1940 displacement in the border area is a resilient asperity (Meltzner et al., 2014; Rockwell and Klinger, 2013).

Another aspect of forecast development is to search for earthquake precursors. It has been hypothesized that earthquakes may be preceded by aseismic slip transients, which may exhibit tremor-like signals. The presence or lack of emergent seismic signals is therefore of interest because they could provide information about any aseismic slip leading up to earthquakes. Hawthorne and Ampuero (2014) conducted a systematic search for tremor-like signals prior to 10,000 M 2.5-6 earthquakes in southern California. They found no evidence for emergent seismic signals, suggesting that emergent precursors are rare or small.

b. UCERF3: The SCEC community continued the Development of OpenSHA in Support of Operational Earthquake Forecasting, Hazard Assessment, and Loss Modeling [Field et al, 2015]. Major developments were made in support of UCERF3. This includes implementation of the long-term time dependent component of the UCERF3 model (UCERF3-TD). A preliminary short term operational UCERF3- based forecast was also implemented and has gone through initial testing (UCERF3-ETAS). CyberShake collaboration has also been strong in this report period, including addition of Maximum Considered Earthquake Response (MCER) calculations for the Utilization of Ground Motion Simulations committee.

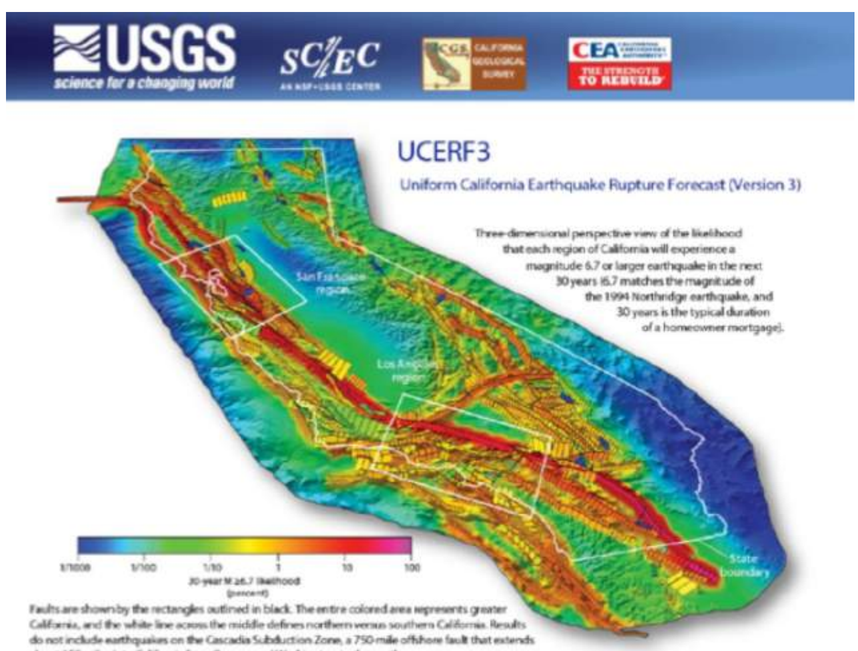


Figure 3.33. Postcard for final UCERF3 Long Term Time Dependent model showing M>=6.7 participation probabilities throughout California.

The final UCERF3 time dependent model was released on March 10, 2015 and received broad media attention. There are many groups in many different disciplines currently taking steps to adopt it. The CyberShake MCER work will hopefully soon lead to inclusion of CyberShake results in the building code for the Los Angeles region.

In addition, Ward performed a study to step up from the existing ALLCAL2 fault system to one that represents the UCERF3 fault system as closely as possible and to compare earthquake simulator output with UCERF3 forecasts. The current UCERF3-ES (the name of the product) for California includes 25,586 elements. The study resulted in the first statewide rupture forecast and seismic hazard calculation based on earthquake simulation. Also, see a YouTube movie https://www.youtube.com/watch?v=-ztj-uw4_uo.

c. Earthquake clustering: SCEC EFP community continued studies of earthquake clustering. Shearer had focused on studying earthquake triggering models and their relationship to swarms and foreshock sequences. The project identified several aspects of the space/time clustering of seismicity that cannot be explained with standard (i.e., ETAS) triggering models, including details of the foreshock and aftershock behavior for small earthquakes. In particular, it was found that a significant fraction of small earthquake clustering is swarm-like and probably caused by underlying physical drivers, such as fluid flow or slow slip. A search begun for correlations of seismicity with aseismic transients observed in geodetic data, in particular near the laser strainmeters at Piñon Flat Observatory (PFO) and surrounding borehole strainmeters from the Plate Boundary Observatory (PBO). At least ten examples have been identified where strain anomalies are associated with peaks in the local seismicity rate.

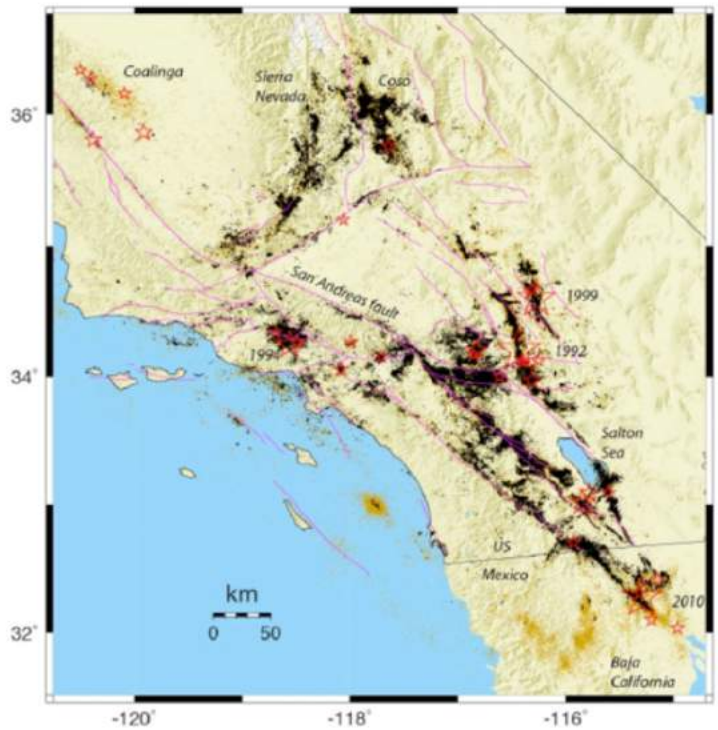


Figure 3.34. Event locations from the HYS catalog (1981 – 2014). Similar event clusters that have been relocated by using waveform cross-correlation are shown in black. Events in the SCSN catalog (and uncorrelated events in the other catalogs) are shown in brown. Events with M ≥ 5.5 are shown as stars. Faults are from Jennings (2010) with late Quaternary faults in shades of red.

Zaliapin and Ben-Zion investigated seismic cluster anomalies in relation to different loadings and large earthquakes. The results of this project suggest that (i) the cluster properties systematically evolve in time, according to several robust cluster measures, in the spatio-temporal vicinity of the largest earthquakes in southern California, and (ii) seismic clustering differs, and probably can be used to discriminate between the regions dominated by tectonic vs. human-induced seismicity.

Overall, the cluster studies combined novel approaches to earthquake cluster identification/classification and high quality earthquake catalogs from different environments toward improved understanding of seismicity in relation to large events, human-induced earthquakes, and aseismic transients. Ability to track the evolving response of the crust to different loadings may be used to monitor the build up of stress in a region. This knowledge contributes to quantitative assessments of earthquake potential and seismic hazard in southern California.

d. High-quality data: A project by Shearer and Hauksson focused on automatic processing of the SCSN waveform archive. This continued work has resulted in improving earthquake locations and focal mechanisms using waveform cross-correlation and S/P amplitude ratios, and on computing spectra for use in studies of earthquake source properties and attenuation. The latest version of the relocated catalog (so-called HYS catalog) contains high-precision locations of over 560,000 events from 1981 through 2014. The project also resulted in a newly created stress drop catalog for earthquakes between M1 and ~M3.5

with occasional events up to M5. The new catalog includes stress drops for more than 24,000 earthquakes between 2000 and 2014.

Sammis and Sumy analyzed data from a dense, near-fault temporary borehole array deployed within the San Andreas Fault Observatory at Depth (SAFOD) main borehole by Paulsson Geophysical Services (PGS) between late April to early May 2005. The project objective is to illuminate fine-scale fault structures in unprecedented detail, and to look for evidence of interaction between the individual events. Preliminary analysis by PGS has located approximately 100 small magnitude earthquakes that appear to delineate three separate fault strands of the SAF.

e. Induced Seismicity: Geothermal power generation commonly induces seismicity. Brodsky has shown that the earthquakes in the Salton Sea region are directly related to the net extraction of fluid in the field. The study used an ETAS model to decluster the catalog and then related the background rate to publically available monthly injection and production data. The success of this project also shows that the induced earthquakes have aftershocks, which can potentially occur on other faults in the region. A work is now performed with CSEP to implement the Salton Sea algorithm in predictive mode.

Chen et al (2011) studied stress drops in the Salton Sea geothermal region, and found that stress drop increases from 1.5 MPa closest to injection wells to 5 MPa at 300 m from injection wells, demonstrating the impact of the geothermal activity on the strength of the surrounding crust. Earthquake relocations show depth separation between shallow larger (M≥2.5) and deeper smaller (M<2.5) events.

f. Modeling Stress and Earthquake Stress Triggering: One path to studying the predictability of earthquakes is to better understand the relationship between earthquake occurrence and stress, including the background stress and static and dynamic stress changes from natural and human-made sources.

The level of background stress is a first-order unsolved problem, with implications for a wide variety of earthquake physics problems including stress triggering. Luttrell et al. (2015) made significant progress on this problem, using models compiled by the SCEC Community Stress Model project. They integrated three stress models, each estimating a different component of stress due to a different set of physical processes (plate driving, fault loading, topography) with stress orientation observations from focal mechanisms, to determine a minimum estimate of the 3D stress tensor across southern California at seismogenic depth. They found that the stress field must have a differential stress magnitude of at least 60 MPa at seismogentic depth in order to maintain the stress orientation inferred from focal mechanism observations in the presence of the observed rugged topography.

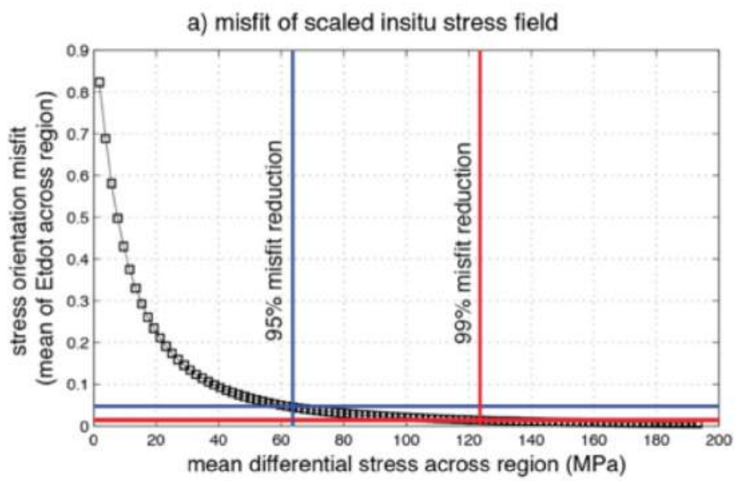


Figure 3.35. Mean misfit between in situ stress orientation (from focal mechanisms) and scaled in situ stress with modeled topography stress. Misfit function is one minus the mean of the tensor dot product between the two stress fields, such that a value of 0 indicates a perfect fit and a value of 1 indicates complete non- correlation. For 95% misfit reduction, regional differential stress must be > 60 MPa. (From Karen Luttrell)

The amplitude and length-scale of heterogeneity of the background stress field at seismogenic depths is also poorly understood. A better documentation of stress heterogeneity in southern California is essential to constrain rupture propagation of major earthquakes and associated regional seismic hazards. Goebel et al. (2015) investigated stress orientations in the SCEC Special Fault Study Areas in San Gorgonio Pass and Ventura Basin. They found that principle stress orientations are substantially more heterogeneous within the San Gorgonio area indicating a general heterogeneity of stress accumulation and release within the area. Persaud et al. (2015) used well logs from drill holes in the Los Angeles basin to interpret principal horizontal stress directions from borehole breakouts. High-density observations in one oil field indicate variation of the direction of the stress axis orientations over horizontal distances less than 1 km at depths from 2-3 km. This variation is over a smaller scale than what is envisioned for the current community stress field models, and agrees with some theoretical models.

Earthquake stress drops may also provide information about the stress field. Goebel et al (2015) found that stress drop are approximately inversely correlated with fault slip rate along the profile of the San Andreas fault zone, implying that slower-slipping sections reach higher stress levels because they have longer to heal and strengthen between earthquakes.

In addition to static and dynamic stress changes, earthquakes may trigger other earthquakes due to viscoelastic stress relaxation. This time evolution of stress may play an important role in explaining delayed earthquake triggering. Meade et al. (2013) modeled these anelastic processes to study the basic behavior of long-term viscoelastic stress transfer using a novel fault system geometry, periodic and aperiodic earthquake sequences, and phenomenologically motivated polyviscous rheologies.

Non-volcanic tremor appears to be more sensitive to dynamic stress triggering than tectonic earthquakes. Gonzalez-Huizar et al. (2015) detected new cases of dynamically triggered tremor at Parkfield. They model the local static stress, and the dynamic stresses caused by passing triggering seismic waves from remote earthquakes, and show that the triggered tremor are correlated with the largest dynamic stresses. Peng and Yang continued the effort of a systematic search of tremors in California. The lack of additional triggered tremor beneath the San Gabriel Mountain in southern California indicates that near-lithostatic fluid pressure is necessary but not sufficient for tremor to occur.

In addition to earthquakes and tremor, fault creep is also affected by the local stress field. Lindsey et al. (2014) find that localized fault creep corresponds to transpressional areas of the southern San Andreas fault, while a 1–2 km wide zone of distributed yielding is most likely to occur along segments of the fault where the local stress state is transtensional. Using a two-dimensional boundary element model, they show that stresses resulting from slip on a curved fault can promote or inhibit inelastic failure within the fault zone in a pattern matching the observations.

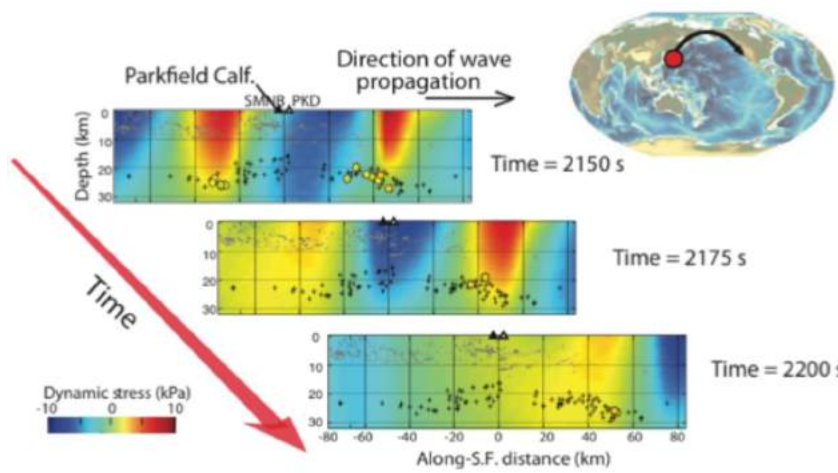


Figure 3.36. Modeling of the dynamic Coulomb stress caused by the surface waves from the Tohoku-Oki event, and is correlation to triggered tremor. Tremor were identified and located by Hill et al. [2013]. Yellow circles represent families of trigged tremor and plus (+) signs represent ambient tremor families identified by Shelly and Hardebeck [2010]. Small dots are the ambient seismicity [Waldhauser and Schaff, 2008]. (From Hector Gonzalez-Huizar.)

