Southern California Earthquake Center

Annual Report: Year 2

November 15, 2012 – November 15, 2013

Funded by Cooperative Agreements with:
NSF Award 1033462 | USGS Award G12AC20038

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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 first 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.

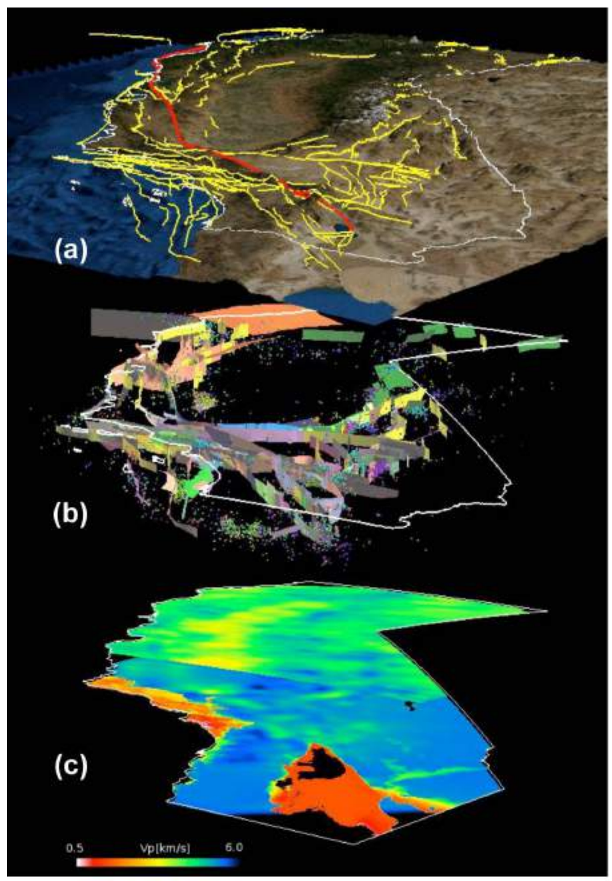

Figure 1.1. Perspective of California, looking northwest and showing elements of the Unified Structural Representation (USR): **(a)** traces of active faults (yellow lines) and the San Andreas master fault (red lines), **(b)** the statewide Community Fault Model (CFM), and **(c)** statewide Community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

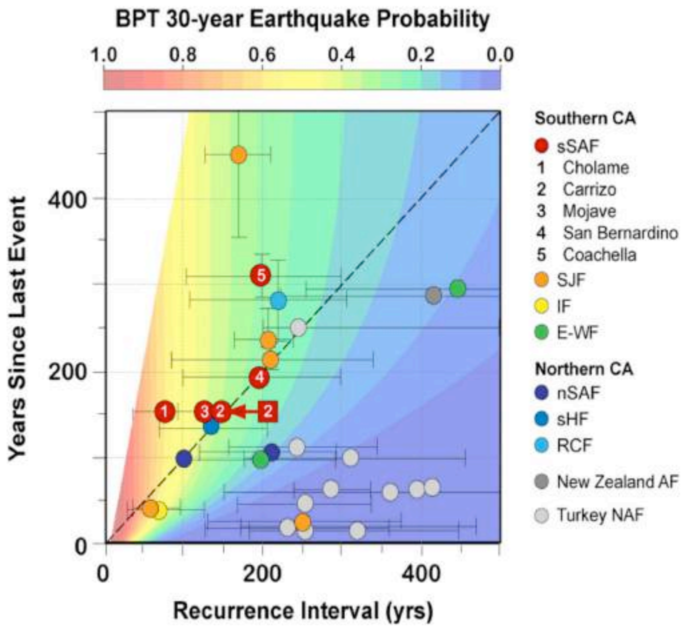

Figure 1.2. A plot of time since the last event vs. mean recurrence interval for sections of the southern San Andreas fault (red points) and other strike-slip faults in California and elsewhere. The arrow indicates the reduction in the mean recurrence interval for the Carrizo section implied by the new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

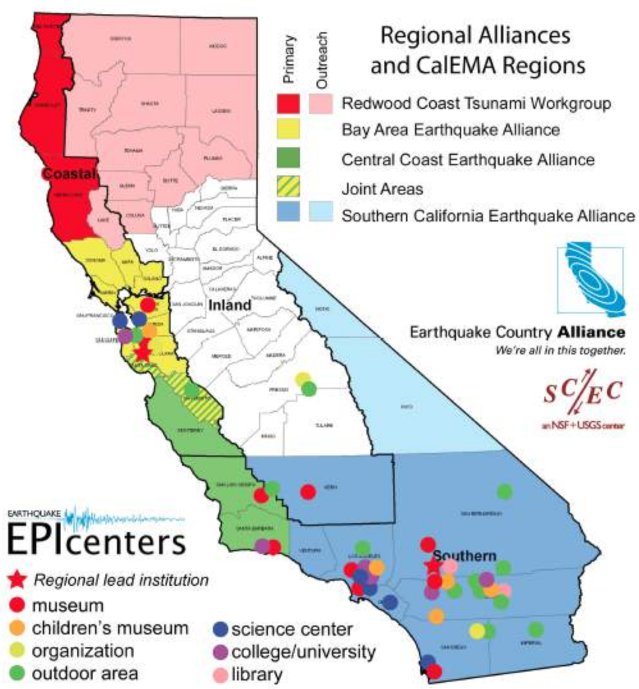

Figure 1.3. Four chapters of the Earthquake Country Alliance (colored areas) and locations of the EPIcenters (colored symbols), two key partnerships developed by the SCEC CEO program.

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 49 (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 (1632 as of November 2013) and the registrants at the SCEC Annual Meeting (560 in 2013). Annual Meeting registrations for SCEC's entire 23-year history and other demographic information are shown in Figure 1.4.

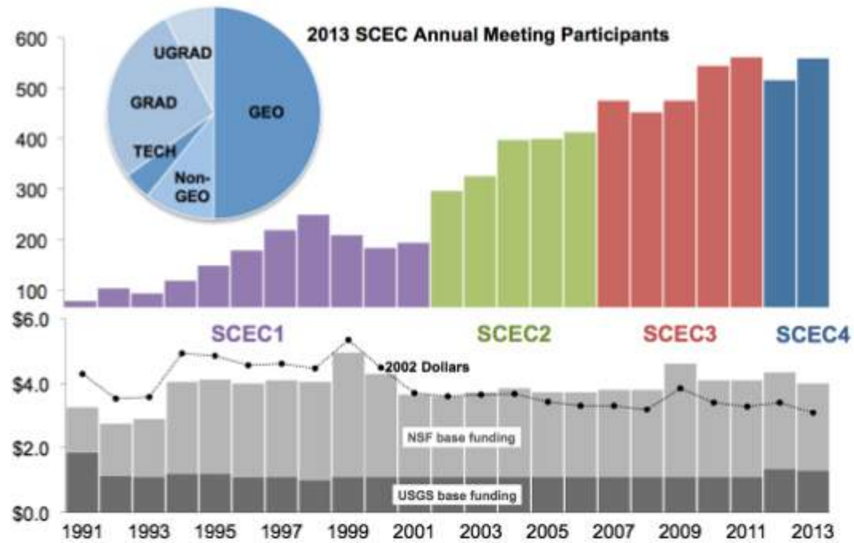

Figure 1.4. Colored bars show total registrants at SCEC Annual Meetings, one measure of how the collaboration has grown during its 23-year history, 1991-2012. Pie chart shows the demographic profile for pre-registrants (560 total) at the 2013 SCEC Annual Meeting. The lower bar chart is the history of SCEC base funding in as-spent dollars; the connected dots are the base-funding totals in 2002 dollars.

2. SCEC is a ***collaboratory for earthquake system science*** that uses advanced IT to synthesize and validate system-level models of earthquake processes. Components include the Community Modeling Environment (CME) and the Collaboratory for the Study of Earthquake Predictability (CSEP). SCEC strives to be a world-leading VO through the innovative use of "vertically integrated" platforms—cyberinfrastructure that combines hardware (equipment), software (knowledge tools), and wetware (professional expertise) to solve system-level problems. SCEC has developed a number of new computational platforms that apply high-performance computing and communication (HPCC) to large-scale earthquake modeling.

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

Table 1.1. SCEC Member Institutions (November 30, 2013)

Core Institutions (17)	Participating Institutions (49)
California Geological Survey California Institute of Technology Columbia Univ Harvard Univ Massachusetts Institute of Technology San Diego State Univ Stanford Univ U.S. Geological Survey, Golden U.S. Geological Survey, Menlo Park U.S. Geological Survey, Pasadena Univ of California, Los Angeles Univ of California, Riverside Univ of California, San Diego Univ of California, Santa Barbara Univ of California, Santa Cruz Univ of Nevada, Reno Univ of Southern California (lead)	Appalachian State Univ; Arizona State Univ; Brown Univ; California State Polytechnic Univ, Pomona; California State Univ, Fullerton; California State Univ, Long Beach; California State Univ, Northridge; California State Univ, San Bernardino; Carnegie Mellon Univ; CICESE (Mexico); Colorado School of Mines; Cornell Univ; DPRI, Kyoto Univ (Japan); ERI, Univ of Tokyo (Japan); ETHZ (Switzerland); Georgia Tech Univ; GNS (New Zealand); Indiana Univ; Inst. Earth Sciences, Academia Sinica (Taiwan); Jet Propulsion Laboratory; Lawrence Livermore National Laboratory; Nat'lCentral Univ, Inst. Geophysics (Taiwan); Nat'l Chung ChengUniv, Inst. of Seismology (Taiwan); Nat'l Taiwan Univ, Dept. Geosciences (Taiwan); Oregon State Univ; Pennsylvania State Univ; Purdue Univ; Smith College; SUNY at Stony Brook; Texas A&M Univ; Univ of Alaska, Fairbanks; Univ of California, Berkeley; Univ of California, Davis; Univ of California, Irvine; Univ of Cincinnatti; Univ of Illinois; Univ of Kentucky; Univ of Massachusetts; Univ of Michigan, Ann Arbor; Univ of New Hampshire; Univ of Oregon; Univ of Texas-Austin; Univ of Texas-El Paso; Univ of Western Ontario (Canada); Univ of Wisconsin, Madison; URS Corporation; Utah State Univ; Utah Valley Univ; Woods Hole Oceanographic Institution

4. SCEC is a ***reliable and trusted partner*** that collaborates with other organizations in reducing risk and promoting societal resilience to earthquake disasters. SCEC has partnered with the USGS and CGS to create UCERF and coordinate So-SAFE, with UNAVCO to transfer 125 stations of the SCIGN array to the PBO in Southern California, and with the Computational Infrastructure for Geodynamics (CIG), the Geosciences Network (GEON), and the Incorporated Research Institutions for Seismology (IRIS) to develop user-friendly software packages, IT tools, and educational products. The SCEC

Communication Education and Outreach (CEO) program has steadily grown a diverse network of partnerships. The statewide ECA now comprises 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.

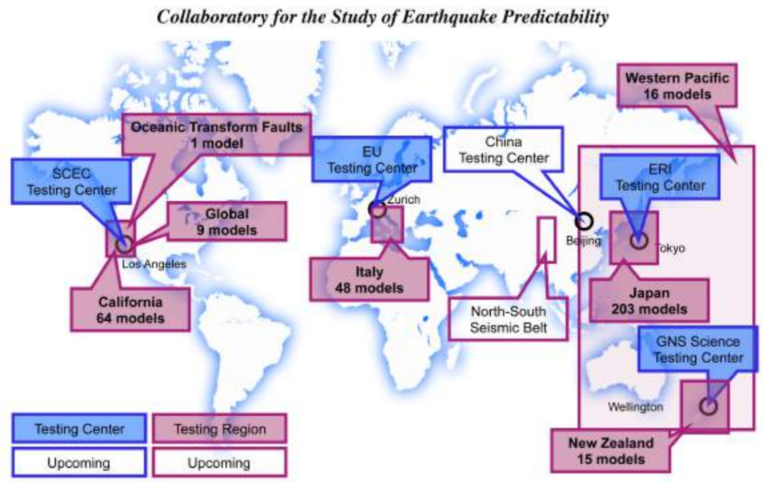

Figure 1.5. Map showing the worldwide distribution of activities developed under the Collaboratory for the Study of Earthquake Predictability (CSEP).

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.

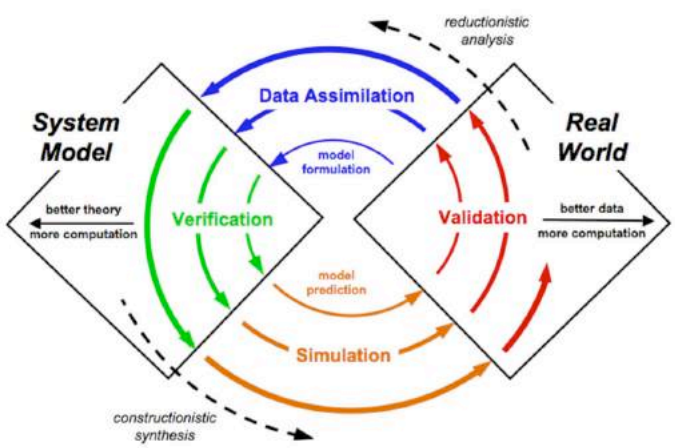

Figure 1.6. The inference spiral for system science, illustrating the improvement of system-level models through an iterated cycle of model formulation (blue), model verification (green), simulation-based prediction (orange), validation against observations (red), and data assimilation (blue). Verification 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 2013, the institutional membership stands at 66, comprising 17 core institutions and 49 participating institutions (Table 1.1). SCEC institutions are not limited to universities, nor to U.S. organizations. The California Geological Survey has joined SCEC4 as a core institution, and URS Corporation will continue as a participation institution. We are very pleased that three of the major USGS offices—Menlo Park, Pasadena, and Golden—will remain core institutions represented by liaison (non-voting) members on the SCEC Board. There are currently 10 foreign institutions recognized as partners with SCEC through a growing list of international cooperative agreements. SCEC currently involves more than 600 scientists and other experts in active SCEC projects. Registrants at our Annual Meetings, a key measure of the size of the SCEC community, is shown for the entire history of the Center in Figure 1.4.