Critical to making progress in understanding the stress field and its impact on earthquake occurrence is supporting collection and analysis of geodetic data. To this end, SCEC supported a workshop of the Community Geodetic Model. The goal of this project is to produce a comprehensive geodetic time series data product that leverages the complementary spatial and temporal features of Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) data. SCEC also continues to support the Piñon Flat Observatory, which records high-quality continuous crustal deformation data in proximity to the San Andreas and San Jacinto faults. The long span of the PFO records provides a unique basis for identifying and evaluating new signals.

g. Paleoseismic Data and Earthquake Forecasting: Paleoseismic events are central to earthquake forecasting because of the short historic/instrumental record. Jackson et al. (2015) found that the paleoseismic events used in the UCERF3 hazard report occur at an average of more than 4 per century. However, none have occurred since 1910, about the dawn of the instrumental seismic era in California. The hiatus since 1910 is very unlikely (about 1 % probability) to occur at random given the previous rate, whether the recurrence of previous events is Poissonian or Quasi-periodic, or whether it is computed from physics-based simulators. The hiatus of the last century points to remarkable statewide clustering not previously recognized and not yet modeled, or to inconsistencies that could require corrections to UCERF3 earthquake rates. This work highlights the importance, for understanding earthquake predictability, of continuing work to increase the number of paleoseismic sites in California and to develop improved paleoseismic methods.

Possible new paleoseismic sites were explored on both sides of a sag pond along the San Andreas fault near the southern boundary of the Carrizo National Monument (Akciz, 2015). They found that 3-8 earthquakes occurred in the last 2000 years, with abundant liquefaction evidence. However, due to limited, discontinuous sedimentation, high water table, and the narrow fault zone with few splays deforming the stratigraphic units that fill the sagpond, they concluded that it was not an ideal site for further investigation. Evans et al (2014) focused on fieldwork in the Mecca Hills, where they have examined the five largest faults east of the San Andreas fault, with 12 study sites where detailed fault-related data were collected. Rockwell et al. continued to improve the age control for Lake Cahuilla sediments to correlate individual lakes across the Salton Depression. The goal is to place the past 1500 years of earthquakes in the southern San Andreas fault system into a common chronology. From such a paleoseismic database, the relative timing and sequencing of large events among the different fault zones can be constructed. Berelson et al. (2015) investigated whether grey layers in the sediments in Santa Barbara Basin may represent tsunami or seismically triggered sedimentation. Seismic shaking and a resultant turbidity current or nephaloid layer deposit is their preferred interpretation for origin of grey layers.

h. CSEP/USGS/GEM Workshop: Next Steps for Testing Operational Earthquake Forecasts and Seismic Hazard Models: The Collaboratory for the Study of Earthquake Predictability (CSEP), operated by the Southern California Earthquake Center (SCEC), provides a research cyber-infrastructure for independent and prospective testing of earthquake forecasts. As such, CSEP is well situated to evaluate operational forecasting models of earthquake potential and ground motions by the USGS, GEM and other international governmental and non-governmental organizations. The ongoing development and implementation of operational models, however, entail new requirements for CSEP's infrastructure, methods and experiment design. The purposes of this workshop were: (i) to assess the evolving needs of agencies for CSEP-based testing of OEF and seismic hazard models, (ii) to disseminate and review recent CSEP and GEM Testing & Evaluation (T&E) results, (iii) to assess the adequacy of CSEP's current methods and infrastructure in light of evolving needs, and (iv) to gather community input on the next steps for testing OEF and seismic hazard models. Website: http://www.scec.org/workshops/2014/csep/index.html

i. Virtual Institute for the Study of Earthquake Systems (VISES) Summer School: Wave and Rupture Propagation with Realistic Velocity Structures, September 28 – October 2, 2014. To foster the collaboration and to introduce early career scientists to methods being developed both at SCEC and at ERI and DPRI, the second Summer School on Earthquake Science was held September 28 – October 2, 2014 at the Embassy Suites Mandalay Bay, in Oxnard, California. The theme of the school was Wave and Rupture Propagation with Realistic Velocity Structures. The emphasis was hands-on experience with SCEC Community Velocity Model (CVM), Community Fault Model (CFM) and the SCEC Broadband Platform (BBP). As such the school included both lectures and exercises where participants would delve into complex velocity structure and create seismograms from kinematic representations of earthquakes as propagating ruptures.

j. SCEC Utilization of Ground Motion Simulations (UGMS) Committee. The goal of the UGMS committee, since its inception in the spring of 2013, has been to develop long-period response spectral acceleration maps for the Los Angeles region for inclusion in NEHRP and ASCE 7 Seismic Provisions and in Los Angeles City Building Code. The work of the UGMS committe is being coordinated with (1) the SCEC Ground Motion Simulation Validation Technical Activity Group (GMSV-TAG), (2) other SCEC projects, such as CyberShake and UCERF, and (3) the USGS national seismic hazard mapping project. Significant progress toward developing the maps was made in 2014, and this summary report highlights the accomplishments and future work.

The results generated during 2014 are encouraging and indicate that the UGMS committee should continue its efforts toward generating long period ground motion maps for Southern California for possible inclusion in (1) the next edition of the Los Angeles City building code, which would be a variation to the ground motions for Southern California in the ASCE 7-16 standard, and (2) the 2020 NEHRP seismic provisions and the ASCE 7-22 standard. The code cycle for the latter has already begun.

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. This past year's accomplishments include:

- Withers et al. incorporated frequency-dependent Q into AWP-ODC as a power-law, and demonstrated the effects using realistic parameters for the Chino Hills earthquake.
- Lozos et al. simulated rupture on the northern San Jacinto fault using complex fault geometry with step overs, and a 3D velocity model. The results were combined with high-frequency scattering functions to generate broadband synthetics. The broadband synthetics were found to be in good agreement with the presence of precariously balanced rocks and leading GMPEs.
- Graves and Pitarka characterized kinematic ruptures for ground motion simulation of shallow crustal earthquakes, including shallow and deep 'weak' zones and mapping the effects of perturbations to the fault surface.
- Baker derived a predictive model for fling period and amplitude and compared to existing models. They found that ground motion simulations provided a rich and reliable data source for fling step, indicating an additional engineering use case for simulations. The work also validated the ability of simulations to predict fling in conditions not well captured by empirical data sources.

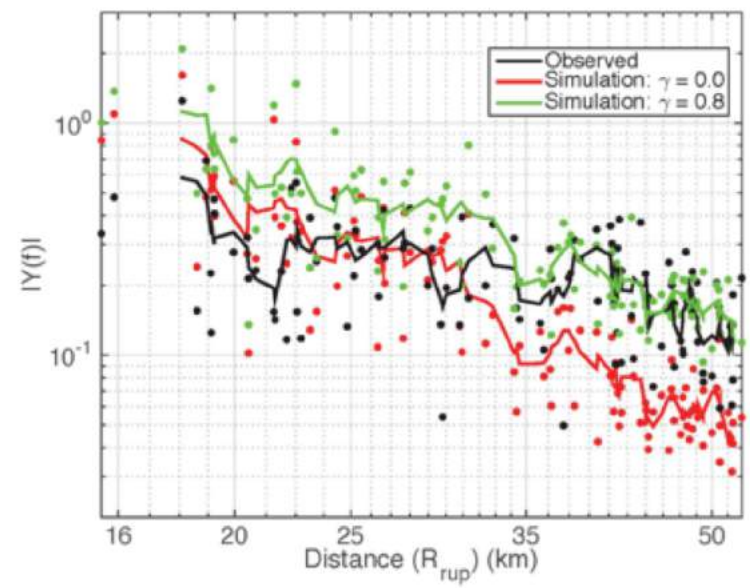


Figure 3.37. Fourier amplitude as a function of distance centered at 0.25 Hz for a simulation of the 2008 M5.4 Chino Hills, Ca, earthquake, with constant Q and frequency-dependent Q. Dots depict values for individual stations and lines depict a 5-point moving average. From Withers et al., 2015.

- Bradley et al. developed a new 3D seismic velocity model of Canterbury, New Zealand. The model explicitly represents the Canterbury sedimentary basin, and other significant geologic horizons, which are expected to have important implications on observed ground motions.
- Archuleta illustrated the undesired effects of rapid amplitude decay with distance of high-frequency (HF) synthetic ground based on 1D crustal velocity structures. He showed a simple solution to this problem by separating the wave propagation problem into a simplified single layer on top of a half-space for the HF portion of ground motion and a more realistic 1D multilayer model for the low-frequency portion of ground motion.
- Holden and Gerstenberger conducted broadband ground motion simulations using a suite of moderately sized aftershocks (M5.3+) from the Canterbury sequence. They used these simulations to investigate the sensitivity of near field ground motions to key engineering parameters including stress drop and rupture details such as velocity, directivity and slip distribution. Results show that adoption of parameters derived from spectral inversions of the strong motion dataset and method provides an improved and robust fit to the observed data, emphasizing the need for region-specific considerations and the implications this has for GMPEs.
- Beroza and co-workers worked on using ambient seismic field data to explore amplification in urban Tokyo. They used a combination of 375 Hi-Net deep borehole seismometers across central

Honshu as virtual sources and 296 seismic stations of the MeSO-Net work shallow-borehole seismometers within the basin as receivers to map the basin impulse response. They found 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 found that the strength of basin amplification depends strongly on the direction of illumination by seismic waves.

- Shaw and Jordan presented a statistical description of fine-scale velocity structure in the sedimentary basins of southern California that is intended to support high frequency ground motion simulations for earthquake hazards assessment. They defined the variability in both Vp and Vs, and established vertical and horizontal correlation lengths for fine-scale velocity structures using wells across the basin as well as in tightly clustered oil fields.
- Roten et al. continued to examine the effects of elasto-plastic rheology on ground motions. Previous nonlinear simulations of the ShakeOut scenario based on a kinematic source have suggested that plastic yielding in the fault damage zone may reduce ground motion levels in the Los Angeles basin (LAB) by 30 - 70 % with respect to linear solutions. New simulations of spontaneous rupture were carried out on a planar, vertical fault roughly following the surface trace of the southern San Andreas fault (SAF) along ~250 km between Indio and Lake Hughes. Because the source in these simulations is fully dynamic, these simulations are comparable to benchmarks TPV26 and TPV27 of the SCEC/USGS dynamic rupture code verification exercise, which have been used to verify the AWP-ODC FD code with plasticity against several other FD and FE methods. These new simulations confirm that long-period (< 1 Hz) peak ground velocities in the LAB would be reduced by up to 50% if sedimentary and crustal rocks are assumed to be nearly cohesionless. However, the dynamic simulations also show that PGVs in the LAB may still exceed 2 m/s if the strength of crustal rocks and sediments is very high (> 10 MPa). This result indicates that ground motions are more sensitive to the strength of crustal rocks than indicated by previous dynamic simulations, and highlight the need to better constrain the friction angles and cohesions used in such nonlinear simulations of dynamic rupture and wave propagation.

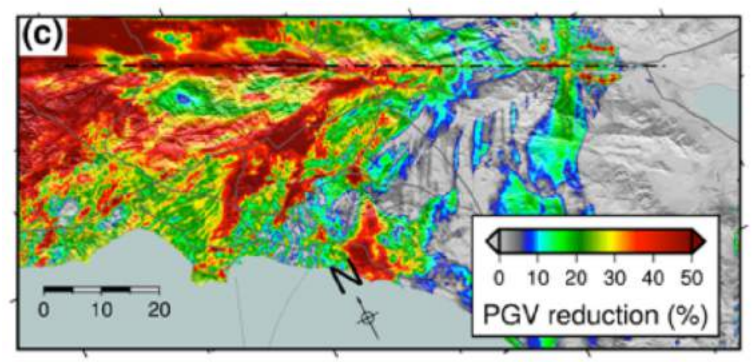


Figure 3.38. Elasto-plastic reduction of peak ground velocity with respect to a visco-elastic conditions from dynamic simulation (fmax = 2 Hz) of a M 7.8 earthquake rupturing the southern segment of the San Andreas fault.

- Nakata and Beroza developed random-field model representations of a 3D P-wave velocity model under Long Beach, CA, estimated from dense-array recordings of the ambient seismic wavefield. They find that a von Karman model fits the imaged velocity model best, with horizontal and vertical correlation lengths of 0.51 km and 0.1 km, respectively, and a Hurst number of 0.040. They validate their results by showing that their model accurately predicts the observed decay of scattered waves in the coda of a nearby earthquake.
- Using noise correlation measurements from the Long Beach Array, processed to maintain relative amplitude information, Tsai et al. produced maps of surface-wave ground motion amplification over a range of frequencies from 0.67 Hz to 2.0 Hz. These maps show that ground motion site amplification can vary by a factor of 4 over distances as short as a few hundred meters, throughout the city of Long Beach, CA. The spatial amplification patterns are generally consistent with those that would be predicted from shallow velocity anomalies, but provide direct measures of amplification and are therefore more robust than amplification computed indirectly from velocity structure.

- Dunham et al. performed 2D dynamic rupture simulations on rough faults in heterogeneous media to determine the relative importance of source complexity and scattering in destroying coherence of the high-frequency seismic wave field. Their simulations demonstrate that random elastic heterogeneity of the off-fault material, at levels representative of the crust, have only minor influence on the rupture process. Fluctuations in slip and rupture velocity are instead controlled by complex fault geometry. This conclusion is expected to carry over to 3D. An additional result of this study was that the effects of scattering became appreciable only beyond a few kilometers from the fault. At closer distances, incoherent high-frequency ground motion was dominated by source complexity. This result will likely change in 3D, and Dunham's group has developed a 3D version of their rupture dynamics code to address this problem.

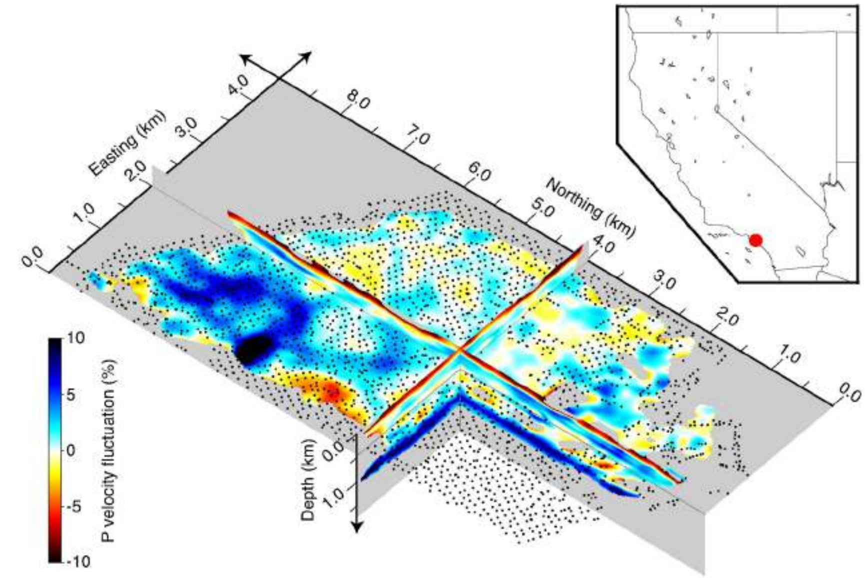


Figure 3.39. P-wave velocity model in 3D view obtained from ambient seismic wavefields. The color illustrates the fractional fluctuation of P-wave velocities. The grey area shows the poorly resolved area according to the ray coverage. The black dots are the location of the stations projected at the depth of the horizontal slice. The red dot in the inset shows the location of the survey. From Nakata and Beroza, 2015.

a. SCEC Broadband Platform Validation Exercise and SRL Focus Section: SCEC has completed phase 1 of its Broadband Platform (BBP) ground-motion simulation exercise, evaluating the potential applications for engineering of the resulting 0.01–10 s pseudospectral accelerations (PSAs) generated by five different methods. The exercise included part A, in which the methods were evaluated based on the bias of simulation results to observations for 12 well-recorded historical earthquakes: 7 in the western United States, 2 in Japan, and 3 in the eastern United States/Canada. In addition, part B evaluated simulation results for Mw 5.5, 6.2, and 6.6 scenarios at 20 and 50 km from the fault. The methods were assessed based on the bias of the median PSA for the 12 events in part A and on a specified acceptance criterion compared with Next Generation Attenuation-West (NGA-West) ground-motion prediction equations (GMPEs) in part B. The results were evaluated by the bias of mean PSA from simulations using 1D velocity models with average shear-wave velocity in the upper 30 m of 863 m/s with respect to recorded data corrected for site effects. Nine articles describing the scientific and technical accomplishments were published in a focus section of the January/February 2015 issue of Seismological Research Letters.

b. SCEC High-Frequency Ground Motion Validation Exercise: As part of SCEC's High-F research initiatives, verification and validation of deterministic ground motion prediction for the 2014 M5.1 La Habra, CA, earthquake is underway. Three codes currently participate in the comparisons, namely AWP-ODC and AWP-RWG (4th-order finite difference, FD) and Hercules (2nd-order finite elements, FE). The exercise uses a point source with mechanism derived from strong-motion data and a slip-time history obtained from a dynamic rough-fault model with frequency content up to 5 Hz. The areal extent of the simulation region is 180 km x 135 km, with a target depth of 62 km. The model covers the entire greater Los Angeles basin and other structural features in its vicinity. The verification has progressed in incremental steps from a simple halfspace model via a smooth 1D crustal model, to ongoing efforts involving 3D crustal variation and a minimum S-wave velocity of 500 m/s. Comparisons between codes have been made with lossless and frequency-independent anelastic attenuation, with tests exploring the significance of frequency-dependent Q. Results from the verification exercise at the various complexity levels have allowed to identify the numerical parameters necessary for the codes to yield synthetics with a satisfactory level of agreement. Current efforts include verification and validation in a 3D volume of the CVM-S4.26, where strong motion data is available at 350+ stations within the model region. The simulations have primarily been carried using parallel processing on NCSA Blue Waters.

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. An important area of EEII work is in the validation and utilization of ground motion simulations. With the important milestone of completion of the BroadBand Platform validation, there is now significant data and computational infrastructure that is being utilized in this area.

a. Implementation of Ground Motion Simulation Validation (GMSV) Gauntlets on the Broadband Platform: Following several years of work by SCEC researchers to develop and evaluate metrics for validating ground motion simulations, a committee has been formed and work is underway to implement the most useful or promising metrics on the SCEC BroadBand Platform. These new calculation tools enable users of the Platform to compute these metrics automatically while simulating ground motions. These features are intended to enable engineers or ground motion simulators to validate simulations easily via standardized procedures, as has successfully been achieved previously for response spectral metrics.

A Technical Activity Group (TAG) has been working for several years to develop and implement testing/rating methods for simulations that resulted from collaboration between ground motion modelers and engineering users. The GMSV activity was undertaken in concert with the BBP for developing simulations that reproduced the GMPE's, which were based on elastic response spectra associated with single degree of freedom oscillators. The GMSV was focused on how simulations could be used in probabilistic seismic hazard analysis (PSHA), structural nonlinear response history analysis, and geotechnical site response analysis. Validating (as opposed to verifying) simulation algorithms was a daunting task, as the simulations of greatest interest are those from conditions that have not been well observed (e.g., motions a short distances from large magnitude earthquakes)—so how can one rigorously evaluate whether such simulations are valid? The work required specifying application areas, and then developing "Validation gauntlets" that simulated motions should pass in order to be deemed reasonable. Gauntlets have been evaluated for single-degree-of-freedom oscillators, simple multi-degree-of freedom oscillators and geotechnical systems, used as proxies for more complex structural and geotechnical systems. For example, how can simulations be used in the analysis of structural nonlinear response history for 3D multi-degree-of-freedom buildings? Will the simulations have the temporal behavior and frequency content to produce the response of structures up to and beyond their elastic limit? Can simulations be used in the geotech-

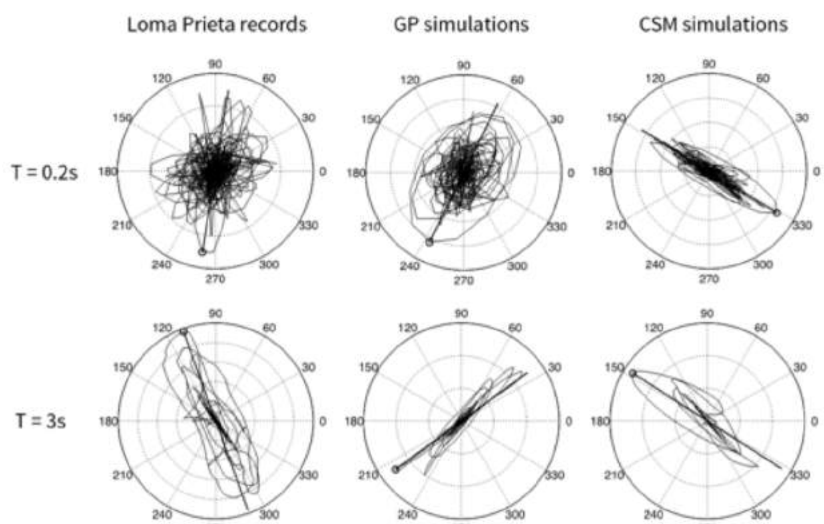


Figure 3.40. Observed and simulated ground motions with median levels of directional polarization in elastic oscillator response. GP = Graves and Pitarka simulation algorithm, CSM = Composite Source Model simulation algorithm (from Burks and Baker, 2014). Deviation in polarization, relative to expected levels observed in recordings, is a simulation validation metric that has been implemented on the BroadBand Platform.

nical analysis of slope displacements and soil liquefaction, both of which are duration sensitive? These projects are demanding that simulations do more than produce an elastic response spectrum; the simulations have to have the duration and frequency content that are observed from data.

b. Utilization of Ground Motion Simulations to Produce Urban Seismic Hazard Maps: The Committee for Utilization of Ground Motion Simulations has been working toward the goal of utilization of ground-motion simulations to develop long period spectral acceleration maps for the Los Angeles region. The objective is to utilize the CyberShake platform to compute seismic hazard at long periods, and produce maps that are compatible with, though supercede, traditional empirical maps. The maps could then be adopted in the America Society of Civil Engineers 7-21 Standard, which will be released in 2021 and govern earthquake-resistant design requirements in the United States. By integrating the full suite of earthquakes and ground motions, CyberShake provides a numerically based seismic hazard map for the Los Angeles area. Because CyberShake can account for the 3D velocity structure, including basins, it provides much greater refinement than the current state-of-the-art seismic hazard analysis based on empirical ground motion prediction equations that have limited ability to capture basin effects. In essence, CyberShake provides a means for producing urban seismic hazard maps. As can be imagined, this effort requires considerable expense in computational resources. At the same time it integrates many of SCEC's collaborative efforts: the community fault model, the community velocity model, the Broadband Platform for a product that is directly useful to the engineering community, emergency planners and political entities responsible for the safety of the greater Los Angeles metropolitan area. This committee is using SCEC science to guide engineering regulations, while enabling the detailed oversight and consensus-building associated with building code development.

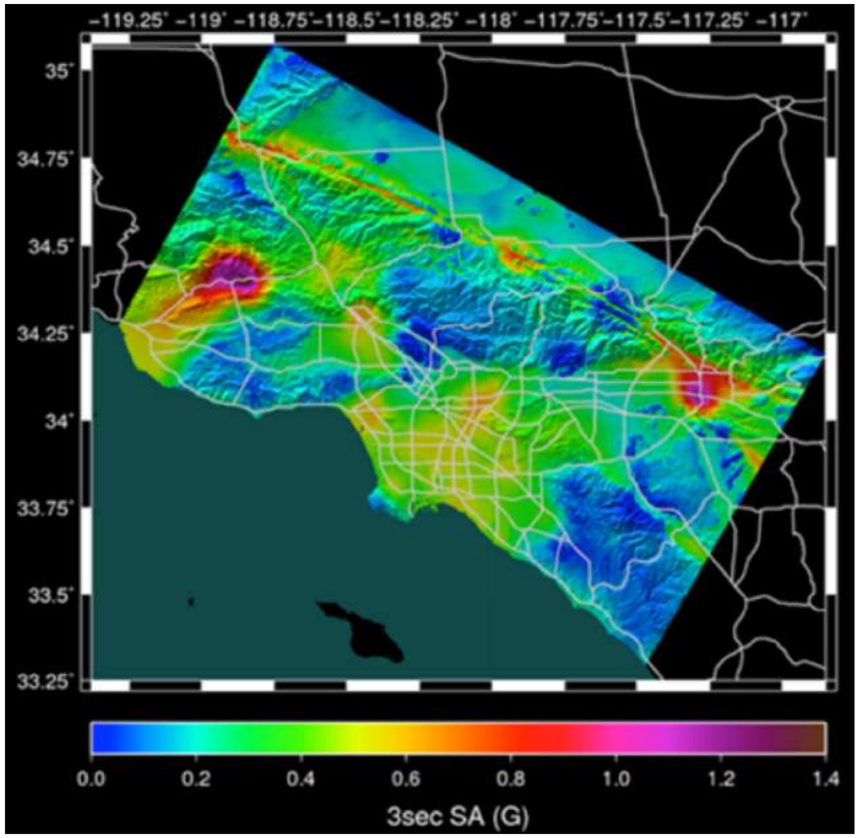
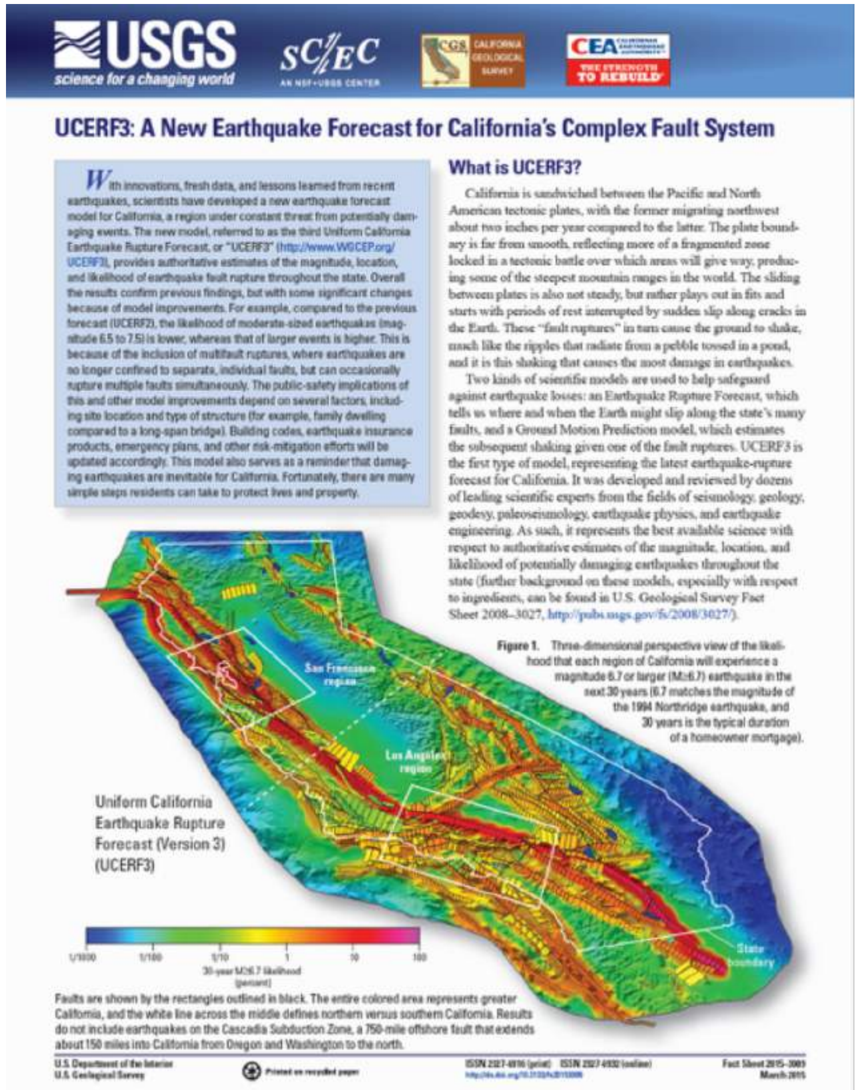


Figure 3.41. Example Los Angeles Region Hazard Map, 2% in 50-yr Sa(3 sec) (Graves et al. 2010).

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 (http://www.earthquakeauthority.com). The previous WGCEP model was the Uniform California Earthquake Rupture Forecast version 2 (UCERF2, http://www.scec.org/ucerf2/), which was published in 2008. Since that time we have been working on the next model, UCERF3, for which the main goals have been to: 1) relax segmentation and include multi-fault ruptures; 2) develop an algorithm for computing more self-consistent long-term elastic-rebound-based probabilities; and 3) include spatiotemporal 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 has been exemplified by several recent earthquakes, including the 2011 M9 Tohoku earthquake with respect to segmentation, both the 2010 M7.2 El Mayor-Cucapah and 2012 M8.6 Sumatra earthquakes in regard to multi-fault ruptures, and the 2011 M6.3 Christchurch earthquake in terms of spatiotemporal clustering. Progress on each of these goals is given below.


USGS
science for a changing world
SCEC
AN NSF+USGS CENTER
CGS CALIFORNIA GEOLOGICAL SURVEY
CEA
THE STRENGTH TO REBUILD

UCERF3: A New Earthquake Forecast for California's Complex Fault System

With innovations, fresh data, and lessons learned from recent earthquakes, scientists have developed a new earthquake forecast model for California, a region under constant threat from potentially damaging events. The new model, referred to as the third Uniform California Earthquake Rupture Forecast, or "UCERF3" (http://www.WGCEP.org/UCERF3), provides authoritative estimates of the magnitude, location, and likelihood of earthquake fault rupture throughout the state. Overall the results confirm previous findings, but with some significant changes because of model improvements. For example, compared to the previous forecast (UCERF2), the likelihood of moderate-sized earthquakes (magnitude 6.5 to 7.5) is lower, whereas that of larger events is higher. This is because of the inclusion of multifault ruptures, where earthquakes are no longer confined to separate, individual faults, but can occasionally rupture multiple faults simultaneously. The public-safety implications of this and other model improvements depend on several factors, including site location and type of structure (for example, family dwelling compared to a long-span bridge). Building codes, earthquake insurance products, emergency plans, and other risk-mitigation efforts will be updated accordingly. This model also serves as a reminder that damaging earthquakes are inevitable for California. Fortunately, there are many simple steps residents can take to protect lives and property.

What is UCERF3?

California is sandwiched between the Pacific and North American tectonic plates, with the former migrating northwest about two inches per year compared to the latter. The plate boundary is far from smooth, reflecting more of a fragmented zone locked in a tectonic battle over which areas will give way, producing some of the steepest mountain ranges in the world. The sliding between plates is also not steady, but rather plays out in fits and starts with periods of rest interrupted by sudden slip along cracks in the Earth. These "fault ruptures" in turn cause the ground to shake, much like the ripples that radiate from a pebble tossed in a pond, and it is this shaking that causes the most damage in earthquakes.