A. Board of Directors

Under the SCEC4 by-laws, each core institution appoints one member to the Board of Directors, and two at-large members were elected by the Board from the participating institutions. The Board is the primary decision-making body of SCEC; it meets three times per year (in February, June, and September) to approve the annual science plan, management plan, and budget, and deal with major business items. The liaison members of the U.S. Geological Survey are non-voting members. The Board is chaired by the Center Director, Tom Jordan, who also serves as the USC representative. Nadia Lapusta of Caltech serves as its Vice-Chair.

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

B. Administration

The Director, Tom Jordan of USC, acts as PI on all proposals submitted by the Center, retaining final authority to make and implement decisions on Center grants and contracts, and ensuring that funds are properly allocated for various Center activities. He serves as the chief spokesman for the Center to the non-SCEC earthquake science community and funding agencies, appoints committees to carry out Center business, and oversees all Center activities.

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

The Associate Director for Administration, John McRaney of USC, assists the Center Director in the daily operations of the Center and is responsible for managing the budget as approved by the Board, filing reports as required by the Board and funding agencies, and keeping the Board, funding agencies, and Center participants current on all Center activities.

C. External Advisory Council

An external Advisory Council (AC) elected by the Board is charged with developing an overview of SCEC operations and advising the Director and the Board. Since the inception of SCEC in 1991, the AC has played a major role in maintaining the vitality of the organization and helping its leadership chart new directions. The AC comprises a diverse membership representing all aspects of Center activities, including basic and applied earthquake research and related technical disciplines (e.g., earthquake engineering, risk management, and information technology), formal and informal education, and public outreach. Members of the AC are drawn from academia, government, and the private sector. The Council meets annually to review Center programs and plans and prepare a report for the Center. AC reports are submitted verbatim to the SCEC funding agencies and its membership (Appendix C).

The SCEC4 external Advisory Council was chaired by Dr. Jeffrey Freymueller of the University of Alaska, who stepped down following this year's review of SCEC. Gail Atkinson (University of Western Ontatio) has accepted the invitation to AC chair. She has been on the AC since 2005, is very knowledge-able of the SCEC program, and we look forward to her leadership of the Council. Also joining the AC this year is Kate Long of Cal EMA.

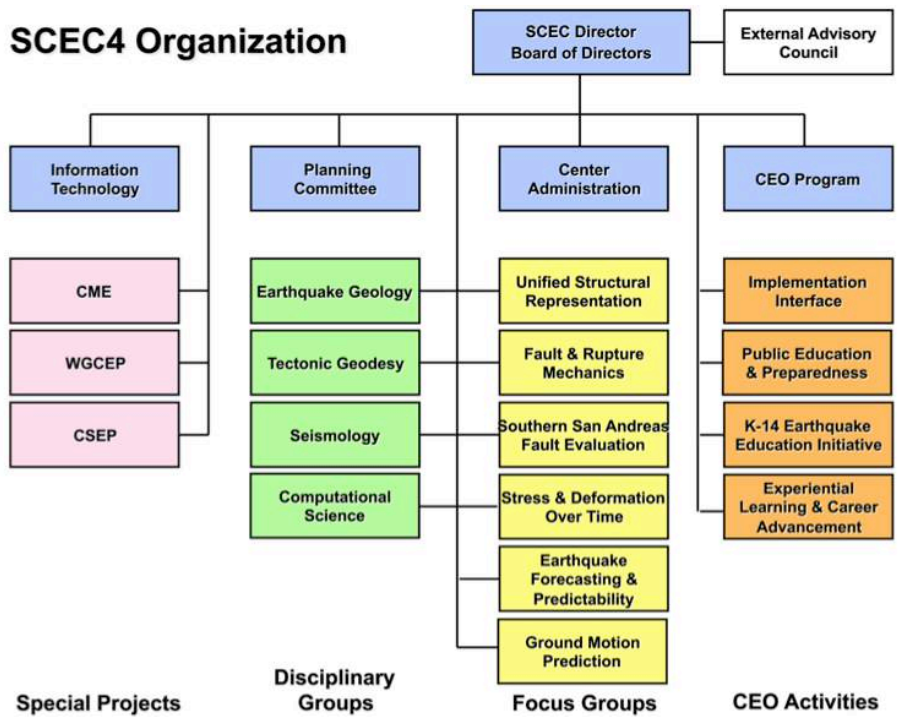

Figure 2.1. The SCEC4 organization chart, showing the disciplinary committees (green), focus groups (yel-low), special projects (pink), CEO activities (orange), management offices (blue), and the external advisory council (white).

D. Working Groups

The SCEC organization comprises a number of disciplinary committees, focus groups, special project teams, and technical activity groups (Figure 2.1). The Center supports disciplinary science through stand-ing 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 responsi-ble for disciplinary activities relevant to the SCEC Science Plan, and they make recommendations to the Planning Committee regarding the support of disciplinary research and infrastructure.

SCEC coordinates earthquake system science through interdisciplinary focus groups (yellow boxes). Four of these groups existed in SCEC3: Unified Structural Representation (USR), Fault & Rupture Me-chanics (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.

Two new working group leaders, Max Werner of Princeton University, replaced Tom Jordan as the leader of the Collaboratory for the Study of Earthquake Predictability (CSEP), and Christine Goulet of the

PEER Center at Berkeley, replaced Rob Graves as the co-leader of the Ground Motion Prediction focus group.

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.

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.

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

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

G. SCEC Participants and Diversity Plan

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

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

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

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

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

Table 2.1. Center database of SCEC participants in 2013.

	Ethnicity			**Race**					
	Latino	Not	N/A	White	Native	Asian	Black	Pacific	N/A
University/College Faculty	7	103	23	87	0	13	0	0	33
University/College Research Faculty	3	30	15	29	1	6	0	0	12
Postdoctoral Scholar	0	30	6	20	0	5	1	0	10
Staff Scientist (Doctoral Level)	1	57	23	58	0	10	0	0	13
Staff Scientist (Other)	2	25	7	20	0	2	1	0	11
Technician	0	1	2	1	0	0	0	0	2
Teacher	6	5	0	9	0	1	0	0	1
Other: Management/Administration	0	18	6	16	0	2	0	1	5
Other: Communication/Outreach/PR	0	6	2	5	0	1	0	0	2
Graduate	14	107	38	80	1	25	0	0	53
Undergraduate	15	31	15	27	1	7	2	0	24
REU Participants Only	7	12	4	11	0	3	2	0	7

	Gender			Citizenship		
	Male	Female	N/A	US	Other	N/A
University/College Faculty	104	24	5	89	32	12
University/College Research Faculty	40	5	3	24	17	7
Postdoctoral Scholar	23	11	2	18	11	7
Staff Scientist (Doctoral Level)	52	25	4	59	13	9
Staff Scientist (Other)	20	11	3	26	4	4
Technician	1	0	2	1	0	2
Teacher	4	7	0	11	0	0
Other: Management/Administration	13	9	2	20	0	4
Other: Communication/Outreach/PR	5	3	0	6	0	2
Graduate	90	59	10	91	42	26
Undergraduate	32	20	9	45	6	10
REU Participants Only	13	9	1	18	5	0

	Disability							
	None	Hearing	Visual	Mobility	Learning	Speech	Other	N/A
University/College Faculty	92	1	1	0	0	0	0	92
University/College Research Faculty	31	0	1	0	0	0	0	31
Postdoctoral Scholar	21	0	0	0	0	0	0	21
Staff Scientist (Doctoral Level)	64	0	0	0	0	0	0	64
Staff Scientist (Other)	21	0	0	0	0	0	0	21
Technician	1	0	0	0	0	0	0	1
Teacher	7	0	0	0	0	0	0	7
Other: Management/Administration	13	0	1	0	0	0	0	13
Other: Communication/Outreach/PR	5	0	0	0	0	0	0	5
Graduate	105	0	0	0	1	0	0	105
Undergraduate	37	1	0	0	0	0	0	37
REU Participants Only	15	0	0	0	0	0	0	15

H. International Collaborations

- **SCEC Advisory Council**. We have one international member, Gail Atkinson of the University of Western Ontario.
- **CEO/ShakeOut**. SCEC collaborates with Canada, New Zealand, Japan, Italy, and Tajikistan on holding ShakeOut drills. SCEC hosts the websites for all ShakeOut drills worldwide.
- **ERI/Tokyo and DPRI/Kyoto**. SCEC has long term MOU's with the Earthquake Research Institute in Tokyo and the Disaster Prevention Research Institute in Kyoto. A new partnership between SCEC and these two institutions was funded in 2012 by NSF under its Science Across Virtual Institutes (SAVI) initiative. This program will establish 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 Japan in September 2013 for students of both countries. 17 students participated from U.S. universities.
- **CSEP (Collaboratory for the Study of Earthquake Predictability).** SCEC founded CSEP in 2006. CSEP testing centers are now located at USC, ERI/Tokyo, GNS/New Zealand, ETH/Zurich, and CEA/China. Matt Gerstenberger and David Rhoades of the New Zealand testing center visited SCEC in September 2013.
- **ACES (APEC Cooperative for Earthquake Simulation).** SCEC and JPL are the U.S. organizations participating in ACES. Information on ACES can be found *http://www.quakes.uq.edu.au/ACES/*. Andrea Donnellan of SCEC/JPL is the U.S. delegate the ACES International Science Board and John McRaney of SCEC is the secretary general. The next ACES meeting is scheduled for late summer 2014 in Chengdu, China.

- **ETH Zurich/Switzerland**. Stefan Wiemar and Jeremy Zechar are participants in the SCEC/CSEP projects. Daniel Roten participates in the source inversion validation project. Luis Dalguer and Seok Goo Song participate in the rupture validation project. Georgia Cua participates on earthquake early warning algorithm testing.
- **KAUST/Saudi Arabia**. Martin Mai is the leader in the Source Inversion Validation TAG.
- **IGNS/New Zealand**. Mark Stirling, David Rhoades, and Matt Gerstenberger of the Institute for Geological Nuclear Sciences of New Zealand are involved in the CSEP program. Charles Williams 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.
- **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 2013 annual meeting from Australia, China, Japan, India, Mexico, Canada, France, Switzerland, Germany, Russia, Italy, Taiwan, Turkey, and New Zealand.
- **International Participating Institutions**. ETH/Zurich, CICESE/Mexico, University of Western Ontario, and Institute for Geological and Nuclear Sciences/New Zealand; and 4 institutions from Taiwan (Academia Sinica; National Central University; National Chung Cheng University; National Taiwan University) are participating institutions in SCEC.
- **International Travel by PI and SCEC Scientists**. The PI and other SCEC scientists participated in many international meetings and workshops during the report year. They include: 1) the CORSSA workshop in Japan in January 2013, 2) the PI visited INGV in Rome in January for CSEP collaboration, 3) the EGU assembly in Vienna, Austria in April 4) the AGU meeting of the Americas in Cancun, Mexico in May, 5) the Erice, Italy meeting on “Properties and Processes of Crustal Fault Zones” in May, 6) the IASPEI assembly in Sweden in July, 7) the REAKT workshop in Zurich in October, and 8) the workshop on statistical seismology in Beijing 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. There are currently five active TAGs. We organized this report to emphasize progress on implementing these activities - particularly those that are new to SCEC4.

1. Seismology

The Seismology Group gathers data on the range of seismic phenomena observed in southern California and integrates these data into physics-based models of fault slip. This past year's accomplishments include:

1. Archival and distribution of seismic waveforms through the Southern California Earthquake Data Center;
2. Refinement and updating of catalogs of earthquake locations and focal mechanisms and application of refined catalogs to the Community Fault Model;
3. Analysis of foreshocks, aftershocks, and triggered events to examine changes in focal mechanism variability, seismicity rates, and stress drops;
4. Application of new tremor detection techniques and analysis of crustal structure in regions where tremor is observed;
5. Development of new techniques to investigate scattering, site response, and attenuation using very dense array data.

a. Earthquake Locations, Focal Mechanisms, and Fault Representation Refinements: Revised earthquake location catalogs and focal mechanisms have been produced for the period from 1981-2011 and made available to the scientific community. The archived seismic waveforms, improved catalog, and focal mechanisms are used by SCEC researchers to investigate earthquake processes. Refined catalogs were used in updating the 3D fault representation in the Community Fault Model, particulalry within the Special Fault Study Areas of San Gorgonio Pass and Ventura Basin. Revised 3D fault representations for the major active, through-going faults of the San Andreas Fault system, including the Banning, Garnet Hill and Mission Creek strands were added (Figure 3.1).