Two kinds of scientific models are used to help safeguard against earthquake losses: an Earthquake Rupture Forecast, which tells us where and when the Earth might slip along the state's many faults, and a Ground Motion Prediction model, which estimates the subsequent shaking given one of the fault ruptures. UCERF3 is the first type of model, representing the latest earthquake-rupture forecast for California. It was developed and reviewed by dozens of leading scientific experts from the fields of seismology, geology, geodesy, paleoseismology, earthquake physics, and earthquake engineering. As such, it represents the best available science with respect to authoritative estimates of the magnitude, location, and likelihood of potentially damaging earthquakes throughout the state (further background on these models, especially with respect to ingredients, can be found in U.S. Geological Survey Fact Sheet 2008–3027, http://pubs.usgs.gov/fs/2008/3027/).

Figure 1. Three-dimensional perspective view of the likelihood that each region of California will experience a magnitude 6.7 or larger (M≥6.7) earthquake in the next 30 years (6.7 matches the magnitude of the 1994 Northridge earthquake, and 30 years is the typical duration of a homeowner mortgage).

Faults are shown by the rectangles outlined in black. The entire colored area represents greater California, and the white line across the middle defines northern versus southern California. Results do not include earthquakes on the Cascadia Subduction Zone, a 750-mile offshore fault that extends about 150 miles into California from Oregon and Washington to the north.

U.S. Department of the Interior
U.S. Geological Survey
Fact Sheet 2015–3009
March 2015

Figure 3.42. First page of the UCERF3 fact sheet (http://dx.doi.org/10.3133/fs20153009).

a. UCERF3-TI, The Time-Independent Model: The backbone of UCERF3 is the long-term, time-independent model (UCERF3-TI), which was 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 (as Field et al. (2014) and Page et al. (2014), respectively). 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 an efficient simulated annealing algorithm. The approach is more derivative than prescriptive (e.g., magnitude-frequency distributions are no longer assumed), so new analysis tools were developed for exploring solutions. Epistemic uncertainties were also accounted for using 1440 alternative logic tree branches, necessitating access to supercomputers. The most influential uncertainties include alternative deformation models (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. As a notable first, three deformation models are based on kinematically consistent inversions of geodetic and geologic data, also providing slip-rate constraints on faults previously excluded due to lack of geologic data. The grand inversion constitutes a system-level framework for testing hypotheses and balancing the influence of different experts. For example, we have demonstrated serious challenges with 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. Finally, the supporting products may be of general interest, and we listed key assumptions and avenues for future model improvements in the report.

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, which posits that rupture likelihood drops on a fault after experiencing a large rupture and then builds back up as tectonic stresses re-accumulate with time. A new methodology was developed (Field, 2015) that solves applicability issues in the previous approach for un-segmented models. The new methodology also supports magnitude-dependent aperiodicity and accounts for the historic open interval on faults that lack a date-of-last-event constraint (Field and Jordan, 2015). Epistemic uncertainties are represented with a logic tree, producing 5,760 different forecasts. Results for a variety of evaluation metrics have been presented, including logic-tree sensitivity analyses and comparisons to the previous model (UCERF2). 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. Such changes are due mostly to differences in the time-independent models (e.g., fault slip rates), with relaxation of segmentation and inclusion of multi-fault ruptures being particularly influential. In fact, some UCERF2 segments were simply too long to produce M 6.7 sized events. Probability model differences are also influential, with the implied gains (relative to a Poisson model) being generally higher in UCERF3. Accounting for the historic open interval is one reason. Another is an effective 27% increase in the total elastic-rebound-model weight. The exact factors influencing differences between UCERF2 and UCERF3, as well as the relative importance of logic-tree branches, vary throughout the region, and they 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, as well as known limitations, means the applicability of UCERF3 should be evaluated on a case-by-case basis. Overall, UCERF3 represents the best model currently available for forecasting California earthquakes. UCERF3-TD was been reviewed by our Scientific Review Panel, including the aforementioned supporting papers, and the main report was published in the Bulletin of the Seismological Society of America (Field et al, 2015). A USGS fact sheet was also published (http://pubs.usgs.gov/fs/2015/3009/), and we had a press release on the day the model went public (*http://www.usgs.gov/newsroom/article.asp?ID=4146*).

c. UCERF3-ETAS, Spatiotemporal Clustering for OEF: With the time-independent and time-dependent models published (described above), we have now turned our attention to including 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). In short, OEF aims to provide real-time forecasts to help communities prepare for earthquakes. To this end, we have added an Epidemic Type Aftershock Sequence (ETAS) component to UCERF3 (UCERF3-ETAS). Most notably, our model represents a merging of ETAS with finite-fault based forecasts, as well as the inclusion of elastic rebound (both firsts, as far as we are aware). In fact, inclusion of elastic-rebound turns out to be critical in terms of getting spatiotemporal clustering statistic correct (otherwise ~85% of large triggered events simply re-rupture the same fault, which we don't see in nature). UCERF3-ETAS is currently being "test-driven". Our intent is to continue documenting the model and subjecting it to more rigorous testing (e.g., via CSEP) over the next year. Toward operationalization, the USGS and SCEC are co-funding a series of OEF-related workshops at the USGS Powell Center in Fort Collins, CO (https://powellcenter.usgs.gov). The first workshop, held in March 2015, addressed the "Potential Uses of OEF", for which a report has been written and submitted to Seismological Research Letters (Field et al., 2016). Forthcoming workshop topics include "Best Available Science for OEF", "Operationalization Challenges for OEF", and "Verification and Validation of OEF", where the latter includes testing effectiveness of product messaging.

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

CSEP activities have continued within a vigorous international collaboration, ranging from software development via model development and testing to workshops and conference sessions. Software development at SCEC has focused on installing new models, evaluating results, and upgrading CSEP software and hardware. CSEP also hosted a workshop at the 2014 SCEC annual meeting in collaboration with the USGS and the Global Earthquake Model (GEM) Foundation.

a. Testing the USGS Hazard Model: Testing seismic hazard assessments (SHAs) generally faces one over-riding challenge: the lack of data. This challenge consists of two components: the lack of earthquake occurrence, and the lack of records even when there are earthquakes. Compared with testing individual components of a SHA, it is even more challenging in this aspect for testing the whole outcome of a SHA because, regardless of the seismicity of a region, earthquakes that sufficiently contribute to the hazard of interest are always rare events.

Mak et al. from GFZ Potsdam have confronted this challenge by two means: to use a spatial-temporal aggregation approach, and the tentative use of a new form of data. Spatial-temporal aggregation means testing the hazard of the region as a whole, instead of point hazard that is the direct outcome of a SHA. This converts rare event (with respect to a point location) to a less rare event (with respect to an area). Even so, most regions in the world are not instrumented with sufficient accelerometers to record earthquake ground motion. Macroseismic intensity data generated by an internet-based earthquake ground-motion collection system, "Did You Feel It?" (DYFI), was used as a proxy for true ground motion data.

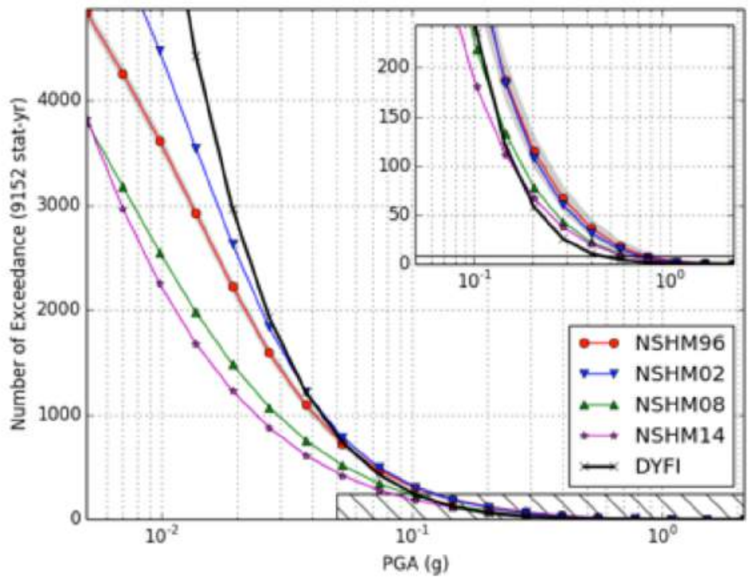


Figure 3.43. Hazard curves of all NSHM models (in color) compared with the observation from DYFI (black). The inset shows the hatched part enlarged. For the higher ground motions, the models overestimate the recurrence compared to the observation. [Mak et al., in preparation]

With a control of data completeness, the observed seismic hazard as a whole by DYFI data collected from 2000 to 2015 in California was compared with the corresponding hazard predicted by the National Seismic Hazard Maps (versions 1996, 2002, 2008, 2014). The same comparison was also performed using instrumental data. Both the DYFI data and instrumental data provided consistent results, and so confirm the usefulness of DYFI data. This analysis was then extended to compare the observed seismic hazard by DYFI to the predicted one at the Central and Eastern US (CEUS), where instrumental data are lacking.

This study reveals a conservative (slight but statistically significant) hazard prediction for California, and a slight (but statistically significant) underprediction for CEUS. It also shows the most recent version of the hazard maps is the most consistent with the observed hazard.

b. Retrospective evaluations of a rate-and-state Coulomb stress model: The GFZ group developed and tested a rate-and-state Coulomb-based seismicity rate forecast for the Japan CSEP testing regions (all of Japan, Mainland and Kanto). Unlike previous physics-based forecasts submitted to CSEP, stress is calculated through inverting variations in past seismicity rates for Coulomb stress steps over defined time intervals (Dieterich et al., 2000). Compared to deriving the stress tensor from a fault dislocation model, the rate-and-state Coulomb stress inversion relies upon fewer (often) assumed physical parameters such as the coefficient of friction or receiver-fault orientation. Additionally, stress singularity artifacts, which often distort the Coulomb stress field near fault patch boundaries, are smoothed when inverting seismicity for Coulomb stress changes. Using background seismicity rates derived from inter-earthquake distances (Ogata, 2011), the model calculated the Coulomb stress evolution and expected seismicity rates over three years, one year, three months and one day in 2009 and following the Tohoku earthquake. The hybrid Coulomb-ETAS forecast underestimates the number of earthquakes during the testing periods; however, the stress perturbations improve the spatial distribution of these events compared to the original ETAS forecast. As anticipated from Dieterich's study, the stress inversion method yields more consistent associations between stress change and earthquake distribution over longer time intervals, displaying potential to be applied in long-term, alarm-based earthquake forecasts. This model is now under prospective testing in CSEP Japan.

c. Collaboration with CSEP Japan: We have intensified the collaboration with CSEP Japan. D. Schorlemmer has visited the Earthquake Research Institute (ERI) at the University of Tokyo two times in 2015 and will visit again in October 2015. Besides keeping the testing center at ERI running and using the latest CSEP software distribution, scientific collaborations are ongoing. Together with H. Tsuruoka and N. Hirata, CSEP is investigating the resolution dependence of current CSEP seismicity rate testing metrics. Initial results indicate a noticeable dependence but these findings need further investigation to deliver recommendations for further CSEP testing strategies. A. Strader from GFZ Potsdam was visiting ERI and is developing a physics-based rate-and-state Coulomb model for the testing regions of California and Japan (see previous section). This model development will include several Japanese researchers to further strengthen the collaboration. D. Schorlemmer has finished a study on the network recording completeness of the Japan Meteorological Agency covering the entire period of instrumental earthquake recording (1923 to 2014). The results will soon be publicly available. Currently, D. Schorlemmer is developing a system at ERI to track recording completeness in near real-time from 2015 on.

d. Collaboration with the Global Earthquake Model: CSEP has worked together with the Global Earthquake Model (GEM) Foundation in the field of testing earthquake forecasts, ground-motion prediction equations and hazard. The result of testing the USGS hazard model have been presented in a previous section. This work continues with testing the Japanese hazard model to cover two of the most important hazard models. In the domain of seismicity model testing, investigations of the GEAR1 model are upcoming, see next section.

e. Installing and Evaluating Global Earthquake Forecasting Models: CSEP has installed two new global earthquake forecasting models for prospective testing. The first model SHIFT-GSRM2f by Bird and Kreemer (2015) calculates seismicity rates from a new global strain rate map and provides an interesting alternative to seismicity-based forecasts. The second global model (GEAR1) was developed by Bird et al. (2015) in collaboration with the GEM Foundation and optimally combines a smoothed seismicity model and a strain rate model to provide complimentary forecasting skill. CSEP is now developing the software codes for new testing metrics (based on Kagan's information gain scores) to investigate the forecasting power of these and other global models. Software development and the evaluation is being led by the GFZ Potsdam CSEP/GEM team.

f. Retrospective Evaluation of Time-Dependent Earthquake Forecasting Models during the 2010-12 Canterbury, New Zealand, Earthquake Sequence: The M7.1 Darfield earthquake triggered a complex earthquake cascade that provides a wealth of new scientific data to study earthquake triggering and evaluate the predictive skill of short-term earthquake forecasting models. To provide maximally objective results, a global CSEP collaboration of scientists from the US, New Zealand and Europe conducted a retrospective evaluation of short-term forecasting models during this sequence. Their primary objective was to assess the performance of newly developed physics-based Coulomb/rate-state seismicity models and hybrid statistical/Coulomb models against observations and against extant Omori-Utsu clustering models such as the Epidemic-Type Aftershock Sequence (ETAS) model. In stark contrast to previous CSEP results, Werner et al (2015) observed that Coulomb/rate-state models and hybrid Coulomb/statistical models provided more informative

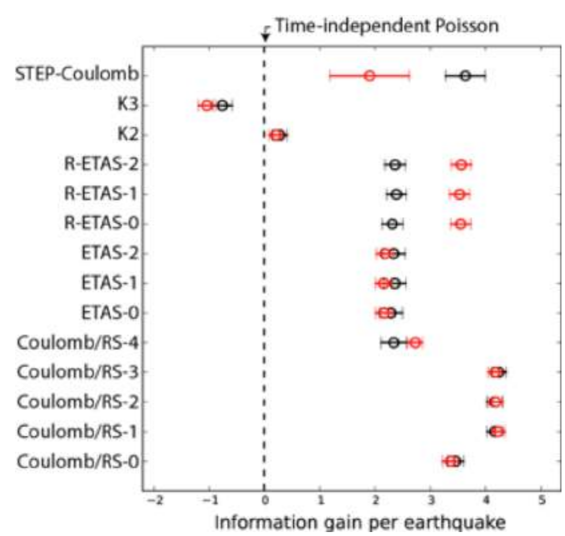


Figure 3.44. Figure 1: Information gains of 1-year forecasts issued right after the 2010 Darfield earthquake and updated once in September 2011. Black: retrospective mode using best available data. Red: pseudo-prospective mode using near-real-time data. [Werner et al., 2015].

forecasts during the sequence than statistical models over all tested forecast horizons (1-year, 1-month and 1-day). They also evaluated the effect of near-real-time data on the quality of the forecasts by using daily real-time catalog snapshots obtained by the CSEP New Zealand testing center during the sequence. Surprisingly, forecasts do not universally degrade in quality when real-time data is used as input; results are model-dependent.

g. Ensemble Modeling: CSEP is implementing strategies for combining multiple models for optimal forecasts. Both linear as well as multiplicative combination strategies are being pursued. Werner et al. (2015b) combined 1-day forecast models in California using Bayesian Model Averaging (BMA). Their preliminary results (Figure 3.45), which cover a one year period from 2012 to 2013, show that the optimal ensemble model is heavily dominated by just several models, while the weights of other models quickly diminish towards zero. Specifically, the models K3 and ETAS_K3 (which is itself an ensemble model) comprise the lion's share of the weights for the ensemble model after several months of data.

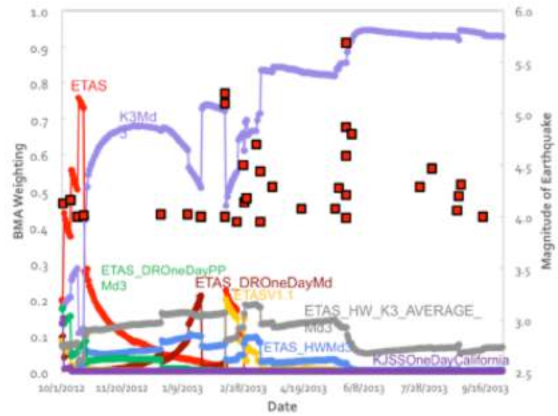


Figure 3.45. Bayesian model averaging of 1-day earthquake forecast models over a one-year period from 2012 to 2013 within the CSEP California testing region. Red squares indicate magnitudes of observed earthquakes. Curves indicate model weights. [Werner, Coe and Rougier, 2015].

h. Development of External Forecasts and Predictions (EFP) Experiments: CSEP has designed and implemented a communication protocol for registering externally generated predictions in collaboration with the QuakeFinder group. A machine-readable xml schema was developed to transmit earthquake predictions from QuakeFinder to CSEP, as well as a file transmission protocol to automate and sanity-check the delivery of earthquake predictions.

14. Community Modeling Environment

SCEC Community Modeling Environment (CME) researchers develop structural models of California faults and geology, develop and validate rupture physics models, perform large-scale regional wave propagation simulations, collaborate with engineers studying engineering response to ground motions, and integrate computational improvements into probabilistic seismic hazard calculations. This past year's accomplishments include:

- Implemented the UCERF3 time-dependent model in OpenSHA leading to the release of UCERF3 time-dependent model in 2015 (Field et al., 2015). OpenSHA, a USGS and SCEC software development project since 2001, was recently approved by USGS for use producing national seismic hazard maps.
- Used a version of the SORD dynamic rupture software to simulate ruptures on rough faults (Shi, et al., 2013). These simulations produce ruptures with frequencies up to 10Hz. The group then used the output from these simulations as ruptures for high frequency deterministic ground motion simulations.
- Continued to develop deterministic ground motion software that models advanced physics of earthquakes. Both groups have developed versions of their codes that model frequency dependent Q. Roten et al. (2014) developed code that models plastic yielding. Jacobo's group has performed simulations for Japan with water-based wave propagation, and simulations using topography (Restrepo et al., 2014).
- Developed GPU versions of earthquake wave propagation codes for both AWP-ODC and Hercules. The GPU version of the AWP-ODC code is about 4-6x faster than the CPU version (Poyraz et al., 2014), while the GPU version of the Hercules code is about 2x faster than the CPU version.
- Performed a series of validation studies that evaluate alternative SCEC CVMs at frequencies up to 5Hz. Taborda et al. (2014) evaluated CVM-S4, CVM-H, and CVM-S4.26 using Chino Hills and La Habra events. They also explored the impact of various GTL implementations, working to identify the one that performs best.

- Created 3D velocity models for central California. As part of SCEC's Geoinformatics project, the group is improving these models using full 3D tomographic methods including both observed earthquakes and ambient noise (Lee et al., 2014). They have shown significant improvement in how well 3D ground motion simulations fit observed waveforms when results using the improved central California model are compared to results using the starting central California model.
- Produced a public release of the Unified Community Velocity Model (UCVM) software in March 2014, and a public release of the CVM-H velocity model in January 2015. The most recent UCVM software provides access to CVM-S4.26, includes functionality to add small-scale heterogeneities into output models, and provides an improved installation approach. The CVM-H release provides access to the CVM-H discussed in the 2015 USR publication (Shaw et al., 2015).
- Produced two public releases of the SCEC Broadband Platform in March 2014 (Maechling et al., 2015) and in March 2015. The released software was used in two scientific and engineering evaluations including the Southwest US Ground Motion Characterization SSHAC Level 3 Study and the PEER NGA-E project (Dreger et al., 2015).
- Received 167M SUs and nearly 800TB of temporary storage on DOE INCITE computers in 2015, and received 12.2M node hours (~390M CPU hours) and nearly 2PB temporary data storage on NSF Blue Waters computer in 2015-2016. SCEC also received allocations on USC HPC and XSEDE computers in 2015.
- Jordan presented plenary research talks at both the 2014 Blue Waters Meeting and the 2014 Oak Ridge National Lab User Meeting, and Maechling presented at the 2015 Blue Waters Meeting.
- In 2014, used NSF Blue Waters to calculate four alternative southern California Physics-based PSHA CyberShake hazard models based on CVM-S4, CVM-H, BBP 1D model, and CVM-S4.26. These simulations integrated results from UCERF-2, BBP project, USR, full 3D tomography, and SCEC's HPC GPU code development efforts.
- In 2015, used NSF Blue Waters and DOE Oak Ridge Leadership Computing (OLCF) Titan computers to calculate a 1Hz Los Angeles Region CyberShake hazard model. These calculations are being used to extend the CyberShake urban seismic hazard model for the Los Angeles region up to seismic frequencies as high as 0.5 Hz.
- Held two meetings to discuss CyberShake calculations in collaboration with ASCE and USGS engineering groups.
- Iinitiated a ground motion modeling validation activity that will simulate historic earthquakes at 4Hz and higher frequencies. Two groups have produced ground motion simulation results at 4Hz using alternative methods. Initial results are for simple velocity models, and will build complexity towards validation against observations.
- Continued to extend, enhance, and operate the CSEP testing center. Liukis has worked with CSEP scientists in order to create a series of new CSEP releases including January, April, and October 2014, and January and April 2015.

a. SCEC Velocity Models: We have continued to develop the Unified Community Velocity Model (UCVM) platform as a common framework for comparing and synthesizing Earth models and delivering model products to the geoscientists (e.g., the EarthScope community). UCVM is an integrated software framework designed to provide a standard interface to multiple, alternative, 3D velocity models. It includes an easy-to-use CVM query interface; the ability to integrate regional tomographic, basin structure, and geotechnical models; and automated CVM evaluation. The UCVM software enables users to quickly build meshes for earthquake simulations through a standardized, high-speed query interface. We have registered seven different CVMs into the UCVM including southern and central California velocity models improved using F3DT.

b. Hercules Code Development: Hercules wave propagation code development continues under the leadership of Bielak and Taborda. Their research during this period focused on four main areas: GPU and performance tools implementation; Hercules Git release and documentation; modeling topography effects; and modeling of coupled earthquakes and tsunamis. We completed the implementation of a GPU module and a performance monitoring module on Hercules, one of the parallel codes in our High-F simulation software framework. Hercules is a multifaceted finite element-based solver capable of simulating either elastic or anelastic wave propagation effects. We developed a numerical scheme based on a fictitious domain ground motion in the presence of realistic surface topography of the Earth's crust. We showed that by adapting a non-conforming octree-based meshing scheme associated with a virtual representation of the topography, we can obtain accurate representations of ground motion. We incorporated acoustic wave propagation and gravity effects into Hercules in order to capture the generation and offshore propagation of tsunamis triggered by suboceanic earthquakes. We addressed the coupled nature of earthquakes and the resultant tsunamis through a case study of the 2011 Tohoku-Oki event. We focused on the generation, offshore propagation of the tsunami waves using publicly available velocity and source models. Initial results are consistent with the arrival times, wave heights, and location where the tsunami first hit the coast of Japan. To effectively use hybrid parallel architectures such as the ORNL Titan and NCSA Blue Waters systems, Hercules was refactored to utilize Nvidia GPU accelerators. Specifically, the stiffness contributions, attenuation contributions, and the displacement updates modules of the code now use the CUDA SDK. These operations comprise the majority of the physics calculations performed by the solver when determining the solution to the anelastodynamic equations. As part of our SEISM software engineering efforts, Hercules was moved from a private to a public GitHub repository. With this change the code is now offered openly to users, and is on path to become a community software of wider use beyond SCEC activities. Currently, the code is in use by researchers from 6 different universities in the U.S., Mexico, Colombia, and Europe (France), as well as by researchers from the USGS.

c. AWP Code Development: We have made important advancements improving the underlying physics of our AWP Software. We have implemented non-associated Drucker-Prager nonlinear rheology following the return map algorithm in the scalable AWP-ODC Wave Propagation finite difference code to model wave propagation resulting from the ShakeOut source description. We are making good progress on implementing frequency-dependent Q(f) into AWP-ODC, for both CPU and GPU versions. Preliminary results indicate that the efficient coarse-grained approach is accurate for Q as low as 20 over a bandwidth of two decades. The AWP-ODC-GPU software has matured rapidly, and after careful evaluation in 2014, we are now using this highly scalable and efficient code for high-frequency deterministic, CyberShake reciprocity-based, and non-linear plasticity project simulations. The exceptional capabilities of SDSC and SCEC GPU-based high performance code were publically recognized by the NVIDIA Corp. The HPGeoC team at San Diego Supercomputer Center, led by Yifeng Cui, was selected to receive the 2015 NVIDIA Global Impact Award for development and use of the AWP-ODC-GPU code, in recognition of this GPU code's outstanding performance on GPU-enabled supercomputers including Blue Waters and Titan, and for the broad impact application of the code, including its use for SCEC CyberShake calculations.

d. CyberShake Hazard Model: During year 3 of the SEISM project, we have continued development of the CyberShake Platform. CyberShake is capable of generating the very large suites of simulations (>108 synthetic seismograms) needed for physics-based probabilistic seismic hazard analysis (PSHA). A CyberShake PSHA Study 14.2, begun in February, 2014 during SEISM project year 2, used the UCERF2 earthquake rupture forecast and calculated hazard curves for 286 sites in southern California at frequencies up to 0.5 Hz for multiple 3D velocity models. Starting in April 2015, in SEISM Project year 3, SCEC's research team used NCSA Blue Waters and OLCF Titan supercomputers to perform CyberShake Study 15.4 which was completed within 38 days, before end of May, 2015. This computation produced a Los Angeles region seismic hazard model, shown in Figure 3.46, that doubled the maximum seismic frequency represented in the Los Angeles urban seismic hazard model, from 0.5 Hz to 1 Hz. Seismic hazard curves were derived from large ensembles of seismograms at frequencies below this maximum for 336 surface sites distributed across the Los Angeles region. This new probabilistic model uses refined earthquake rupture descriptions through revisions to the conditional hypocenter distributions and the conditional slip distributions. This seismic hazard calculation used the CVM-S4.26 3D velocity model, which was validated and improved using ALCF Mira, as the best available southern California 3D velocity model. In order to complete our first 1Hz CyberShake simulations within weeks, rather than months, we divided the computational work between OLCF Titan and NCSA Blue Waters. We defined the distributed calculation using scientific workflows that automatically executed our parallel GPU intensive calculations on OLCF Titan, executed GPU parallel jobs and CPU-based post-processing on Blue Waters, and transferred scientific data products back to SCEC systems for visualization and archiving. Combined uses of both systems enable us to complete a CyberShake hazard model within the practical operational limits of our research group. Our previous CyberShake Study 14.3 used only Blue Waters. Adding OLCF Titan resources enabled us to complete a 1Hz CyberShake hazard model for the first time by proving timely access to large number of GPUs, and support for automated, distributed end-to-end scientific production simulation projects. The CyberShake 15.4 model provides new seismic hazard information of interest to broad impact customers of CyberShake, including seismologists, utility companies, and civil engineers responsible for California building codes.

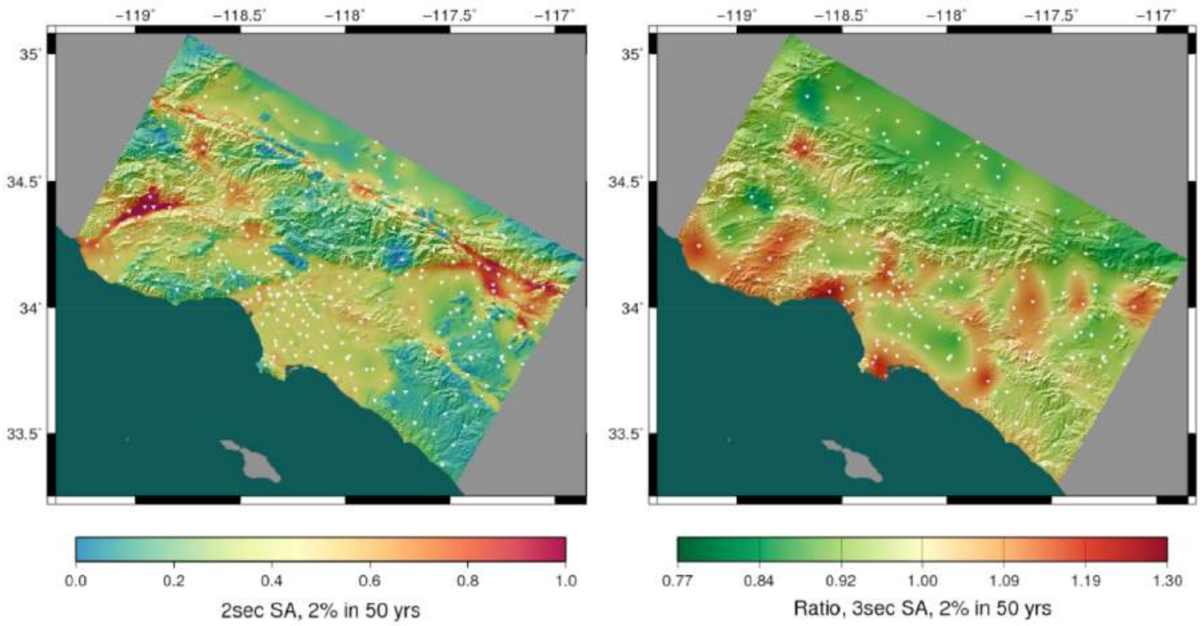


Figure 3.46. (left): CyberShake Study 15.4 hazard map for 336 sites in the Los Angeles region. Map displays response spectral acceleration at 2 seconds period in units of surface gravitational acceleration (g) for a 2% probability of exceedance in 50 years. Warm colors represent areas of high hazard. (right): Ratio of CyberShake Study 15.4 spectral acceleration at 3 seconds period to values from our previous CyberShake Study 14.2. Red colors represent areas where Study 15.4 has higher hazard, green colors where it has lower values.

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. Bob deGroot is assistant director for CEO's Education, Experiential Learning and Career Advancement activities. In June SCEC welcomed Sharon Sandow to the CEO team as assistant director for Strategic Partnerships. John Marquis is digital products manager and webmaster. Jason Ballman is Communications Specialist. David Gill provides support to CEO as web developer. Several contractors for ECA and ShakeOut activities complement the SCEC CEO staff, along with 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.

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.

Evaluation of the CEO program is conducted each year by SCEC's external Advisory Council, via annual reporting of milestones and metrics to funding agencies, as part of individual activities (post-ShakeOut surveys, teacher workshop evaluations, post-internship discussions, etc.), and as part of proposal reviews. In Spring 2015 a new "CEO Planning Committee" comprised of members of the SCEC Advisory Council and SCEC Community Stakeholders, selected to represent the four CEO focus areas, was established to provide additional guidance and support for the portfolio of SCEC CEO activities and partnerships that have significantly expanded during SCEC4, review reports and evaluations, and identify synergies with other parts of SCEC and external organizations. In addition, an experienced program evaluator has reviewed the CEO program overall including its evaluation structures in 2015. Analyses for each CEO area were provided along with recommendations for how to expand and improve evaluation, including a new comprehensive logic model to tie all CEO activities to a set of long term intended outcomes. The results indicate that the SCEC CEO program plays an important role in earthquake education and preparedness, and the evaluation's recommendations have influenced the CEO program plan for SCEC5.

SCEC CEO has been very successful in leveraging its base funding with additional support. For example, since 2010 FEMA has provided SCEC and its Earthquake Country Alliance partners nearly $1.5 million for ECA activities and national ShakeOut coordination. ShakeOut regions in the U.S. and internationally have also provided funding, and 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 Most recently NOAA has provided funding to SCEC for developing the TsunamiZone.org website.