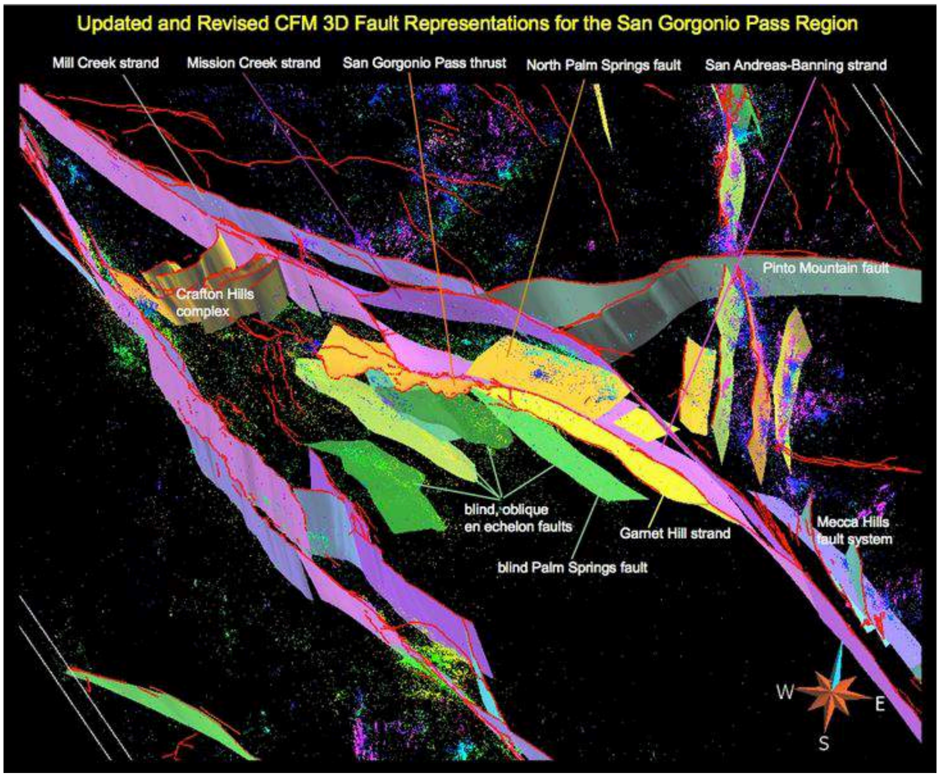

Figure 3.1. Updated and revised 3D faults developed for CFM in the region of the San Gorgonio Pass Special Fault Study Area. Revised 3D fault representations for the major active, through-going faults of the San Andreas fault system, including the Banning, Garnet Hill and Mission Creek fault strands have been added.

b. Foreshocks, Aftershocks, and Triggered Events: P. Shearer developed evidence that foreshock sequences more closely resemble swarms than cascades of triggered events, in which there is no fundamental difference between foreshocks, mainshocks, and aftershocks. This suggests that major California foreshock sequences are not caused by static stress triggering but may be driven by aseismic processes. Moreover, foreshock sequences before the Landers, Hector Mine, and El Major earthquakes have lower stress drops than aftershocks in the same region. This lends further support to the idea that the foreshocks are not primarily caused by earthquake-to-earthquake triggering. Ross and Ben-Zion (2013) found that the mechanisms of the early aftershocks are more scattered and less aligned with the mainshock than those that occur later in the Landers sequence. This observation is most pronounced around the northern end of the Landers rupture. A matched filter technique (Meng et al., 2012) was used to lower the detection level compared to standard catalogs in several regions of southern California following the El Mayor-Cucapah earthquake. From these observations, they observed increases in seismicity rates in the Salton Sea and southern San Jacinto. The section of the San Jacinto Fault located a little farther away may show a delay in seismicity rate change (Figure 3.2).

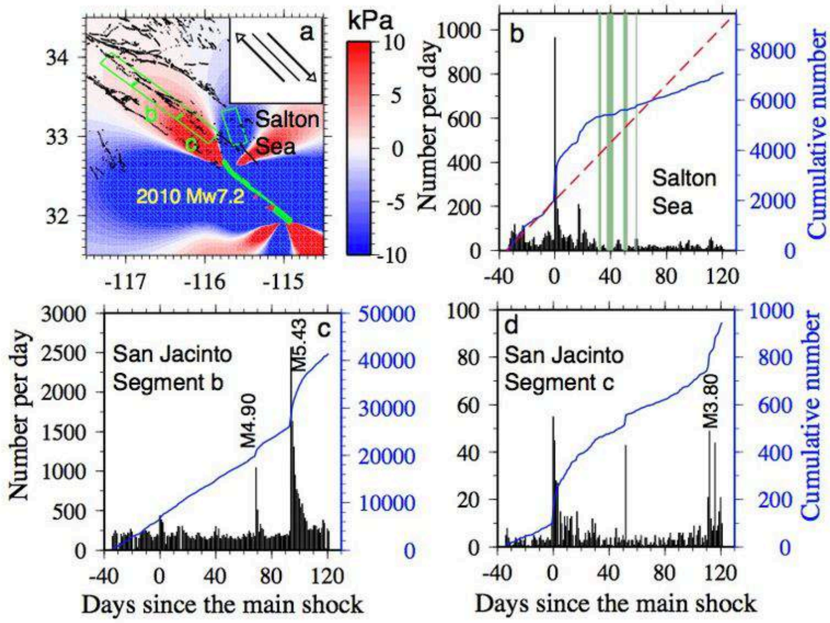

Figure 3.2. (a) Map of the estimated Coulomb stress changes due to the 2010 M7.2 El Mayor-Cucapah earthquake; and number of earthquakes per day (black) and cumulative number of earthquakes (blue) versus days since the mainshock at (b) Salton Sea, (c) San Jacinto segment b, (d) San Jacinto segment c.

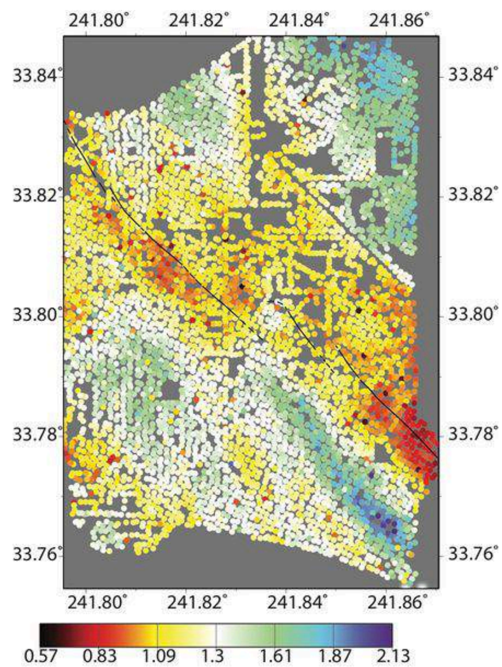

Figure 3.3. Preliminary estimate of site response at 1 Hz using ambient noise data collected by a very dense array in Long Beach, California. High amplification is shown in blue and low amplification is shown in red. The features are consistent with known variations in velocity structure and fault structure.

c. Dense Seismic Array Processing: Several groups investigated the 5,000 node seismic array data collected in Long Beach, California by Nodal Seismic. One analysis technique used a measure of entropy to track the spatial coherence of the coda after the S wave to determine the onset of spatially incoherent coda (Dominguez et al., 2013). They suggest that the transition between spatially coherent and incoherent coda marks when forward scattering from spatially coherent structures such as layering is replaces by scattering from random heterogeneities. Victor Tsai's research group used array measurements of ambient field correlations to extract site response and attenuation. Their approach allows analysis of surface-wave wavefields without the need for knowledge of the source. Preliminary results are consistent with known velocity structure and fault structure, but provide information at shorter length scales (Figure 3.3).

2. Tectonic Geodesy

Tectonic Geodesy activities in SCEC4 focus on data collection and analysis that contribute to improved earthquake response and a better understanding of fault loading, stress transfer, the causes and effects of transient deformation, and the structure and evolution of fault zones and systems.

Work by the SCEC community in the area of Tectonic Geodesy this year has focused on three areas: development of a Community Geodetic Model (CGM), implementation of automated transient detection algorithms, and the analysis of high resolution geodetic data.

a. Community Geodetic Model: Densification of GPS arrays as part of EarthScope, the rapidly growing volumes of InSAR data from various satellites, and the development of time series analysis for InSAR data all motivated the development of a Community Geodetic Model (CGM). The CGM should improve geodetic studies of non-secular strain, including post-seismic deformation. It is distinct from the past SCEC Crustal Motion Map (CMM) because it is time dependent and incorporates InSAR data to constrain both the vertical deformation field and small-scale details of the regional deformation. This will lead to refined and improved tectonic geodesy data products. The CGM will be used with other SCEC community models to infer the evolution of sub-surface processes. It will also provide a time-dependent reference frame for transient detection algorithms, as well as models of inter-seismic loading to evaluate stress changes and update rupture forecast models as tectonic conditions evolve in California. The challenge of the CGM is to exploit the spatially sparse, temporally dense 3D GPS time series and spatially dense, temporally sparse InSAR line-of-site time series consistent with GPS time series. SCEC research in support of this effort takes many forms including data collection to fill gaps in coverage, assessment of appropriate modeling approaches, and exploration of ways to mitigate noise and merge datasets.

CSU San Bernardino and University of Arizona researchers continued a field program that involves undergraduates and local teachers in collecting and interpreting GPS data in the San Bernardino Mountains where previous data coverage was sparse. Researchers at UC Riverside and MIT are using a dataset that combines campaign GPS data from their own field surveys with data from continuous networks and archives, to investigate the degree to which the San Jacinto Fault (SJF) slip rate varies along-strike. Data collection conducted between Scripps Institution of Oceanography (SIO) and CISESE resulted in new GPS observations across the Imperial and Cerro Prieto faults as well as improved GPS coverage in the Mexicali Valley. Continued efforts by MIT scientists to merge PBO and USGS continuous GPS solutions for southern California are vital to the CGM.

InSAR observations complement GPS by providing spatially dense deformation measurements. SIO scientists have used ALOS InSAR data, with constraints from GPS, to map small spatial scale deformation signals such as fault creep throughout the San Andreas system (Figure 3.4). Ongoing work by this group aims to improve InSAR processing methods to mitigate decorrelation in areas with large coseismic offsets. Research at Cornell is focused on improving the results of InSAR time series analysis by mitigating the effects of atmospheric noise as well as using synthetic tests to explore the optimal ways to combine InSAR and GPS data in building the CGM. Scientists at JPL are applying InSAR time series analysis to 18 years of SAR data from southern California to produce a line-of-sight velocity map constrained by GPS to investigate time-varying deformation.

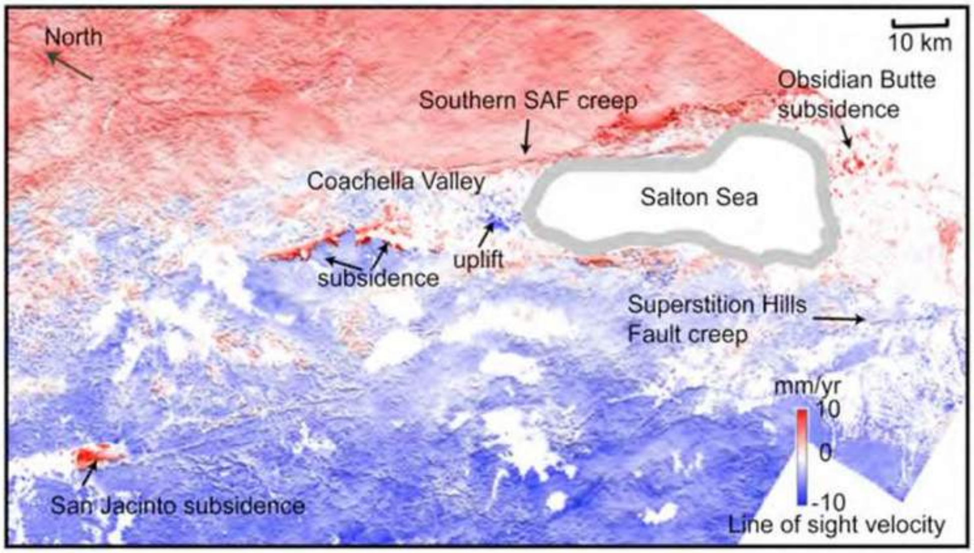

Figure 3.4. Inter-seismic deformation of the southern San Andreas Fault system derived from integrating GPS observations with ALOS radar interferograms (2006-2010) (Tong et al., 2013). The positive value (red color) shows the ground moving away from the satellite (81° azimuth, 37° from vertical). Shading highlights gradient in the velocity field. Southern part of the SAFS shows the broad transition in velocity across the San Andreas and San Jacinto Faults as well as shallow creep across the San Andreas near the Salton Sea. Regions of subsidence due to groundwater extraction are apparent.

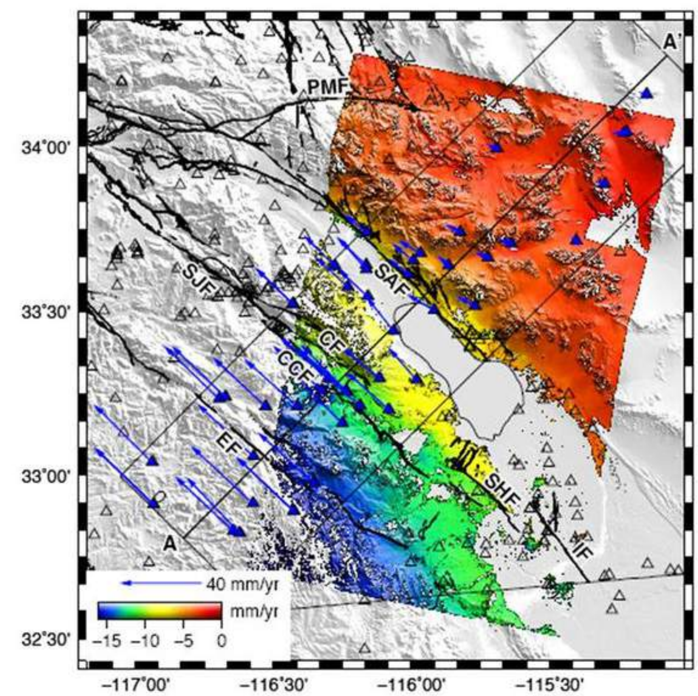

Figure 3.5. Map showing horizontal GPS velocities in a North America fixed frame and InSAR data from ERS-1/2 track 356, in addition to USGS mapped quaternary faults and shaded topography. Elsinore fault (EF), Coyote Creek fault (CCF), Clark fault(CF), and San Andreas fault (SAF), Superstition Hills (SHF), Imperial (IF), northern San Jacinto (SJF), and Pinto Mountain fault (PMF) (Lindsey and Fialko, 2013).

Modeling of dense GPS and InSAR line-of-sight velocity transects crossing the Southern San Andreas Fault (SAF) and SJF (Figure 3.5) by investigators at SIO revealed evidence that the SAF dips 60 degrees NE and that the southern SJF is comprised of two active strands (Clark strand and Coyote Creek strand). These researchers used data from using data from a profile crossing the SJF near Anza to identify increased strain within 2-3 km of the fault that could be explained by distributed inelastic deformation or heterogeneous frictional properties.

The 2010 El Mayor Cucapah earthquake provided opportunities to investigate crust and upper mantle rheology. As with other recent events (e.g., the San Simeon and Parkfield earthquakes) new GPS sites were established after the EMC earthquake to observe post-seismic signals. One challenge in this situation is the lack of pre-earthquake reference velocities for these sites. Researchers at the University of Arizona are developing block models of deformation for southern California and northern Baja using pre-earthquake data to constrain pre-earthquake velocities. Their post-seismic deformation models suggest a lower crustal viscosity of 4×10^{19} Pa-s and uppermost mantle viscosity of only 9×10^{18} Pa-s.

Ongoing collaborative activities of the CGM include:

- SCEC Community Geodetic Model (CGM) workshop (Menlo Park, CA, 30-31 May, 2013): This workshop addressed the major problems and paths towards generation of a joint GPS-InSAR 3-dimensional deformation field. The workshop was summarized in a Meeting report in EOS, Volume 94, Number 35, 2013 (presentations at: *http://www.scec.org/workshops/2013/cgm*).
- Focus Groups: We formed GPS and InSAR focus groups that will assess and validate potential time series generation approaches for the individual data types.
- InSAR exercise: We initiated an exercise within the InSAR community to process data for a particular frame in Southern California, for the purposes of comparison of the result of different approaches, validation against GPS data and data from overlapping tracks, and assessment of the appropriate errors to use in joint GPS-InSAR efforts. Initial results will be compared at the 2013 annual SCEC meeting.

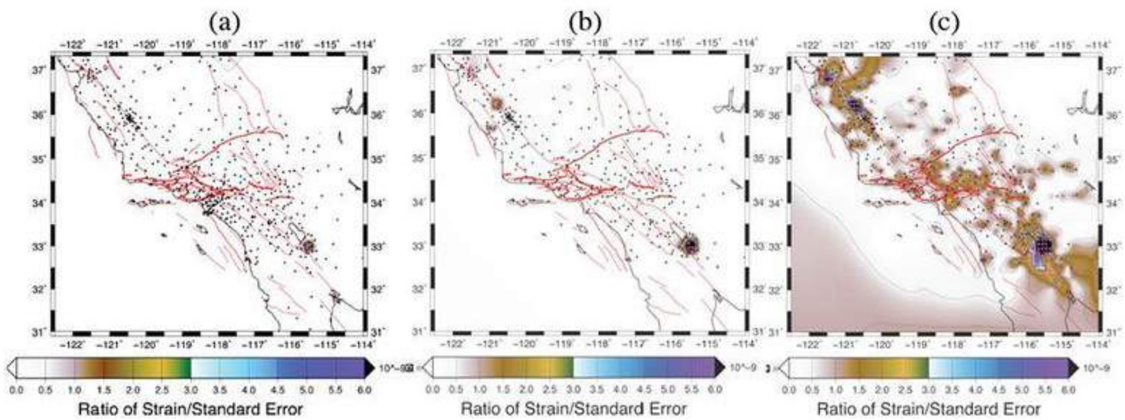

Figure 3.6. Contour plots of t-statistic that quantifies significance of detected anomalous strain. Black triangles give location of cGPS stations; pink stars = significant strains at 95% confidence. (a) for one-day solution for August 26, 2012; bulls-eye in area of Brawley swarm indicates strains there are significant at much greater than 99% confidence. (b): Same as (a) but for accumulated strain between 8/9/12 – 11/9/12. (c): Same as (a) but for 2 year period of strain accumulation (8/9/10 – 8/9/12) (Holt and Shcherbenko, 2013).

b. Transient Detection: Results from the SCEC transient detection effort were published in a special section of *Seismol. Res. Lett.*, including submissions related to the generation of synthetic data and development of algorithms that use geodetic observations to detect transient deformation signals. Two completely different testing approaches are now running automatically at the CSEP online testing center, one with several versions. A third approach entered the phase of uploading and testing code.

Investigators at MIT continued to develop and apply their targeted projection operator (TPO) algorithm for transient detection in various tectonic settings. They successfully detected and tracked inflation at Akutan volcano and Long Valley caldera, ETS events in Cascadia, and post-seismic signals from southern California earthquakes such as Hector Mine and EMC. Adaptation of this algorithm for the

CSEP testing framework is underway. A transient detection algorithm based on time-dependent displacement gradient fields and statistical analysis of measured strain anomalies has been developed at Stony Brook University and is now implemented in the CSEP testing system (Figure 3.6).

b. High-resolution Geodetic Measurements: PBO borehole strainmeters in the Anza region and laser strainmeters at the Pinon Flat Observatory continue to provide high-resolution observations of transient deformation. Triggered aseismic slip on the San Jacinto fault was inferred from these data following the 2005 Anza earthquake and again after the El Mayor Cucapah earthquake at the southern end of the Anza gap. Transient deformation consistent with aseismic slip during 2010 – 2011 at the location of the 2005 earthquake was also observed. A March 2013 M4.7 event on the San Jacinto fault near Anza triggered strain rate changes consistent with fault parallel shear slip acceleration of short duration (1 – 2 hours). Further analysis and modeling will be required to investigate causes of the variability in the occurrence and timing of strain recorded at different locations for the same events.

Another SCEC-funded effort being carried out by scientists at SIO focuses on the utility of fiber optic strain measurement using standard telecommunications cables and a dedicated fiber optic strainmeter at Pinon Flat. Initial results indicate that these systems can record small earthquakes (for example a M1.2 at a distance of 15 km from the source) and that observations are consistent with those from other instruments. Fiber optic systems could provide a low cost complement to other monitoring networks.

Development of an Earthquake Early Warning system, now mandated for California, is an area of active research. We are exploring ways that real time GPS data could contribute to EEW. Work conducted at SIO focused on combined use of co-located real-time GPS instruments and accelerometers to produce broadband displacement time series that capture the *P*-wave and the static offset. Ongoing work focuses on testing prototype systems at the Pinon Flat Observatory and development of scaling relationships that might be used to infer magnitude from the first few seconds of the GPS-accelerometer data.

3. Earthquake Geology

Research activities for Earthquake Geology include field studies and analysis of paleotsunami deposits, assessment of faulting and Late Quaternary deformation in the Ventura Special Fault Study Area (SFSA), targeted studies of faults beyond the San Andreas - San Jacinto system and Ventura SFSA, as well as development of new research methods for geochronology and measurement of tectonic deformation.

a. Paleotsunami investigations: Several groups conducted fieldwork to search for paleotsunami deposits in southern California coastal wetlands. Rhodes et al (2013) surveyed data from several areas. Cordova et al. (2013) found a shell-hash layer in the Los Penasquitos Marsh, San Diego County, and identified it as a potential paleotsunami deposit. Creager et al. (2013) and Leeper et al. (2013) collected core from Seal Beach marsh in Orange County, and reported possible evidence of abrupt coseismic subsidence and tsunami during the late Holocene. In the Santa Barbara area, Reynolds et al. (2013) reported sedimentological evidence of the historic 1812 tsunami preserved in Carpinteria marsh.

b. Ventura SFSA: The Ventura Special Fault Study area was established to understand one of the fastest deforming areas in southern California, with the potential to generate large earthquakes and tsunami through uplift along the coast. Several research groups investigated Ventura area faults and interaction of the Ventura, San Cayetano and Pitas Point faults. Ucarkus et al. (2013) report Holocene folding associated with large uplift events on the Ventura Avenue anticline, while Dolan et al. 2013 continued subsurface investigations of recent deformation along the Ventura fault scarp within the city of Ventura.

c. Other Investigations: New technologies (LiDAR and new/higher precision geochronology) enabled measurement of slip rates over multiple time intervals. New results from McAuliffe et al. (2013 and in prep) show that the rate of strain accumulation and release along the central Garlock fault varied from ~0 mm/yr to > 12 mm/yr over different Holocene time intervals (Figure 3.7). Studies of deformation along other faults, including the South Bristol Mountains fault in the eastern Mojave (Harvey and Stock, 2013), the Hector Mine 1999 rupture (Sousa et al., 2013), the Agua Tibia - Earthquake Valley fault zone in San Diego County (Gordon et al., 2013), the eastern Sierra Madre fault zone in the San Gabriel Valley (Treiman, 2013) and the Purente Hills thrust in the Los Angeles basin (Bergen et al., 2013), are in progress. Oskin et al. (2013) and Elliot et al. (2013) used airborne, differential and terrestrial LiDAR time-series observations of the 2010 El Mayor-Cucapah earthquake rupture to investigate variability in fault rupture slip measurements (Figure 3.8). They document the lack of detectable afterslip, and the small scale post-seismic geomorphic changes along the 2010 rupture. These results will inform paleoseismic studies and interpretation of paleoevents. Johnson et al. (2013) applied new methods called Structure-from-Motion to conduct rapid, decimeter-resolution mapping/imaging of fault zone topography. Rhodes et al. (2013) are developing methods to date sediments using IRSL of K-feldspar single grains. This promises to be useful in quartz-poor sediments that resist OSL dating. Fragilities of precariously balanced rocks (PBRs) were refined for 10 previously documented rocks, and two new rocks (Grant Ludwig and Brune, in progress).

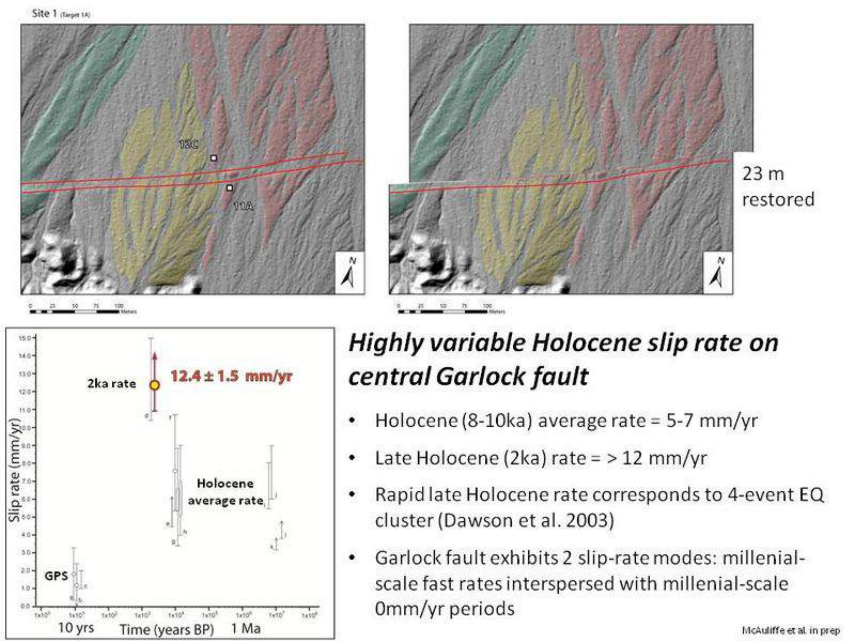

Figure 3.7. Studies of the Garlock fault show that slip rate has varied over time (from McAuliffe et al, in prep.).