Summary of 2015 CEO Evaluation

- SCEC CEO programs embody the advancement of discovery and understanding while promoting teaching, training, and learning.
- The SCEC Internship Programs are a key way in which SCEC CEO has successfully broadened participation of under-represented groups.
- SCEC CEO program activities are integrated in that [ShakeOut] drill efforts coordinate with K-14 education programs.
- SCEC programs are uniformly high quality, science-based, and effective.
- SCEC has been successful in teaching safety skills and motivating earthquake preparedness.
- As a trusted "honest broker", SCEC continues to provide essential leadership by bringing together and supporting key audiences to improve earthquake safety.
- Since its inception, SCEC CEO has grown and expanded its programs in strategic ways.

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 2015 conference is titled "Strengthening our Cities: From Policy to Reality" and will be held November 4-5 in Los Angeles. Also in November SCEC/ECA is supporting two "Quakesmart Business Preparedness Summits" in the San Francisco Bay Area, whch will educate business owners and managers on non-structural and structural mitigation practices. 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 SCEC, earthquake science, and how to become prepared for earthquakes and tsunamis. SCEC's work in this area spans California, the nation, and the world.

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, under the guidance of a Steering Committee comprised of three representatives of the regional alliances in Southern California, the Bay Area, and the North Coast. 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. Participants develop and disseminate common earthquake-related messages for the public, share or promote existing resources, and develop new activities and products. SCEC develops and maintains all ECA websites (*www.earthquakecountry.org*, *www.shakeout.org*, *www.dropcoverholdon.org*, and *www.terremotos.org*) and social media accounts (*facebook.com/earthquakecountryalliance* and *twitter.com/eca*) and has managed the printing of the "Putting Down Roots" publication series throughout the state. In 2014 a special “Northridge Earthquake Virtual Exhibit” (*earthquakecountry.org/northridge*) 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 were also made for the Loma Prieta 25th anniversary (*earthquakecountry.org/lomaprieta*).

In 2015, SCEC and its ECA partners organized a special webpage in response to the movie *San Andreas* at *earthquakecountry.org/sanandreas*, with FAQs about earthquake science and preparedness, a listing of what the movie got wrong and what it got right, and the “Seven Steps to Earthquake Movie Safety” with animated graphics.

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
- Public Sector
- Healthcare
- K-12 Schools
- Non-Profits and Faith-Based Organizations
- Seniors and People with Disabilities
- Speakers Bureau (Southern California)

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.

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 2014 ECA was given an award from the American Red Cross for “Excellence in Disaster Preparedness”.

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. 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 (Tokyo), New Zealand, Southern Italy, and a new “Global” site for all other areas.
2013: 24.9 million
All above plus: CO, DE, HI, MT, OH, WV, WY, 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: 26.5+ million
All above plus FL, KS, NM, Yukon, Quebec, participation in 20+ other countries via Aga Khan Development Network.
2015: 43.9 million
All above plus IA, LA, NE, TX, and partnerships with several new countries, including national school drills in Iran.

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.

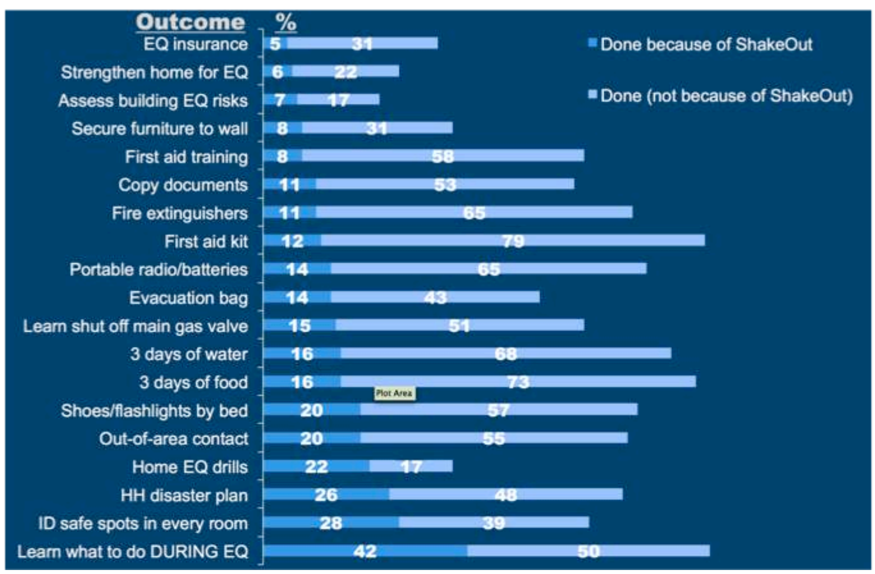
As of 2015, 28 Official ShakeOut Regions (each with their own website managed by SCEC) now span 45 states and territories, three Canadian provinces, New Zealand, Southern Italy, and a rapidly growing number of Japanese cities and prefectures. All of these areas are holding ShakeOut drills annually (see the global homepage at *www.ShakeOut.org*), except New Zealand (every few years, including 2015). 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, including Iran (which has annual earthquake drills in its schools involving more than 14 million students and staff).

The 2015 ShakeOut on October 15 at 10:15 a.m. again broke records with over 10.5 million participants registered in California and more than 43.9 million worldwide. Including drills held on other dates in 2015. Our goal was 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."

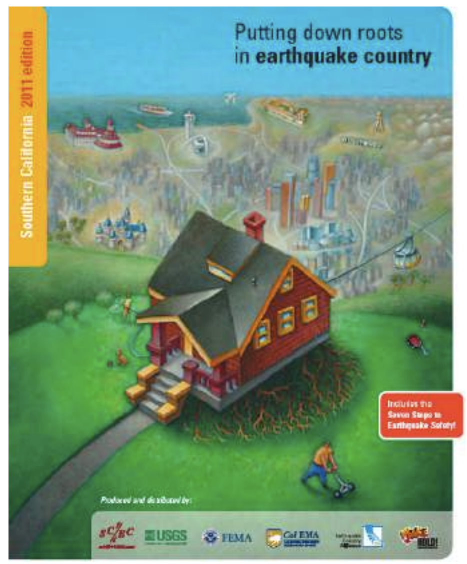
c. Other Preparedness Campaigns

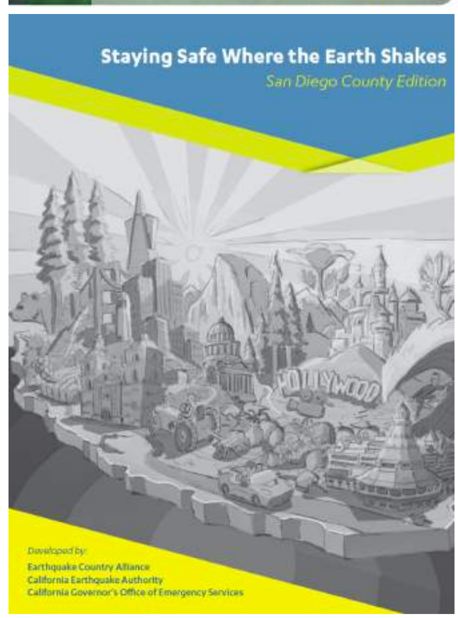
ShakeOut is the model for FEMA's "America's PrepareAthon!" national campaign (*www.ready.gov/prepare*), designed to assess preparedness activities nationwide as directed by Presidential Policy Directive 8 [http://www.dhs.gov/presidential-policy-directive-8-national-preparedness]. ShakeOut registration totals are included in this assessment, and SCEC provides contracted support to FEMA for the expansion of ShakeOut, to advise FEMA on the development of the PrepareAthon effort (including advice for strategies related to other hazards), and to assist in overall recruitment efforts.

To expand our educational and preparedness efforts for tsunamis, SCEC created *www.tsunamizone.org* in 2014 for California's participation in National Tsunami Preparedness Week (last week of 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. In 2015 the site was expanded to provide similar services for other parts of the US and internationally, with 120,000 participants registered. Like ShakeOut, TsunamiZone registrations are included in America's PrepareAthon.

d. Putting Down Roots in Earthquake Country and Other Publications

Putting Down Roots in Earthquake Country, a 32-page handbook, has provided earthquake science, mitigation, and preparedness information to the public since 1995. *Roots* was first updated in 2004, including the creation of the *Seven Steps to Earthquake Safety* to organize the preparedness content. Since then the handbook has undergone five additional revisions and printings totaling 3.5 million copies. The first Spanish version of *Roots* was produced in 2006. The Fall, 2008 version added overviews of the ShakeOut Earthquake Scenario and the Uniform California Earthquake Rupture Forecast study (*Field et al., 2009*). The 2011 version included new tsunami science and preparedness content.





The booklet has spawned the development of region specific versions for the San Francisco Bay Area, California's North Coast, Nevada, Utah, Idaho, and the Central U.S. (totaling an additional 4 million copies). 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. 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.

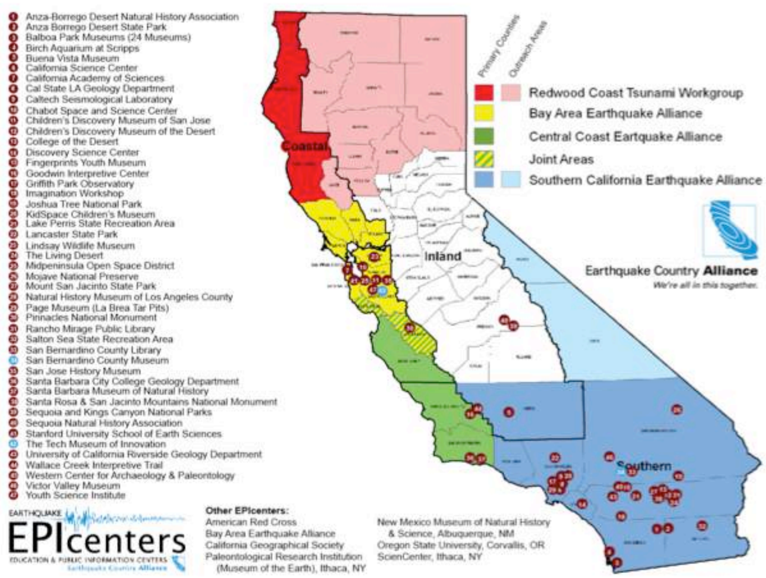
Beyond updates focusing on content, new versions or translations of the publication will expand the reach of *Roots* with particular emphasis on underserved communities. This will involve partners that specialize in communicating in multiple languages and via culturally appropriate channels. Additionally, 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. All regional editions as well as statewide Spanish and Chinese versions are available at earthquakecountry.org/stayingsafe 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.

e. 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.

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.

Quake Catcher-EPIcenter Network. In 2015 a new partnership was established between SCEC, IRIS, Caltech, and USGS to continue the expansion and development of QCN worldwide, beginning with installations in summer 2015 by SCEC in several Central U.S. schools. For several years, 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 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.

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.

f. 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 1059 followers, and *facebook.com/scec* has 2,813 “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.

In 2015 SCEC coordinated with USGS, CalOES, FEMA and other partners to address issues with the movie *San Andreas*, including numerous interviews and resources organized by SCEC at *www.earthquakecountry.org/sanandreas*, including “fact or fiction” analysis. The response also included extensive social media engagement, for which SCEC created the “Seven Steps to Earthquake MOVIE Safety” (*www.earthquakecountry.org/moviesafety*), a parody of our standard “Seven Steps” messaging.

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 was conducted again in December, 2014 as part of the combined NSTA/CSTA meeting in Long Beach. The trip was co-hosted by SCEC and the InSight Vital Signs of the Planet Program (see below).

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 October, 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. 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.

InSIght participants Kim Kocaya (Van Avery Prep, Temecula) and Yolanda Seebert (Vernon Middle School, Montclair) occupy a GPS site in Perris, CA.

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.

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 2015, twelve science educators and one student participated and their posters are displayed at the 2015 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. More than 270 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. Due to the Special Olympics World Games being hosted at USC, the USEIT program was not held in 2015.

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 1600 eligible applications for SCEC internship programs were submitted (at *www.scec.org/internships*), with more than 540 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). Since 2010, underrepresented minority interns averaged 36.4% of each year's class, with a high of 43% in 2014. Women represented an average of 48.2% of interns, with a high of 57% in 2014. First generation college attendees have averaged 31.2% of each class. 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.

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.

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.

High School level. Experiential learning opportunities for high school students are 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. One high school student participated in the 2015 Insight VSP program (some years there have been up to 4; this depends on the teachers involved).

Early Career Researchers. 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. 2016 Science Collaboration Plan

1. What's New This Year

The most substantial changes in this year's Science Collaboration Plan include:

- 2016 is the final year of the SCEC4 research program. Proposals should not include plans that will involve multi-year efforts beyond January 2017, except for proposed CCSP-related research projects.
- Develop methods for combining GPS and InSAR data in the CGM by characterizing seasonal/hydrologic/anthropogenic signals, accounting for earthquake effects as needed, and quantifying covariances in order to produce a reliable consensus model. An explicit call for simulations of earthquake ruptures such as those defined in the Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3).
- An explicit call for a synthesis of results at the Ventura and San Gorgonio Pass special fault study areas.
- A call to develop improved representations of, and user interfaces to, the USR.
- The need for develop and implement simulation methods for the modeling of bending faults and multi-segment ruptures.
- A further request to compare and assess engineering metrics in ground motion validation.
- A call to catalog the quality and supporting evidence for unique offsets, and to develop techniques to estimate slip distributions from field, LiDAR, and SfM datasets.
- A call to test potential rupture histories using geometrically realistic fault configurations in dynamic rupture models.

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 crustal motion model consisting of velocities and time series for southern California that leverages the complementary nature of GPS and InSAR observations. This requires development of optimal methods for combining GPS and InSAR data, characterizing seasonal/hydrologic/anthropogenic signals, accounting for earthquake effects as needed, and quantifying covariances in order to produce a suite of reliable models. Proposals should demonstrate coordination with the current activities and established timeline of the CGM project. 2016 work should focus on completion and evaluation of the CGM merged GPS time series solution; estimation and comparison of velocities, seasonal, and earthquake-related motion from these time series; and development of InSAR velocity maps for the southern California region. Technique development to prepare for full utilization of legacy and newly available SAR data for time series analysis and identification of optimal approaches for mitigating temporally and spatially correlated noise in GPS or InSAR time series are also particularly encouraged.

- **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 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 paleoseismic 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 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. PIs are 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.

Priorities for Earthquake Geology

- Support integrative research and synthesis of results at the Ventura and San Gorgonio Pass special fault study areas.
- Requests for geochronology support should include a plan for timely completion of sample collection, processing, and analysis by the end of SCEC4.

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

- Reengineering and optimizations of HPC codes, required to reach SCEC research goals, for parallel systems with multi-core processors, GPU accelerators and/or Xeon Phi coprocessors, with emphasis on issues such as performance, portability, interoperability, power efficiency and reliability.
- 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, advanced seismic data format, visualization and end-to-end approaches.
- 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
    - Validate SCEC community velocity models.
    - Develop high-frequency simulation methods and investigate the appropriate upper frequency limit of deterministic ground motions.
    - 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.
    - Develop wave propagation incorporating more advanced media response, including inelastic material response and scattering by small-scale heterogeneities and topography.
- Tomography
    - Assimilate regional waveform data into the SCEC community velocity models.
- Rupture dynamics
    - 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.
    - 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
    - Model a suite of scenario ruptures, incorporating material properties and fault geometries from the unified structural representation projects.
    - Isolate causes of amplified ground motions using adjoint-based sensitivity methods.
- Data-intensive computing
    - 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.

  - Integrate Big Data analytics techniques involving software stacks such as Hadoop, fault recovery, data format, generation, partitioning, abstraction and mining.
- Engineering applications
  - 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.
  - 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 (NOTE: May choose to highlight specific items following discussions at the Annual Meeting.) into the CVMs with validation of improvements for ground-motion prediction. Perform waveform and geophysical inversions for evaluating and improving the CVMs. Develop and apply procedures (i.e., goodness-of-fit measures) for evaluating updated models against observations (e.g., waveforms, gravity, etc) to discriminate among alternatives and quantify model uncertainties.
- ***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, represented 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 geometry. Evaluate the new CFM version (5.0) with data (e.g., seismicity, seismic reflection profiles, geologic slip rates, and geodetic displacement fields) to discriminate among alternative models. Update the CFM-R (rectilinear fault model) to reflect improvements in the CFM. Improve the statewide CFM in regions outside the SCEC CFM in coordination 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. Develop improved representations of and user interfaces to the CVMs in support of additional features, including characterization of uncertainties and small-scale features, and scalable computing (laptops to large scale clusters). Develop new tools and formats for making the CFM geometries and properties available to the user community. 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. These efforts should be coordinated with SCEC CME efforts.

b. Fault and Rupture Mechanics (FARM)

The primary mission of the Fault and Rupture Mechanics focus group is to develop physics-based models of the nucleation, propagation, and arrest of dynamic earthquake rupture. We specifically 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 source-inversion benchmarks, and generate synthetic data of various types (seismic, static, far-field, near-field) in cooperation with other SCEC groups; collaboration with the Source Inversion Validation (SIV) TAG 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 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).
- Preparatory efforts, including creep law compilations and a database and modeling framework design workshop, to finalize the design criteria for the future Community Rheology Model (CRM), integrating these FARM priorities with the community modelling efforts.
- 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

- Seismological imaging of crust, lithosphere and upper mantle using interface and transmission methods with the goal of characterizing the 3-D distribution of isotropic and anisotropic wave speed variations. Assembly of 3D lithological models of crust, lithosphere, and mantle based on active- and passive-source seismic data, potential field data, and surface geology.
- Contributions to our understanding of geologic inheritance and evolution, on faults and off, and its relation to the three-dimensional structure and physical properties of present-day crust and lithosphere. Contributions to efforts of building a 4-D model of lithospheric evolution over 10s of Myr for southern California.
- 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.
- Development of models of interseismic, earthquake cycle and long-term 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. Incorporation of rheological and geometric complexities and such models and exploration of mechanical averaging properties. Assessments of potential discrepancies of models based on geodetic, geologic, and seismic data. Development of deformation models (fault slip rates and locking depths, off-fault deformation rates) in support of earthquake rupture forecasting.
- 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.
- Contributions to the development of a Community Stress Model (CSM), a set of spatio-temporal (4-D) 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) for validation, 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.
- Preparatory efforts, including creep law compilations and a database and modeling framework design workshop, to finalize the design criteria for the future Community Rheology Model (CRM), which ideally informs many of the core SDOT priorities.

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 Engineering 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 (e.g. in sedimentary basins). 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. Note that the Central California Seismic Project (CCSP, see below) targets this goal specifically for Central California.
- Develop and implement simulation methods for the modeling of bending faults and multi-segment ruptures. The highest priority need is for kinematic rupture generators for implementation on the Broadband Platform (BBP). Proposals are requested for 1) including the software modeling capability itself and 2) scientific research (e.g., analysis of dynamic rupture modeling on multi-segmented faults) to inform input parameters such as the timing of the i^{th} segment rupture, moment distribution on segments and so on (see CME section on this RFP for related efforts).
- 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. Develop and implement methods for computing and storing 3D Green's functions (GFs) for use in the Broadband Platform. Proposals for both source- and site-based GFs are solicited (see CME section on this RFP for related efforts).
- 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).
- 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. Compare and assess engineering metrics in ground motion validation. 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) is encouraged.

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 that will improve understanding of the last 2000 years of this fault system. This includes radiocarbon dating and analysis of stratigraphic evidence of paleoearthquakes.
- 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. Catalogue the quality and supporting evidence for unique offsets, develop techniques to estimate slip distributions from these datasets.
- 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, test rupture histories using geometrically realistic fault configurations in dynamic rupture models.

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 requires 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 2016. 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 Broadband Platform Validation Project.
- Develop validated and efficient methods for either i) adjusting ground motion time series simulated by the SCEC 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)

The WGCEP is a collaboration between SCEC, the USGS, and CGS aimed at developing official earthquake-rupture-forecast models for California. The project is closely coordinated with the USGS National

Seismic Hazard Mapping Program, and has received financial support from the California Earthquake Authority (CEA). The WGCEP has now completed the time-independent UCERF3 model (UCERF3-TI, which relaxes segmentation and includes multi-fault ruptures) and the long-term, time-dependent model (UCERF3-TD, which includes elastic-rebound effects). We are now working on adding spatiotemporal clustering (UCERF3-ETAS) to account for the fact that triggered events can be large and damaging. As the latter will require robust interoperability with real-time seismicity information, UCERF3-ETAS will bring us into the realm of operational earthquake forecasting (OEF). We are also starting to plan for UCERF4, which we anticipate will utilize physics-based simulators to a greater degree (see last bullet below).

Example Research Strategies

- 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 total 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.
- Determine the extent to which seismicity rates vary over the course of historical and instrumental observations (the so-called Empirical Model of previous WGCEPs), and the extent to which this is explained by aftershock statistics.
- Determine the applicability of higher-resolution smoothed-seismicity maps for predicting the location of larger, more damaging events.
- 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

- Retrospective Canterbury experiment: finalizing the retrospective evaluation of physics-based and statistical forecasting models during the 2010-12 Canterbury, New Zealand, earthquake sequence by (i) comparing retrospective forecasts against extent prospective models, (ii) 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);
- Supporting 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), with specific focus on how to automate the identification of a large earthquake with a modeled fault;
- 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 models);
- 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;
- 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)

Note: SCEC has not yet received the final year of funding for VISES. Funding under this program is contingent on SCEC receiving funds for the final year of VISES from NSF. Travel support for successful proposals will be managed from SCEC headquarters. Do not include overhead in the proposed budget.

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.

e. Central California Seismic Project (CCSP)

Note: Terms of the master agreement funding CCSP limits indirect costs to 15%. Please use this rate only for CCSP proposal budgets.

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 seismic hazard estimation with a particular emphasis of reducing the uncertainty in path effects.

A pilot project focused on the central coast of California was 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 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.

f. Collaboratory for Interseismic Simulation and Modeling (CISM)

The Collaboratory for Interseismic Simulation and Modeling (CISM) is an effort to forge physics-based models into comprehensive earthquake forecasts using California as its primary test bed. Short-term forecasts of seismic sequences, in combination with consistent long-term forecasts, are critical for reducing risks and enhancing preparedness. CISM seeks to improve predictability by combining rupture simulators that account for the physics of rupture nucleation and stress transfer with ground-motion simulators that account for wave excitation and propagation. CISM forecasting models will be tested against observed earthquake behaviors within the existing Collaboratory for the Study of Earthquake Predictability.

g. National Partnerships through EarthScope

The NSF EarthScope program (*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/information/publications/science-plan/*). 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 Milestones and Metrics

The SCEC Communication, Education, and Outreach (CEO) program developed a series of milestones and metrics to assess progress during SCEC4. The rationale for adding metrics, as well as milestones, for the CEO program, is that these activities lend themselves well to the type of detail (such as the number of participants in an earthquake preparedness exercise) represented by metrics. The latest CEO milestones and metrics are posted online as part of the 2014 annual report to the agencies (http://www.scec.org/sites/default/files/SCEC4_2014AnnualReport.pdf). The summary that follows is excerpted from *Evaluation of SCEC Communication, Education, and Outreach Program* by M. M. Wood (2015). Each major activity is assessed based on a set of 83 metrics, each with yearly quantitative milestones. The *Evaluation* includes an evaluation of this set and recommended reducing the overall number significantly to allow more focused and sustainable assessment of those metrics that are most diagnostic of a successful program. The account that follows focuses on those recommended by Wood's evaluation.

1. ShakeOut Earthquake Drill

The targeted annual number of California ShakeOut participants has been exceeded for both 2013 (9.6 million actual/9.5 million target) and 2014 (10.4 million actual/10 million target). The number of California individual/family registrants targeted was not met in 2013 (16,513 actual/50,000 target) or 2014 (11,012 actual/70,000 target). The number of participants in other ShakeOut regions was exceeded for both 2013 (11.3 million actual/5.0 million target) and 2014 (9.9 million actual/5.5 million target). Since its inception, the ShakeOut has demonstrated exceptional traction as it has spread across the national and international communities, with growing support and community engagement.

2. Earthquake Country Alliance

To date, SCEC CEO and ECA have recruited 686 ECA associates, exceeding the target of 660, indicating successful engagement. ECA operates eleven functional and sector committees including committees representing: businesses, communications, EPIcenters (museums, parks, libraries, etc.), evaluation, fire advisory committee, government emergency managers and elected officials, healthcare, K-12 schools, non-profits and faith-based organizations, seniors and people with disabilities, and the Southern California Speakers Bureau. In 2014, ECA had more than 150 participants of functional and sector communities, exceeding the target of 80. SCEC CEO has established fewer memoranda of understanding (MOUs) with strategic partners than targeted. Increasing the number of partners with MOUs has been a challenge (4 actual of 15 targeted). While those MOUs already in place represent successful, productive partnerships, SCEC CEO would like more partnerships with which to establish a more formal relationship. SCEC CEO has brought in external funding from FEMA to support ECA activities in recent years. SCEC CEO has met or exceeded targets for developing area-specific versions of *Putting Down Roots in Earthquake Country*. In the past year, new California versions of "*Roots*" in different languages or for other audiences continued, and the publication was updated as planned in 2015. Formal and informal feedback from selected ECA members indicates that SCEC continues to be viewed as a neutral and trusted leader, and employs a collaborative model to organizing stakeholders around a common cause. This "culture of collaboration" has provided for a more organic, bottom-up rather than a top down, approach to building the community. Establishing MOUs with existing partner organizations may help SCEC CEO expand its coordinating influence and work even more effectively in the coming years.

3. EPIcenters

The cumulative total number of participating museums, parks, and other free choice EPIcenter learning venues in California and other states approached the target in 2014 (68 EPIcenter actual/75 target). The cumulative number of partner national organizations met the established target in 2013 (5 of 5) and approached the target in 2014 (5 of 7). The annual number of field experiences exceeded targets (2 actual/1 target) in 2013 and met the target in 2014 (2 of 2). The number of SCEC-developed exhibits, interpretive trails, and other programs exceeded the 2013 target (4 target; 5 actual), and approached the 2014 target (6 target; 5 actual). The cumulative number of EPIcenters and schools with QCN sensors installed exceeded targets in 2014 (126+ actual/30 target). The QCN network stands out as a particular success, with many new EPIcenters and schools adding sensors in 2014. Reaching out to establish partnerships with additional national organizations in the future may facilitate the recruitment of more venues and field experiences.

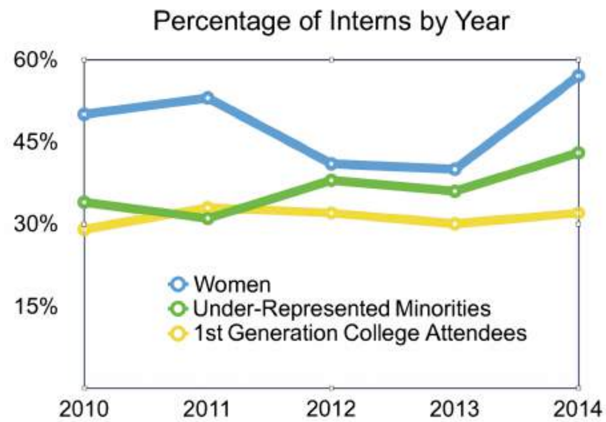
4. Media Relations

Tracking these metrics has been a challenge but SCEC CEO has purchased monitoring services that will make this easier. The annual number of traditional news advisories and releases, audio/video podcasts or online interviews, and virtual news conferences/webinars fell short of targets. The cumulative number of people in the SCEC experts directory and experts identified and trained for interviews in non-English languages also fell short of established benchmarks. SCEC CEO has conducted training events for the SCEC community and media; no milestones have been established, however.

5. K–14 Earthquake Education Initiative

SCEC CEO has excelled in meeting established milestones for this thrust area. In 2014, the annual number of event-based or place-based local/regional education activities (3 actual/2 target), number of educational materials improved or created (3 actual/2 target), number of educator workshops (10 actual/2 target), and number of educators participating in all programs (200+ actual/60 target) all exceeded the established targets. Likewise, there was a cumulative total of 9 participating educational and research institutions as of 2014, exceeding the target of 5.

6. SCEC Internship Program



As of 2014, the cumulative number of undergraduate interns (38 actual, 30 target), women interns (56 actual, 50 target), under-represented minority interns (49 actual, 25 target), and academic year projects (17 actual, 12 target) all exceeded their targets. These numbers indicate that the internship program is recruiting a sufficient number of undergraduate interns and also is successfully recruiting women and under-served minorities.

a. Career Advancement

In of 2014, the number of high school students provided with research, education, or outreach experience fell short (2 actual, 6 target), although the target was met in 2013 (4 actual, 4 target). The number of master's level opportunities exceeded the target in 2013 (5 actual, 2 target) and met the target in 2014 (4 actual, 4 target). The number of 2014 early career research presentations (6 actual, 3 target) exceeded the established target. The percentage of women (29%) and under-represented minorities (10%) in SCEC leadership positions for 2014 did not have established targets set. These could be added in SCEC5.

b. Research-Engineering Partnerships

The number of research engineers attending the 2013 SCEC annual meeting exceeded the target by a wide margin (70 actual, 12 target). There is no data available for documented uses of simulation models and other products.

7. Activities with Technical Audiences

The number of practicing engineers (39 actual, 8 target) attending the SCEC annual meeting in 2013 and the cumulative number of practicing engineers participating in the ECA (100+ actual, 50 target) as of 2014 far exceeded their targets. The annual number of training sessions, seminars, and field trips for practicing engineers, building officials, etc. (organized by SCEC or co-sponsored by) met the target (2 actual, 2 target); and no activity was reported for annual online activity. Conducting online activities is an area where SCEC CEO can improve in coming years.

V. Publications

This section lists the publications recorded in the SCEC community database between November 2014 to November 2015. Each publication is preceded by its SCEC publication number.

A. Journal Articles (164 total)

1931 Agnew, D. C. (2014). Variable Star Symbols for Seismicity Plots. Seismological Research Letters, 85(4), 775-780.

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

1846 Akciz, S. O., Grant Ludwig, L. B., Zielke, O., & Arrowsmith, J. R. (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(6).

6046 Ampuero, J., Gabriel, A., & Pelties, C. (2014). Verification of an ADER-DG method for complex dynamic rupture problems. Geoscientific Model Development, 7(3), 847-866.

6113 Ampuero, J., Shearer, P. M., Hauksson, E., & Goebel, T. H. (2015). Stress-drop heterogeneity within tectonically complex regions: a case study of San Gorgonio Pass, southern California. Geophysical Journal International, 202(1), 514-528.

1997 Anderson, J. G. (2015). The Composite Source Model for Broadband Simulations of Strong Ground Motions . Seismological Research Letters, 86(1), 68-74.

1986 Asimaki, D., & Taborda, R. (2014). Site-specific response in validation studies of physics-based earthquake simulations. Seismological Research Letters, 85(2), 470.

6067 Atkinson, G. M., & Assatourians, K. (2015). Implementation and Validation of EXSIM (A Stochastic Finite-Fault Ground-Motion Simulation Algorithm) on the SCEC Broadband Platform. Seismological Research Letters, 86(1), 48-60.

6089 Baker, J. W., Burks, L. S., & Bradley, B. A. (2015). Ground motion selection for simulation-based seismic hazard and structural reliability assessment. Earthquake Engineering & Structural Dynamics, 44(13), 2321-2340.

1951 Barall, M., & Harris, R. A. (2015). Metrics for Comparing Dynamic Earthquake Rupture Simulations. Seismological Research Letters, 86(1), 223-235.