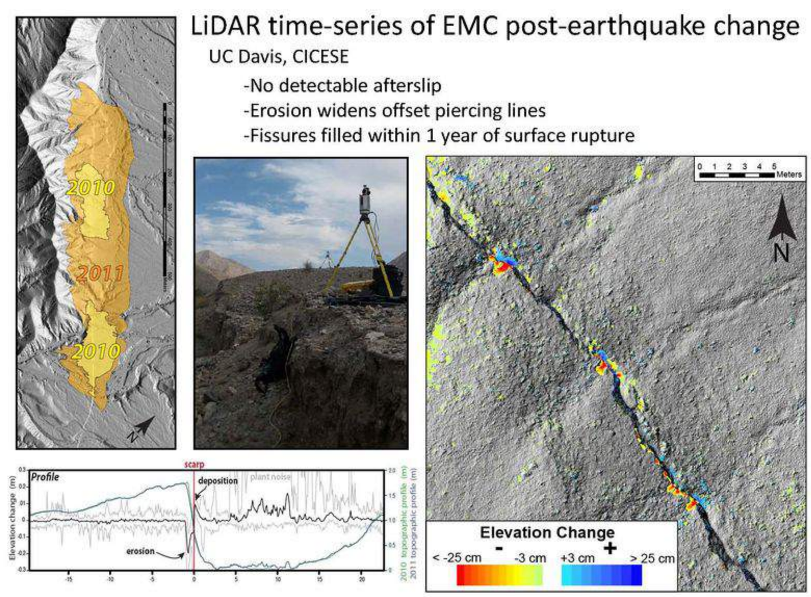

Figure 3.8. LiDAR time series measurements show elevation changes after the 2010 El-Mayor-Cucapah earthquake. From Oskin et al., 2013

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:

- Development of a new rupture dynamics and wave propagation code utilizing mesh refinement techniques to enhance resolution around the rupture and select wavefronts.
- Development of efficient and accurate algorithms and open-source libraries for boundary element solutions of static elasticity problems, as used in earthquake cycle modeling.
- Hybrid MPI/OpenMP parallelization of 3D rupture dynamics code EQdyna.
- Development of GPU-based AWP-ODC for forward problem as well as SGT calculation. Applied these capabilities to obtain the first 10-Hz deterministic simulation on the Titan system and sustain petaflop/s sustained performance. GPU-based AWP provides a factor of 100 speedup in SGT calculations compared to single CPU-core performance. This makes the goal of a statewide hazard model within the reach of existing supercomputers.
- Initial implementation of an HPC community I/O library for large-scale dynamic rupture and wave propagation simulations. The prototype development of the SEISM_IO library with ADIOS and another FORTRAN version interfacing with PnetCDF have been tested on XSEDE systems.
- Added 61 million hours of continuous seismic data for 436 stations and parametric and waveform data for 16,565 local events and 479 teleseismic earthquakes.
- Completion of a series of simulations of the 2008 Chino Hills earthquake using different velocity models (CVM-S, CVM-H and CVM-H+GTL) at Vs_min = 200 m/s and f_max = 4 Hz, which were used for a validation study that highlights the differences in the models and the influence of these differences on the ground motion goodness-of-fit with respect to earthquake data.
- Enabled large-scale scientific workflow using MPI Master/Worker to manage large suites of simulations on the CyberShake platform; and automation of seismic waveform analysis for full-3D waveform inversions.
- Development of a procedure for evaluating the spatial variation of the numerical resolution of a 3D seismic model and mesh.

a. Supercomputing Activities. SCEC was granted a record allocation of core-hours (SUs) on NSF and DOE supercomputers, involving 41 million SUs on XSEDE systems, 20 million SUs on NCSA Blue Waters, 7.5 million SUs on NCAR Yellowstone, and 68 million SUs on DOES INCITE OCLF Titan and ALCF Mira/Intrepid etc. We competed successfully for large allocations and moved calculations up in scale and capability through a series of petascale calculations (HighF platform, 0-10Hz ground motions on a mesh comprising 443-billion elements in a calculation that included both small-scale fault geometry and media complexity, dynamic rupture platform handling complex fault geometries and surface topography), capacity-computing (CyberShake 13.4 with CVM-S and CVM-4), and data-intensive computing (23 iterations of a statewide starting CVM for full-3D inversion).

b. Computational Tools for Earthquake Rupture Dynamics and Wave Propagation: SCEC computational scientists began development of a multi-scale rupture dynamics simulator (Figure 3.9) capable of handling complex geometries and heterogeneous material properties in a stable, accurate, and efficient manner. Wave propagation is done using either a discontinuous Galerkin method or a high-order finite difference method; it is possible to couple the two methods across nonconforming interfaces using interpolation operators. The meshes can be adaptively refined to increase resolution of sharp wavefronts and the stress concentration at rupture fronts. Refinement is accomplished through use of the p4est library. A prototype of the code for 2D dynamic rupture propagation was verified using SCEC rupture dynamics benchmarks.

c. Computational Tools for Earthquake Cycle Simulations: A central problem in earthquake cycle modeling and earthquake simulators is the calculation of slip-induced stress changes on fault networks using the boundary element method. SCEC scientists have developed new, highly efficient and accurate codes for this problem. These include HMMVP for computing the matrix-vector products using an H-matrix compression technique and DC3DM, a library built on HMMVP that very accurately computes static stress changes on receiver fault patches. The latter serves as a modern extension of the classic Okada (1985) code for calculating stress changes from dislocations in a half-space.

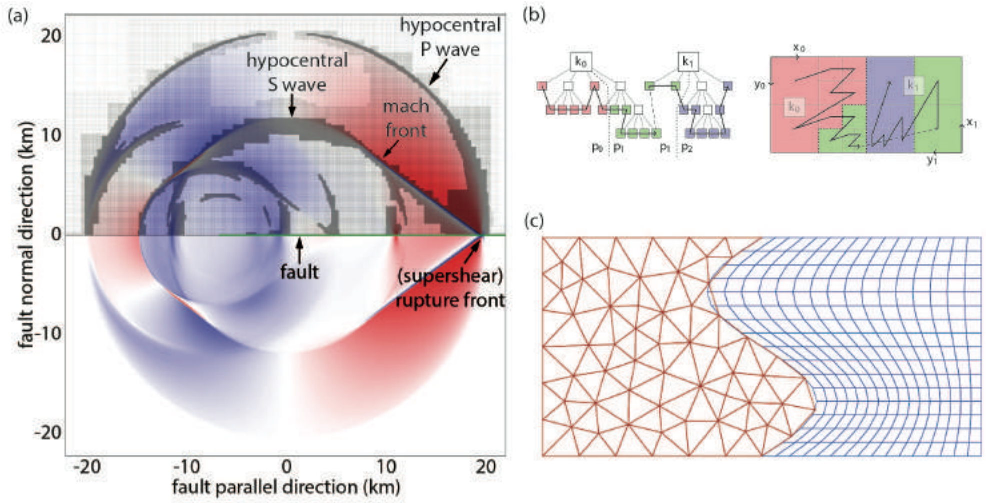

Figure 3.9. (a) Dynamic rupture simulation using adaptive mesh refinement (AMR), which dynamically enhances resolution around the rupture front and wave fronts (like the Mach front emanating from this supershear rupture). (b) The p4est AMR package, based on a forest of octrees, handles mesh adaptivity; a space-filling curve quickly partitions the mesh. (c) Simulations that involve geometrically complex faults and/or topography might benefit from coupling structured and unstructured grids.

d. Updates to HPC codes: SCEC researchers continued the development of codes that produce verified simulations at sustained petaflops. Realistic simulation of both rupture dynamics and wave propagation is based on rheology models that describe plastic yielding near the fault as well as nonlinear damping in soils near the surface. We implemented the Drucker-Prager plasticity based on the return map algorithm in AWP-ODC. We find that long-period ground motions in the downtown Los Angeles area, amplified by a waveguide of interconnected sedimentary basins, could be significantly reduced as compared to viscoelastic solutions. This can be attributed primarily to plasticity near the fault. To address the effects of small-scale fault and media complexity it is important to model anelastic attenuation as accurately as possible. At higher frequencies, ground motion data indicates that anelastic attenuation decreases as frequency increases. We implement frequency-dependent Q in AWP via a power-law function, $Q=Q_0*f^n$, where Q is the quality factor and f is frequency, and Q_0 and n are constants that may vary with the region of interest. We modify the coarse-grained approach, using least squares to optimize the weighting of the anelastic functions to fit a target Q(f) function.

We completed a parametric study using Hercules on the coupled response of building clusters and the effects of multiple soil-structure and structure-soil-structure interaction on the structural response of buildings and the ground motion in the presence of large building inventories in dense urban areas. We also performed 3D calculations of dynamic rupture along non-planar faults using SORD to study the effects of fault roughness on rupture propagation and ground motion. The fault roughness model follows a fractal distribution over length scales spanning three orders of magnitude.

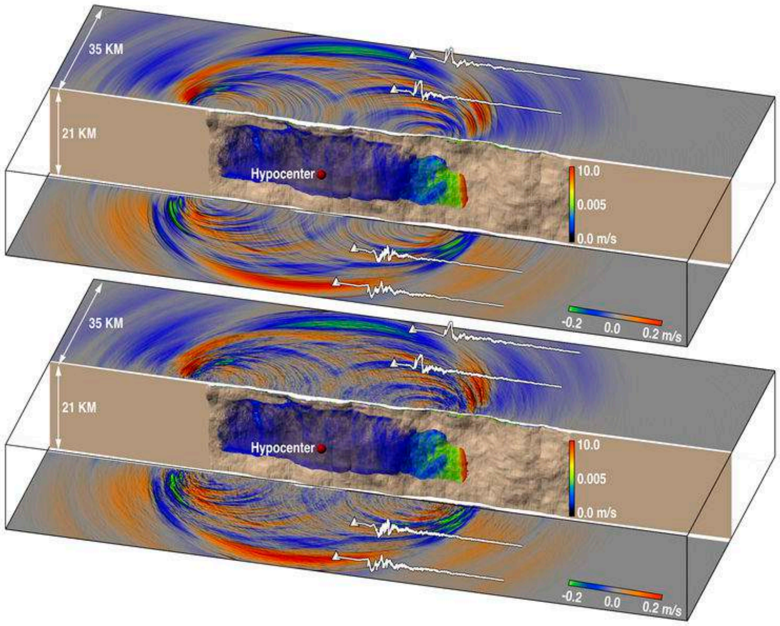

Figure 3.10. Snapshots of 10-Hz rupture propagation (slip rate) and surface wavefield (strike-parallel component) for a crustal model (top) without and (bottom) with a statistical model of small-scale heterogeneities. The displayed geometrical complexities on the fault were included in the rupture simulation. The associated synthetic strike-parallel component seismograms are superimposed as black traces on the surface at selected sites. The part of the crustal model located in front of the fault has been lowered for a better view. Note the strongly scattered wavefield in the bottom snapshot due to the small-scale heterogeneities.

5. Unified Structural Representation (USR)

The Unified Structural Representation (USR) Focus Area develops models of crust and upper mantle structure, including Community Fault (CFM) and Velocity (CVM) models, for use in a wide range of SCEC science. The USR Focus Area also facilitates improvement of these models with a current emphasis on supporting more accurate, higher frequency ground motion simulations and improved structural representations in SFSA's. The past year's accomplishments include development of:

- a new iteration of the Community Velocity Model (CVM-S4.26) based on 3D waveform tomographic inversions of phase and group delays from earthquake and ambient-noise waveforms;
- an improved structural representation of the Santa Maria basin in the CVM-H;
- a statistical assessment of small scale velocity heterogeneity in well data, with the goal of developing a stochastic representation of this variability in the CVM's to support higher frequency wave propagation simulations;
- a more detailed set of fault representations in the CFM and Statewide fault model (SCFM) for the Peninsular and Transverse Ranges, incorporating detailed USGS Quaternary Fault and Fold Database (Qfault) traces, relocated hypocenters, and new focal mechanism catalogs;
- new fault nomenclature for the CFM that is compatible with the USGS Qfault database.

a. Community Velocity Model Updates: The advent of 3-D waveform tomography, largely pioneered by SCEC investigators, offers the opportunity to evaluate and improve the Community Velocity Models through comparison of observed and synthetic waveform for recent earthquakes. In the past year, progress has been made evaluating both the SCEC CVM's. Po Chen and collaborators performed inversions of phase and group delays from earthquake and ambient-noise waveforms for regional models of both Southern and Northern California. Starting with CVM-S4 in southern California, 26 iterations have been made involving 513,000 waveform misfit measurements. The improved model, CVM-S4.26, was released through the SCEC CME. It clearly resolves basin structures not included in the starting model, such as the San Joaquin basin, and thus offers a substantial improvement over previous versions (Figure 3.11). Preliminary evaluations based on Goodness-of-fit criterions using more than 38,000 earthquake seismograms and 12,000 ambient-noise Green's functions show that CVM-S4.26 improves the fit to observed waveforms for frequencies up to 0.2 Hz compared with CVM-S4 and CVMH11.9.1. In parallel, the CVM-H model was updated using 3D adjoint waveform tomography (Tape et al., 2009). Currently, Tape's group (University of Alaska) is performing additional iterations based on refined meshes of the CVM-H.

SCEC developed a new 3D structural seismic velocity model of the Santa Maria basin in southern California to serve as a basis for improved estimates of hazardous ground shaking that will result from future earthquakes in the region. The new model includes a detailed description of the basin shape and major faults in the region that are constrained by dozens of petroleum wells, seismic reflection profiles, and maps and geologic cross sections. The Santa Maria basin model has been embedded in the CVM-H and is available via the SCEC CME website.

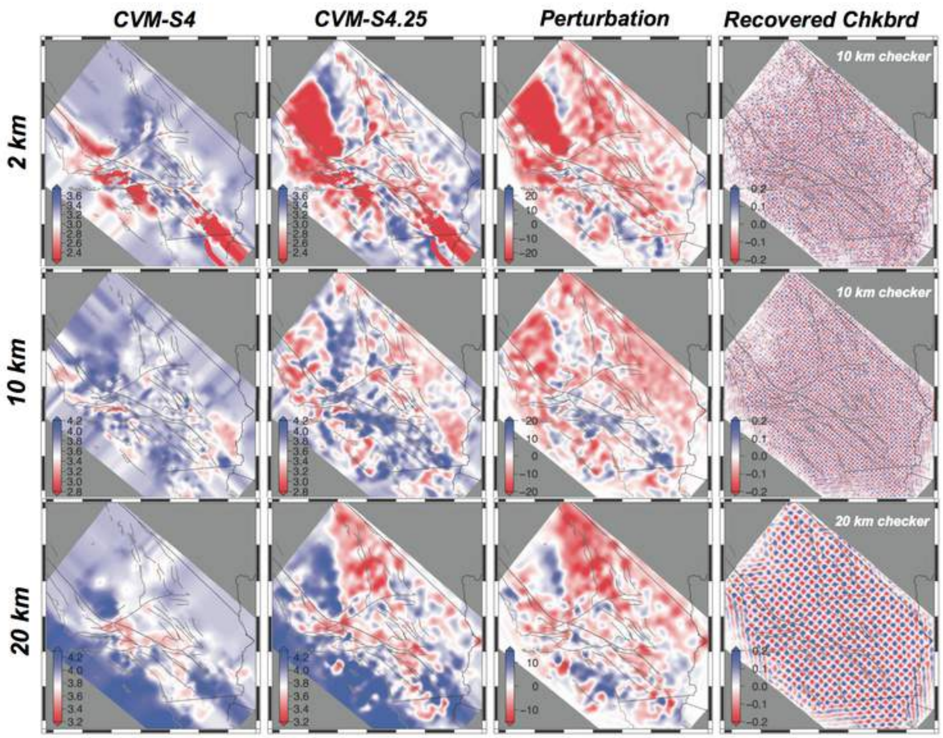

Figure 3.11. S-wave velocity at 2 km (first row), 10 km (second row) and 20 km (bottom row) depths in the starting model CVM-S4 (first column), the updated model CVM-S4.25 (second column), the differences between CVM-S4 and CVM-S4.25 (third column) and results of the checkerboard tests (4th column).

b. Stochastic Representation of fine-scale velocity structure in the CVM's: The goal of extending numerical wave propagation studies to shorter periods creates demand for higher resolution velocity models. SCEC is working to parameterize such models with a stochastic overlay to represent the local variability of the small length scale (<100m) structure. This past year, several collaborative efforts, led by Kim Olsen (SDSU), Tom Jordan (USC), and John H. Shaw (Harvard), examined geotechnical and petroleum industry well logs in the Los Angeles basin to constrain this fine-scale velocity structure. The USC-Harvard group compared the velocity structure from petroleum wells (3 m resolution) with that in the current CVM-H model (100 m resolution), and found a +/- 6% variation in slowness at 1 sigma. In addition, they have examined the vertical and horizontal correlation lengths through a variogram analyses, and defined a ratio of horizontal to vertical correlation lengths of about 11:1. Olsen's group analyzed more than 700 Vs30 measurements and defined a Hurst number of 0.0-0.1, vertical correlation lengths of 50-100 m, and standard deviations of 5-10% to represent this variability. They used these constraints to generate fractal distributions of the small-scale heterogeneities in a subset of the SCEC CVM 4.0, for simulated ground motions for the Mw5.4 Chino Hills earthquake (see GMP results).

c. Community Fault Model Updates: SCEC continued to update fault representations in the southern California CFM and Statewide fault model (SCFM) based on detailed fault traces available in the USGS Quaternary fault and Fold (Qfault) database, and refined earthquake catalogs. In collaboration with the USGS and CGS, Craig Nicholson (UCSB), Andreas Plesch, and John H. Shaw (Harvard), have coordinated efforts to revise fault representations in the CFM in the Peninsular and Western Transverse Ranges. Revised structures in the Transverse Ranges include more precise representations of the western Sierra Madre, Verdugo-Eagle Rock, San Fernando, Mission Hill, Santa Susana faults, Ventura-Pitas Point, and San Cayetano faults. The refined fault surfaces offer far more precise representations of fault geometry and segmentation, which are important for both PSHA and dynamic rupture simulations. In a parallel effort, SCEC implemented a revised fault nomenclature and database scheme to facilitate better access to the CFM and to make the model more readily connected to other fault databases. The nomenclature is based on a fault hierarchy and naming convention that establishes a Fault Area, Fault Zone, Fault Section, Fault Name, Splay, and Alternative Designation for each representation in the CFM.

6. Fault and Rupture Mechanics (FARM)

a. Near surface rupture: Several studies explored the importance of frictional properties during near-surface rupture in poorly consolidated materials – behavior that is important for understanding large-scale behavior during great earthquakes (e.g., Tohoku) and regional behavior within southern California. Brodsky et al. (2013) have made continued advances in understanding the potential for velocity weakening behavior associated with auto-acoustic compaction. Both Mei and McGuire (2013) and Erickson and Dunham (2013) used earthquake cycle models to investigate how variable frictional behavior in the near surface influences shallow seismicity – for example, Mei and McGuire illustrate how the inclusion of a conditionally stable layer promotes transient slip events as observed along the Superstition Hills Fault – behavior that would not be expected with conventional models.

b. Fault dynamics at the base of the seismogenic zone: Understanding processes at the base of the seismogenic were studied by incorporating more realistic (i.e., thermally activated power law creep) lower crustal fault rheologies into earthquake cycle models. Lapusta and Jiang (2013) illustrated how the history of such ruptures may be identified by a lack of microseismicity at the base of the seismogenic zone. Beeler et al., 2013, showed how the extent of rupture into the deep velocity strengthening layer influences slip-area scaling laws. Lower crustal flow and strain localization were also incorporated into long-term deformation studies of lithosphere-scale shear zones (Fialko, 2013); which provides new insights into the evolution of post-seismic creep and the mechanics of stress-transfer from plate-motion to crustal faults.

c. Dynamic Weakening: Experimental, theoretical, and geological studies continued to focus on dynamic weakening mechanisms. Platt and Rice (2013) explored feedbacks between the kinetics of dehydration/decarbonation reactions and thermal pressurization of pore-fluids on strain localization within fault zones. Noda and Lapusta (2013) explored implications of thermal pressurization for large-scale rupture processes, in particular for rupture across nominally stable segments. While there is a strong theoretical basis for thermal pressurization during high-velocity frictional slip, experimental validation of the process has been elusive due to the technical difficulty of measuring changes in pore-fluid pressure within rapidly deforming samples; however, new measurements linking fault zone dilation (determined using fault normal displacement) to frictional weakening provide evidence for this process Goldsby et al. (2013). Research into dynamic weakening mechanisms was stimulated by observations of extreme strain localization in natural fault systems; however, it remains difficult to quantify the magnitude of weakening such features imply. A new analytical technique based on the degree of thermal maturation of organic compounds (Savage et al., 2013) might provide new constraints on dynamic stresses during rupture.

7. Southern San Andreas Fault Evaluation (SoSAFE)

Research activities for SoSAFE focus on documenting the occurrence of paleoearthquakes and densifying slip rate studies along the San Andreas and San Jacinto Faults. SoSAFE research continued to make progress on using state of the art technology to develop new constraints on past earthquake history.

a. Development of new methods for producing high-resolution topographic and imagery data: Field tests of two new approaches for producing point-cloud densities orders of magnitude better than available airborne LiDAR datasets were conducted on small sections of the San Andreas Fault. A mobile laser scanning project completed along sections of the 1857 earthquake used a backpack platform that sampled the ground with more than 102-103 points per m^2 with ~5 cm horizontal accuracies. A photogrammetry project that created digital elevation models and imagery textures utilizing structure from motion techniques was tested on a fault section near Thousand Palms and in the Carrizo Plain. Both methods performed well and are being developed to assist with geologic studies and for rapid post-earthquake deployment.

b. San Gorgonio Pass Special Fault Study Area (SFSA): The overarching question for research in the San Gorgonio Pass SFSA is to understand how deformation is partitioned across the complex fault network in the San Gorgonio Pass (SGP) area. This year saw the collection of new data focused on understanding slip rates at several timescales (Figure 3.12), including campaign occupation of new and existing GPS sites across the SGP and Quaternary slip-rate studies on the Banning and Mission Creek strands of the SAF. A major trenching project was completed on the San Gorgonio Pass thrust fault near Cabazon that suggests individual ruptures are less frequent or have very complex, extensive rupture traces through that region. Focus on the SGP also lead to important updates of the CFM in the region.

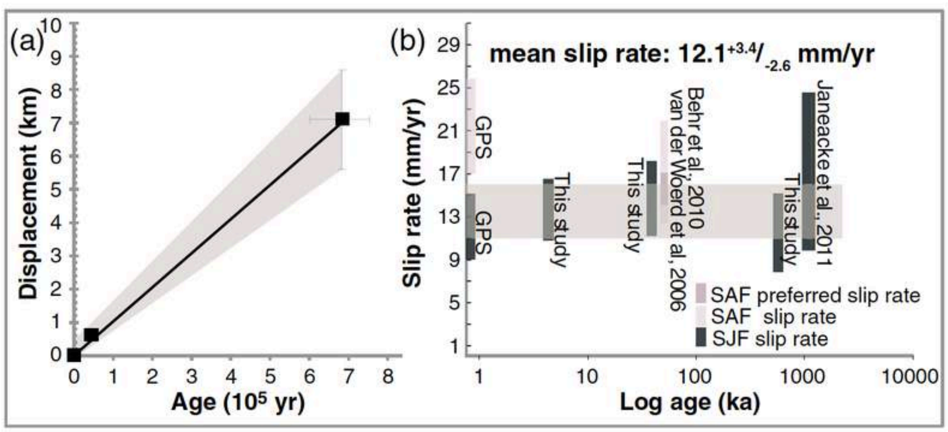

Figure 3.12. Slip rate constancy since inception and similarity with GPS results on the San Jacinto Fault (from Blisniuk et al., 2013).

c. Paleoseismic Studies: Trenching projects conducted at several locations investigated: 1. The possibility that the creeping section of the SAF can also support large coseismic ruptures. No evidence was found for large paleoearthquakes at Dry Lake Valley in the last 1300 years. 2. Channel and fault evolution on the trace of the great 1857 Fort Tejon earthquake on the SAF. 3. The mismatch between the Carrizo-Big Bend earthquake record and the southern Mojave section earthquake record. 4. An extended record at Mystic Lake, on the San Jacinto Fault.

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:

a. Present-Day Crustal Deformation: SDOT continues progress on using GPS measurements of surface velocities to infer slip rates in southern California. Cooke et al. (2013) and Johnson (2013) both show the well-known discrepancy between slip rates across the Mojave Eastern California Shear Zone (~6 mm/yr) and geodetic rates (~15-18 mm/yr) can be reconciled by distributing 20-60% of the total deformation across the region into rock surrounding the faults. Cooke et al. (2013) demonstrated this with an mechanical model and Johnson (2013) demonstrated this with a kinematic deforming block model. Lindsey and Fialko (2013) used InSAR and GPS data spanning the southern San Andreas Fault to show that the inferred San Andreas slip rate is sensitive to fault geometry (Figure 3.5). A dipping fault gives a slip rate of 18 mm/yr, which is closer to the geologic estimate (20 mm/yr) than a model with a vertical fault. Maurer and Johnson (submitted, JGR) use GPS and InSAR data along the creeping section of the SAF to infer the degree of fault coupling and find that an area of the fault between 10 and 20 km depth in the middle of the creeping section could be locked. Total moment accumulation rate on the creeping section is found to be equivalent to a M7.2 – M7.4 every 150 years.