6015 Barall, M., & Tullis, T. E. (2015). The Performance of Triangular Fault Elements in Earthquake Simulators. Seismological Research Letters, (under review).

1800 Barrett, S. A., & Beroza, G. C. (2014). An Empirical Approach to Subspace Detection. Seismological Research Letters, 85(3), 594-600.

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

6091 Bird, P., & Kreemer, C. W. (2015). Revised Tectonic Forecast of Global Shallow Seismicity Based on Version 2.1 of the Global Strain Rate Map. Bulletin of the Seismological Society of America, 105(1), 152-166.

1799 Boese, M., Graves, R. W., Gill, D., Callaghan, S., & Maechling, P. J. (2014). CyberShake-Derived Ground-Motion Prediction Models for the Los Angeles Region with Application to Earthquake Early Warning. Geophysical Journal International, 198(3), 1438-1457.

6068 Bowden, D. C., Tsai, V. C., & Lin, F. (2015). Site amplification, attenuation, and scattering from noise correlation amplitudes across a dense array in Long Beach, CA. Geophysical Research Letters, 42(5), 1360-1367.

1987 Bradley, A. M. (2014). Software for efficient static dislocation-traction calculations in fault simulators. Seismological Research Letters, 85(6), 1358-1365.

1976 Brantut, N., & Viesca, R. C. (2015). Earthquake nucleation in intact or healed rocks. Journal of Geophysical Research: Solid Earth, 120(1), 191-209.

6052 Bruhat, L., Dunham, E. M., & Fang, Z. (2015). Rupture complexity and the supershear transition on rough faults. Journal of Geophysical Research - Solid Earth, (under review).

1964 Burks, L. S., & Baker, J. W. (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., Zimmerman, R. B., & Baker, J. W. (2015). Evaluation of Hybrid Broadband Ground Motion Simulations for Response History Analysis and Design. Earthquake Spectra, 31(3), 1691-1710.

2064 Bydlon, S. A., & Dunham, E. M. (2015). Rupture Dynamics and Ground Motions from Earthquakes in 2D Heterogeneous Media. Geophysical Research Letters, 42(6), 1701-1709.

1973 Chen, T., Akciz, S. O., Hudnut, K. W., Zhang, D., & Stock, J. M. (2015). 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, 105(2a).

1942 Coble, C., French, M. E., Chester, F. M., Chester, J. S., & Kitajima, H. (2014). In situ frictional properties of San Andreas Fault gouge at SAFOD. Geophysical Journal International,.

2060 Cox, P. A., Stubailo, I., & Davis, P. M. (2014). Receiver Functions and Tomography Study along the Monterey Micro-Plate and Isabella Anomaly. Bulletin of the Seismological Society of America, (in preparation).

1980 Crempien, J. G., & Archuleta, R. J. (2014). UCSB Method for Broadband Ground Motion for Kinematic Simulations of Earthquakes. Seismological Research Letters, (accepted).

2085 Crempien, J. G., & Archuleta, R. J. (2015). UCSB Method for Simulation of Broadband Ground Motion from Kinematic Earthquake Sources. Seismological Research Letters, 86(1), 61-67.

1898 Curren, I. S., & Bird, P. (2014). Formation and suppression of strike-slip fault systems. Pure and Applied Geophysics, (under review).

1911 Deelman, E., Vahi, K., Juve, G., Rynge, M., Callaghan, S., Maechling, P. J., Mayani, R., Chen, W., da Silva, R., Livny, M., & Wenger, K. (2014). Pegasus, a Workflow Management System for Large-Scale Science. Future Generation Computer Systems, (under review).

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6057 Shi, Z., & Day, S. M. (2015). Implications of Observed Fault Geometry and Stress Field on Rupture Dynamics Along the SGP Section of the San Andreas Fault. Poster presentation at 2015 SCEC Annual Meeting.

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6049 Withers, K. B., Olsen, K. B., Shi, Z., & Day, S. M. (2014). High-Complexity Deterministic Q(f) Simulation of the 1994 Northridge Mw 6.7 Earthquake. Poster presentation at 2014 SCEC Annual Meeting.

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. ***Community 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.

<u>Year 3 (2014-2015)</u>

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. Develop and evaluate regional velocity models 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.

<u>Year 4 (2015-2016)</u>

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 UCERF2 and large suites of ground motion simulations up to 1 Hz calculated from improved CVMs. Provide interactive access to CyberShake simulation results.[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. Begin applying 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 ground motion simulations of well recorded southern California earthquakes and apply goodness-of-fit measures to evaluate existing southern California CVMs using earthquake waveform data. Calculate southern California CyberShake hazard models based on extensions of UCERF3, southern California CVMs, and large suites of ground motion simulations up to 1 Hz. Provide interactive and programmable access to CyberShake results. [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 secular rates, 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.*** Submit for publication 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.*** Through workshops and at the annual meeting, evaluate the work completed under the SFSA and develop synthesis reports on the utility of the work in improving seismic hazard models for California. [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 complicat-ed) 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, guide-lines, 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. 2015 Report of the SCEC Advisory Council

1. Introduction

The SCEC Advisory Committee (AC) met at the Annual SCEC meeting in Palm Springs from Sept. 13 to 16, 2015 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 (Farzad Naeim, Inc.)
- Tim Sellnow* (University of Kentucky)
- John Vidale* (University of Washington)
- Andrew Whittaker (University of Buffalo; Director, MCEER)

The AC met initially on Sept. 13 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 AC feedback was sought. Following the leadership briefing, the AC discussed the agenda for the next few days and shared initial thoughts. The key focus activities for this meeting were defined at that time as: (i) a review of SCEC4 accomplishments, and any suggestions for areas to focus efforts in the final year of SCEC4; and (ii) an overview-level review of the SCEC5 proposal draft (to be submitted to funding agencies by SCEC no later than Oct. 1). The purpose of the AC preview of the SCEC5 proposal was to provide confidential feedback to SCEC leadership for their consideration in fine-tuning the final proposal. That information was conveyed separately to the SCEC leadership and is not a part of this report.

Over the following three 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, and two members of the AC also participated in the CEO Planning Committee meeting on Tues. evening. The AC also reviewed a comprehensive workbook prepared for us by the SCEC leadership, as well as reviewing a draft of the SCEC5 proposal. 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 over its 25 year history, SCEC has become the world’s most effective, sustained and cohesive collaboration of earthquake scientists, dedicated to understanding the physics behind earthquake hazards at all scales, and addressing their impacts on society. SCEC has international stature and recognition as a model of the benefits of collaboration, wherein the whole is greater than the sum of its parts. This is all the more remarkable because the SCEC parts represent a stunning breadth of expertise. SCEC displays consistently cutting-edge science, making major inroads in understanding earthquake faulting processes and their implications for ground motions. SCEC’s earthquake engineering interactions represent a major SCEC4 accomplishment that provides a compelling rationale for support of SCEC5.

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

2. Structure of the Advisory Council

Director Jordan requested our input on whether the structure of the AC is effective, and solicited ideas on recruiting new members. We believe that the AC structure works well and we do not suggest any changes. Recruiting new and continued engineering participation would be useful. One possibility would be to tap into the globally-oriented engineers in groups such as those coordinated by Brian Tucker or Elizabeth Hausler (those individuals might be asked for suggestions?). It may also be useful to solicit participation of an LA-based engineer. On the simulations side, an AC member with knowledge in earthquake physics would be helpful.

3. SCEC Management Structure

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4. Annual Meeting, and Engagement of New Scientists

SCEC could consider surveying early-career level scientists at the next meeting, and asking for their suggestions on how to best enhance their participation and satisfaction with the meeting. Overall we think that the single-session form of the meeting remains effective, though this does make it more intimidating for younger scientists to ask questions. The poster sessions work well to showcase the work of SCEC scientists at all levels.

5. Feedback on the Major SCEC Initiatives

We congratulate SCEC on the success of its major new initiatives. We recognize that these are essential and important components of the SCEC program, in terms of both scientific scope and funding diversification. These new projects set the stage for a successful SCEC5. They are also providing SCEC with high political visibility and access.

The CISM initiative will enable improved and more comprehensive physics-based earthquake forecasts to be developed from evolved models of faulting in California, thus advancing our understanding of faulting hazards. The AXCESS program will make important computational strides in extending and validating earthquake ground-motion simulations at higher frequencies (>1 Hz), and facilitating physics-based seismic hazard modeling. The Central California project holds real promise for both understanding and reducing the uncertainties in ground motion models that drive seismic hazards at low probabilities. These major SCEC initiatives have transformative potential to increase our knowledge of earthquake hazards.

6. Assessment of CEO Advisory Structure and External Evaluation

An initial meeting of the CEO Planning Committee has been convened. It is off to a good start, and helped inform the direction of CEO for the SCEC5 proposal. It is too soon to make a detailed evaluation of how this structure is working; in another year we should be better positioned to evaluate its functionality. It would be useful to consider how to integrate new SCEC products with CEO activities.

We reviewed the CEO Report prepared for SCEC by Michelle Wood. The last few pages of this report were the most useful. The conclusions and basic recommendations of the Wood report make sense, including the recommendation to reduce the number of metrics that are tracked. It may be more useful to evaluate in greater depth the effectiveness of a small number of metrics, rather than gathering many statistics on the accessing of various documents.

7. SCEC4 Accomplishments

The AC devoted much of its discussions to progress made in SCEC4 in the six fundamental topic areas. We offer the following observations and suggestions for SCEC as it goes into the final year of SCEC4.

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

The imaginative combination of InSAR and GPS spatial and temporal data offers advantages for constraining fault motions in both the far and near field. A better understanding of locked vs. creeping sections of faults is emerging. The promise of newly available InSAR products can provide better temporal coverage and orthogonal-look pairs essential for constraining 3D surface motions in the final year of SCEC4. The discovery of the apparent slip deficit in southern California from paleoseismic data raises important new scientific questions that will extend into SCEC5.

b. Stress-mediated fault interactions and earthquake clustering

Particular achievements of note in this topic include the outstanding work on stress and strain modeling. Beyond the quality, we appreciate the approach to involve all modelers that would like to be involved, and the decision to open the dataset to everyone. There is still a lot of scientific work to be done as testified by the coordinators and explicitly written in SCEC5, but the communities have made excellent progress and are on the right track.

Earthquake simulators are the main target of one recent special project of SCEC (CISM). In SCEC4 simulators started to show their potential, for instance in describing earthquake clustering at different time scales – the short time scale typical for aftershocks, and a longer time modulation that may potentially explain the clustering observed in paleoseismic trenches and the so-called open interval conundrum in California seismicity. CISM is a world-leading initiative.

A retrospective CSEP experiment carried out in New Zealand to forecast the Canterbury sequence shows, for the first time, that some physics-based models may provide better 1-year forecasts than models based on empirical rules. This is certainly encouraging for the future SCEC activities in this field.

Overall, the work in this topic is the foundation for operational earthquake forecasting, which is a key direction for SCEC and for seismic risk mitigation.

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

SCEC4 has made remarkable progress in many diverse areas, ranging from imaging and analysis of fault zone properties, to modeling the non-linear and plastic contributions to fault slip, and incorporating these elements into dynamic rupture simulations. The work on dynamic rupture models moves the ground-motion simulation problem from kinematic models to more fundamental physical behavior of faults and ruptures. The systematic verification of these models through the dynamic rupture TAG has been ongoing for several years and shows that the models can be used and get reliable results. Recent studies have addressed the application of the verified dynamic rupture models to compute ground motions. These studies are mainly sensitivity studies and in many cases show large effects of parameter variations. What seems to be missing at this point is more comprehensive validation of the dynamic rupture models against ground motion data. This should be a focus in the final year of SCEC4.

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

Excellent progress has been made in the last 2 years, especially with the flourishing Special Fault Study Areas (SFSA). Both the San Gorgonio Pass and Ventura SFSAs have been successful at fostering collaborative teams to undertake and assemble paleoseismic and structural studies of multiple fault strands. These show that multiple strands are simultaneously active across regions to accommodate slip, at times producing very large earthquakes. SCEC research in other regions has also demonstrated with geodetic and geologic observations that multiple active strands constitute broad fault zones that may evolve over the long term.

The Ventura SFSA has added offshore seismic interpretations, including constraints from folding and sedimentation. It has also incorporated tsunami modelling. The structural models have enabled numerical rupture calculations which show that throughgoing multiple strand ruptures are possible depending on initial stress and nucleation points.

The SCEC community is on track to successfully complete this SCEC4 component, by considering the probability of suites of plausible rupture scenarios in the two SFSAs.

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

SCEC researchers have developed transient detection methodology, but the main example of such phenomena in southern California remains the 2009 Bombay Beach swarm, which is detectable in searches for anomalous ETAS behavior of an earthquake swarm, and also in searches for a distinct deformation transient.

The only triggered tremor identified, which is thought likely to arise from a deformation transient, remains that from the 2002 Denali Alaska earthquake. New ways to search for LFEs continue to be developed, with the hope of finding deformation transients. This area of investigation appears to have been satisfactorily concluded for SCEC4.

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

Significant accomplishments in SCEC4 have been made in extending physics-based models of ground motion to higher frequencies, and in validating simulations to enable their use in engineering applications. These developments hold the promise of allowing reduced epistemic uncertainty in prediction of ground motions for future large events, which has tremendous practical significance and cost implications in earthquake engineering.

The validation of the broadband platform is a major step forward in developing physics-based ground motion models and it is now in a form that can be used for engineering applications. Several recent studies also showed validation of kinematic ground motion simulation models against empirical data. What has not been addressed is how much do the ground motion models rely on physics and how much of the performance relies on calibration to empirically recorded ground motions. For example, if there are parameters in the models that are adjusted to fit the sparse available GM data, are these models mean-centered? How much better are the constraints than just using the empirical models? For the last year of SCEC4, it may be useful to try to evaluate how much of the current kinematic models are controlled by physics and how much is controlled by empirical calibration.

Several other developments in SCEC4 in this topic area are also noteworthy accomplishments. Significant progress has been made on physics-based high-frequency GM simulations, covering the frequency range from 0 to 10Hz, including evaluation of the goodness of fit of the simulations; an illustration has been made for the Chino Hills earthquake. Going even to 5Hz would be a major improvement that might be more achievable.

The importance of inelastic material response effects, both near fault and near surface, in dynamic rupture simulations has been demonsrated, as applied in particular to CyberShake simulations of large earthquakes on the San Andreas Fault; expected ground motions are reduced by significant amounts, showing the impact of such effects.

Full wave tomography using earthquake and ambient noise fields can be effective to improve the CVM; these techniques have been shown to reduce waveform misfits and can ultimately reduce epistemic uncertainty for path effects in the longer term.

Overall, SCEC4 has been transformative in engaging the earthquake engineering community to realize practical benefits from the evolution of earthquake process and hazards knowledge. This engagement has great momentum and provides a compelling rationale for SCEC5: it is expected that in SCEC5 the fruits of this momentum will be fully realized.

8. CEO Comments for last year of SCEC4

The expansion of CEO and its increasing level of collaborative activities with IRIS, UNESCO, and engagement of a broad spectrum of stakeholders, has been a major success for SCEC4. The SCEC CEO program continues to be a global flagship for successful CEO activities. The creation of the CEO planning committee is a good step to effectively target future activities. The recent evaluation and recommendations in the Wood report provide useful guidance for concluding CEO activities in the final year of SCEC4 and transitioning into SCEC5.

The CEO Director indicated a willingness to identify a list of evaluation research opportunities for graduate students and early career researchers focusing on existing CEO materials, including scholars in Public Health, Sociology, Communication, Education, Marketing, etc. and would be a good conclusion to SCEC4 CEO efforts.

In conclusion, the AC continues to be deeply impressed with the amazing quality of science and collaboration, not to mention the boundless energy, that the SCEC community brings to the task of understanding earthquake hazards in Southern California.