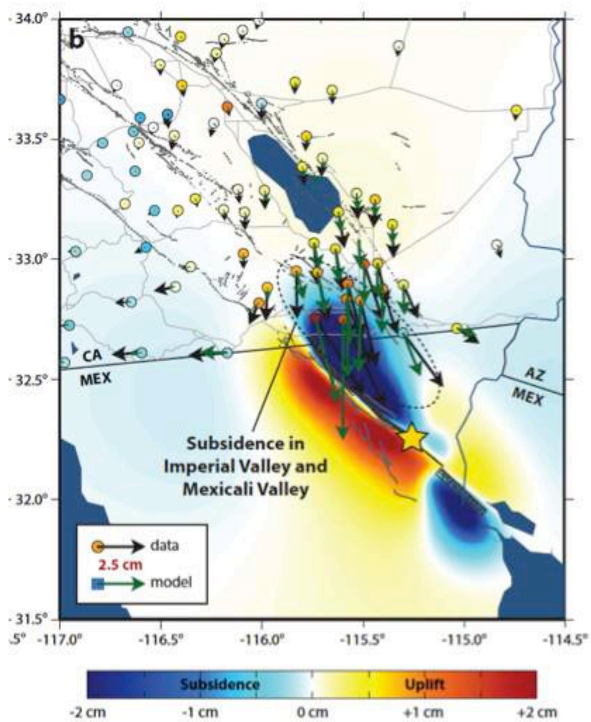

Figure 3.13. Rollins et al. use Barbot's RELAX code to examine the relative contributions of afterslip and mantle flow to postseismic deformation following the El Mayor-Cucapah earthquake. This figure compares an afterslip model with data. The far-field displacements are not reproduced well by afterslip alone and the sign of the predicted vertical motion is incorrect. The conclusion is that afterslip and mantle flow are both needed to explain the geodetic observations.

b. Fault and Lithosphere Rheology: Barbot et al. (2012) conducted simulations of earthquakes at Parkfield with models incorporating rate-state friction. They are able to reproduce many of the primary observations including the location of hypocenters of moderate-sized earthquakes, and patterns of surface displacements during the inter-seismic, co-seismic and post-seismic phases of deformation. Takeuchi and Fialko (in press) have incorporated lower crustal flow and strain localization into long-term deformation models of the lithosphere. They show that numerical simulations that incorporate laboratory-derived flow lows and shear heating produced localized, lithospheric-scale shear zones below the seismogenic fault. Rollins et al. (2013) examined the relative contributions of afterslip and mantle flow to postseismic deformation following the 2010 El Mayor-Cucapah earthquake (Figure 3.13). Far-field geodetic displacements are not reproduced well by afterslip but are reproduced by deep mantle flow indicating that afterslip and mantle flow are both activated postseismic processes.

c. Crustal Structure: SDOT continues research on the architecture of the southern California lithosphere. Miller et al. (2013) computed receiver functions from 145 teleseismic events from 2000 to 2011 recorded by 11 broadband seismic stations and depth converted them using the SCEC CVM. They found a strong step in Moho depth across the region with a deeper Moho beneath the southwestern side of the San Jacinto fault zone (33 km) and shallower Moho on the northeast side (25 km). The 8 km Moho offset across the San Jacinto is significant because it indicates localization of faulting into the mantle.

d. Community Stress Model: Efforts within the Community Stress Model community included the creation of a CSM web site (*http://sceczero.usc.edu/projects/CSM*) that includes visualizations of all previously submitted stress and stressing rate models, automatically generated cross-model comparisons, as well as "validation" of all models against semi-independent constraints, at this point limited to the World Stress Map compilations. All visualization scripts, models (if made publicly available), and validation data are are available for download to ensure full reproducibility. The web site is set up for expansion of model validation, and hosting future candidate releases of a CSM-beta, version 0.1, stress and stressing-rate model. The CSM community also held a workshop in Menlo Park in May 2013, where several issues were discussed. Two conclusions were that more constraint compilations (on borehole data and seismic anisotropy, for example) were needed, and that coupled mantle-lithosphere-crust models with lateral heterogeneities were need to address discrepancies between observational and numerical forward stress models.

e. International Earthquake Summer School: SDOT was one of the project groups proposing the first installment of a SCEC/ERI summer school supported out of the VISES project, and held in September of 2013 in Hakone, Japan, on the topic of Diversity of Earthquakes. Continuation of this summer school effort will ensure consolidation of existing and establishment of new collaborations, and cross-fertilization of research on complementary realizations of earthquake systems in transform and thrust environments.

9. Earthquake Forecasting and Predictability (EFP)

EFP continued to work on analyzing seismic patterns, establishing their relation to large events, developing operational earthquake forecasts algorithms and incorporating them into the CSEP framework. The achieved progress is largely facilitated by SCEC efforts towards improving observational database and designing new approaches to seismic risk. This past year's accomplishments include:

- Development of high-quality earthquake catalogs with improved locations, magnitudes, focal mechanism information
- Improvement of records on historic seismicity
- Development and testing of earthquake prediction models
- Analysis of seismic clustering in Southern California with relations to physics of the crust
- Modeling and laboratory experiments that shed light on earthquake predictability
- Observed correlations between the rate of induced seismicity and the operations of the Salton Sea Geothermal Field

a. Improved/new observations: The latest version of the relocated catalog has been released (HYS catalog) that contains high precision locations of over 500,000 events from 1981 to June 2011 (Hauksson et al., 2012). An extensive new catalog of fault mechanisms for Southern California was also released. It contains 2310 high quality mechanisms from events with $M>3$ (Yang et al., 2012). A multi-tapered spectral fitting was applied to determine the long period S-wave spectra (sometimes called signal moment) to calculate M_{wsp} magnitudes for small to moderate sized earthquakes, $M \leq 5.5$, in Southern California. The new magnitudes may improve studies of earthquake statistics or interactions. The SCEC community used the new catalogs to obtain new results. For example, it led to improved 2-D and 3-D stress field models, a series of detailed studies of the El Mayor-Cucapah and M 5.8, 14 June 2010, Ocotillo, California earthquakes, the 2012 Brawley swarm, as well as in-depth studies of seismic clustering.

Significant results have been obtained in improving records of historic seismicity. In particular, a higher-resolution chronology of Lake Cahuilla was obtained; and new methods to achieve routine reliable luminescence age estimates for paleoseismic and fault slip rate contexts on timescales of 10 years to 100,000 years in Southern California were developed.

b. Premonitory patterns: SCEC researchers continued in-depth studies of seismic clustering and its possible relation to large events (e.g., Shearer, 2012; Zaliapin and Ben-Zion, 2013). Several aspects of the space/time clustering of seismicity have been identified that cannot be explained with standard (i.e., ETAS) triggering models, including differences in precursory seismicity behavior between large and small earthquakes and details of the foreshock and aftershock behavior for small earthquakes. A method was developed to quantify seismicity migration in event clusters and find that most swarms exhibit migration whereas most aftershock sequences do not. A method for comprehensive detection and analysis of earthquake clusters has been developed. It revealed the existence of two dominant types of small-to-medium magnitude earthquake families – burst-like and swarm-like sequences. The burst-like clusters likely reflect highly brittle failures in relatively cold regions, while the swarm-like clusters are likely associated with mixed brittle-ductile failures in regions with relatively high temperature and/or fluid content.

A systematic detection of missing earthquakes in Southern California following the El Mayor-Cucapah mainshock conducted by Peng and collaborators detected about 20x more earthquakes than listed in the SCSN catalog. The obtained seismicity rate changes suggest a clear increase of seismic activity in many regions, including those in stress shadows; however, the seismicity rates correlate better with static stress changes a few months later. These results suggested that dynamic stress changes dominant in the short-term, while static stress changes play a more important role at later time.

c. Models, simulators and experiments: Earthquake-cycle modeling shed light on the predictability of earthquake recurrence times. Barbot et al. (2012) found that dynamic weakening through thermal-pressurization of pore fluids generates a range of mainshock magnitudes for the modeled earthquake cycle at Parkfield (Figure 3.14). The variability in size and stress drop yields a distribution of recurrence times similar to that observed. Thermal pressurization was shown to facilitate rupture through zones of low stress on faults with heterogeneous stress states, producing earthquakes with stress drops on the order of those observed seismologically (Schmitt, 2012). Modeling based on laboratory friction observations, by T. Tullis and colleagues also demonstrated that large earthquake ruptures can propagate dynamically into rate-strengthening regions. These simulations of the depth extent of faulting are the first to include temperature and slip rate dependencies and have implications for the predictability of magnitude/area and magnitude/slip scaling, which are important for estimating hazard.

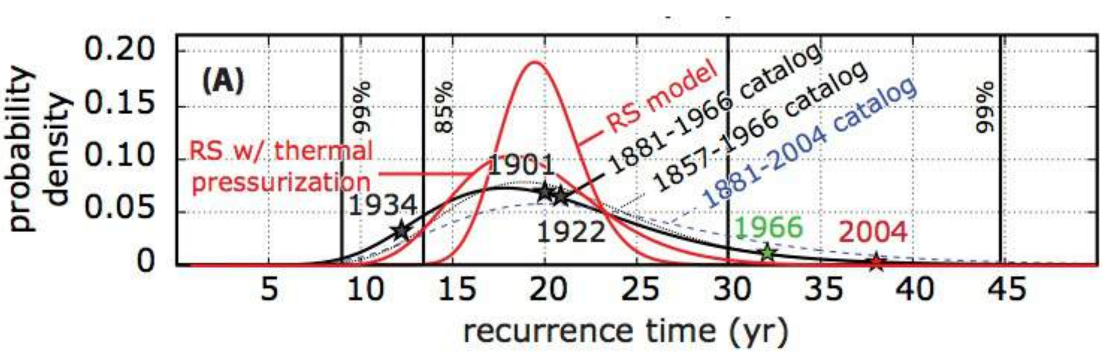

Figure 3.14. Probability density function of the recurrence time of Parkfield earthquakes from physical models with and without thermal pressurization, and the Parkfield catalog (Barbot et al, 2012).

The SCEC Earthquake Simulator TAG published eight papers in an Earthquake Simulator Focus Issue of Seismological Research Letters. Progress of the TAG in 2012 included setting up the problem definition for simulating fault-to-fault jumps. The simulator results will be compared to those from full dynamic rupture modeling. Hiemer et al. (2013) developed a stochastic earthquake simulation technique. The method is similar to the class of smoothed-seismicity earthquake forecast models which are performing well in RELM/CSEP testing, and additionally incorporates information from fault databases that is anticipated to improve forecasts of larger-magnitude earthquakes.

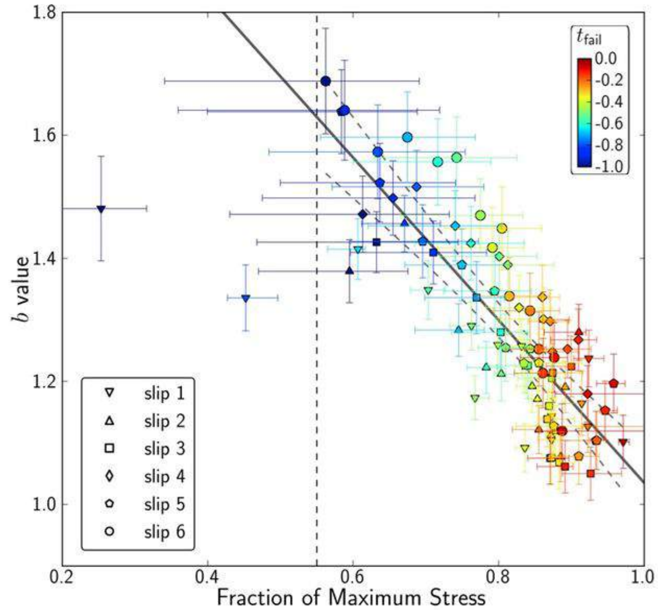

Figure 3.15. The b-value of acoustic emissions drops closer to failure time and shows an inverse linear relationship with the differential stress. Depicted are results of six stick-slip lab experiment, normalized according to the maximum stress. The markers are colored according to the normalized time to failure (tfail) and the marker symbols indicate individual stick-slip sequences. (Goebel et al., 2013).

Experimental observations of acoustic emissions (Figure 3.15) during multiple slip cycles on laboratory fault surfaces confirmed the hypothesis that the b-value (slope of the frequency-magnitude distribution) is inversely proportional to shear stress (Goebel, 2013). Areas of low b-value marked the nucleation points of larger slip events at large asperities within the fault zone that were revealed by post-experimental tomography scans. The b-value evolves during the laboratory seismic cycle, and shows an inverse linear relationship to differential stress over multiple cycles. These experiments provide support for the use of b-values as a proxy for stress accumulation in studies of earthquake forecasting.

SCEC Community Stress Model (CSM) Workshop: At this workshop, held in October, 2012, members of the SCEC community presented a range of stress and stressing-rate models for southern California that were contributed to the CSM. Quantitative model comparisons shown at the workshop demonstrated impressive similarity in crustal stress orientations (Figure 3.16). The orientations and rates of the stressing rate models were also remarkably similar near the major faults of the San Andreas system. The participants identified important future directions for the CSM, including compiling additional observational constraints, validating models against data, and the need for more geodynamic models.

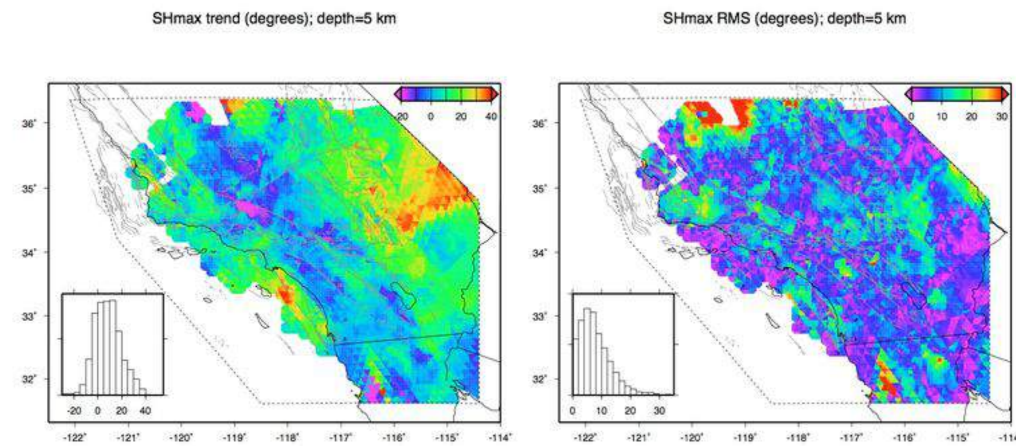

Figure 3.16. Comparison of stress orientation models submitted to the CSM. Left: Maximum horizontal compressive stress axis (SHmax) for an average stress model generated by averaging the normalized stress tensors of the models of Bird; Luttrell, Smith-Konter and Sandwell; and Yang and Hauksson. Right: the RMS difference of the SHmax orientation of the three models relative to the mean.

d. Prediction experiments, hazard studies: A focus of the EFP group remains development of new prediction experiments and novel approaches to hazard assessment. To investigate the predictive skills of earthquake forecasting models, Helmstetter and Werner (2012) developed a suite of event-based, short-term, and intermediate-term forecasting models for California. The event-based forecasts are specified by the conditional intensity function of the ETAS class and evaluated using their exact likelihood functions, as opposed to a discrete grid-based Poisson likelihood function currently used in CSEP experiments. The experiment evaluated the influence of eight popular spatial kernels on the probability gain and found that power-law kernels with scale parameter that grows with mainshock rupture length work best. It was found that lowering the learning catalog threshold to m2+ improves forecasts of target earthquakes m3.95+, providing further evidence that small quakes improve the predictive skill of clustering models.

Final Evaluation of the Regional Earthquake Likelihood Models (RELM) Experiment Workshop: The topics of this two day workshop held June were (i) a thorough evaluation of the five year Regional Earthquake Likelihood Models (RELM) initiative, (ii) lessons for the design of future forecast evaluations, and (iii) operational earthquake forecasting and validation. The RELM experiment, conducted within the Collaboratory for the Study of Earthquake Predictability (CSEP) at SCEC, helped clarify ideas about how to conduct forecast evaluations; it sparked further research into model development and evaluation; and served as a blueprint for numerous similar experiments within CSEP around the globe. This workshop facilitated dissemination of the RELM results and helped focus the community on the challenges and opportunities for generating and evaluating forecasts in the future.

e. Tremor and Induced Seismicity: Tectonic (non-volcanic) tremor may be an indicator of deep aseismic slip transients that might precede or affect the occurrence of large earthquakes. Understanding and characterizing tremor and its relationship to aseismic slip is of great importance to assessing earthquake predictability. Luo and Ampuero (2012) modeled tremor as repeated failure of slip-weakening patches embedded within a slow-slip event, and reproduced the tremor migration patterns and rapid reversals seen in tremor in the Cascadia subduction zone. They found precursory patterns of acceleration of tremor migration speed and shortening of tremor recurrence time at the approach of a large earthquake, highlighting the potential role of tremor as a monitor for aseismic transients (Ariyoshi et al., 2012).

SCEC scientists continued to characterize the tectonic tremor observed beneath the San Andreas Fault near Parkfield. Peterson et al. (2012) used tremor recorded at the PASO array to achieve high-precision locations and to image the three-dimensional P- and S-wave velocity structure down to tremor depths. These detailed tomographic images of the Parkfield tremor zone show slightly reduced P-wave velocity and more sharply reduced S-wave velocity, implying high pore fluid pressure and low effective stress. Precisely located tremor sources align close to the deep extension of the San Andreas. Chao et al. (2013) documented triggered tremor at Parkfield from the M9 Tohoku, Japan, earthquake.

Tremor in southern California continued to be more elusive than tremor at Parkfield. Chao et al. (2013) documented triggering on the San Jacinto Fault near Anza from the Tohoku earthquake, but at lower amplitude than the triggered tremor at Parkfield. Brown et al (2012) continued the search for spontaneous tremor near Anza, but have found only cultural noise.

Brodsky and Lajoie (2013) discovered that the rate of induced seismicity near the Salton Sea Geothermal Field is correlated with the net fluid volume change of the field (Figure 3.17). The earthquakes respond to net volume loss with no phase lag, possibly implying that the seismicity is responding to elastic compaction, rather than diffusion of high pore pressures from injection sites. Brodsky and Lajoie (2013) propose that the relation between net volume and seismicity, along with an appropriate frequency-magnitude distribution and a model of secondary earthquake triggering, could be used to forecast the probability of an induced large damaging earthquake.

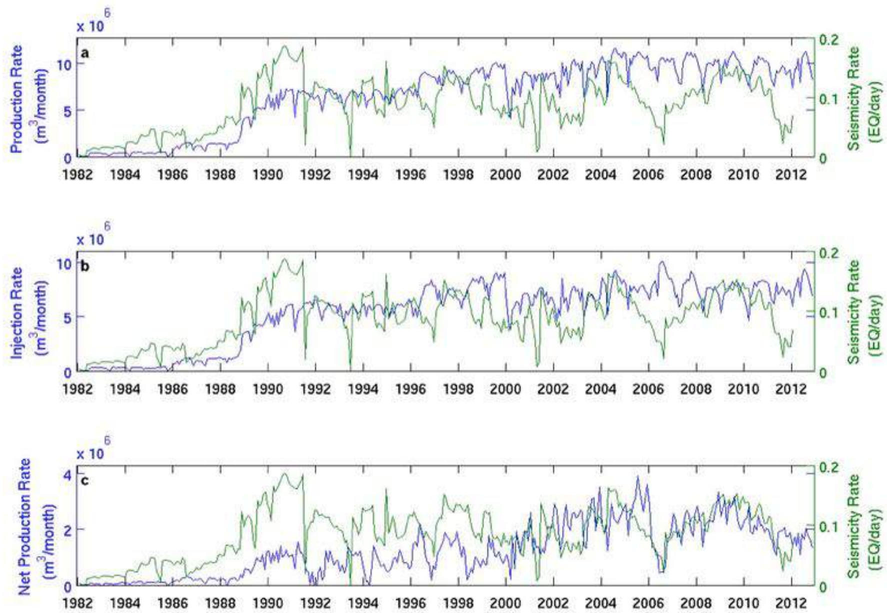

Figure 3.17. Seismicity background rate over time compared to operational fluid volumes at the Salton Sea Geothermal Field. The seismicity rate curve is identical for each panel (right hand axis, green curve) and the comparison fluid volume (left axis, blue curve) in each case is (a) Production rate, (b) Injection rate and (c) Net Production rate. (Brodsky and Lajoie, 2013).

10. Ground-Motion Prediction (GMP)

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

- Development of a new approach for ground motion predictions (Figure 3.18) using Green's functions estimated from ambient seismic noise (SAVELA). The method was applied to simulate ground motion in Los Angeles for s suite of M7 earthquakes on the southern San Andreas Fault.

The SAVELA ground motions predict large amplification in the Los Angeles basin for SE-NW propagating ruptures, in general agreement with the results from the M7.8 ShakeOut scenario (Denolle et al., 2013).

- Implementation of a coarse-grained frequency-dependent Q approach in AWP-ODC via a power-law function (Withers et al., 2013) as mentioned in the CS section.
- Implementation of Drucker-Prager plasticity in AWP-ODC (Roten et al., 2013) as mentioned in the CS section, which has a profound effect on simulated ground motion (Figure 3.19).
- Analysis of Vs30 and borehole data from the Los Angeles area was used to constrain the parameters of statistical distributions of small-scale heterogeneities in the basin (see results for USR). The statistical models were then incorporated into the CVM-S, and used in scenario simulations to test the effects of the statistical model on the ground motions (Savran et al., 2013).
- Simulation of dynamic rupture propagation along a rough fault (Shi and Day, 2013), where the assumed fault roughness follows a fractal distribution with wavelength scales spanning three orders of magnitude from ~10^2 m to ~10^5 m. The rupture irregularity caused by fault roughness generates high-frequency accelerations with near-flat power spectra up to almost 10 Hz.
- SCEC completed phase 1 of its Broadband Platform ground motion simulation results, evaluating the potential application in engineering applications of the resulting PSAs generated by 5 different methods. The evaluation included Part A, where the methods were evaluated based on the bias of simulation results to observations for 7 well-recorded historical earthquakes with station distances between 1 and 193 km, and Part B, where simulation results for Mw 6.2 and Mw 6.6 strike-slip and reverse-slip scenarios were evaluated against Ground Motion Prediction Equations at 20 km and 50 km from the fault. Three methods passed the initial evaluation tests.

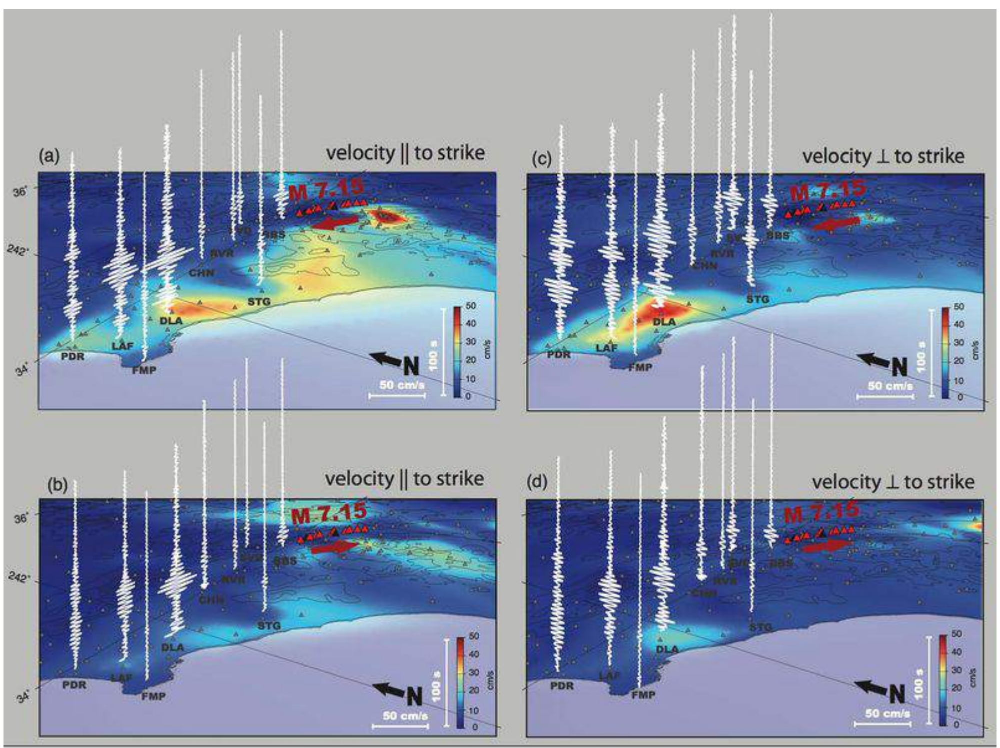

Figure 3.18. Virtual Earthquake Experiment using ambient seismic noise applied to Los Angeles (Denolle et al., 2013). Velocity seismograms (white waveforms) and PGV (color scale) for two M7.15 scenario earthquake ruptures determined using the virtual earthquake approach. Simulations are divide into northwestward propagating ruptures (upper) and southeastward propagating ruptures (lower) for the horizontal fault-parallel and fault-perpendicular components of motion.

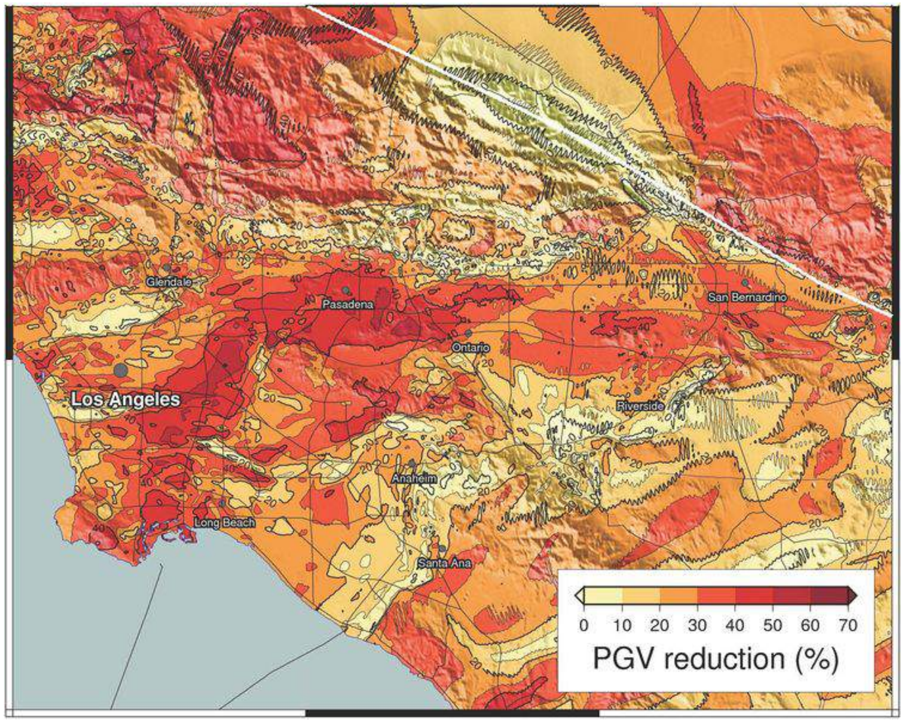

Figure 3.19. Reduction of peak ground velocities for a visco-plastic simulation of the M7.8 ShakeOut scenario, relative to those from a visco-elastic simulation (from Roten et al., 2013).

a. Workshop: 2013 SCEC BroadBand Platform and Ground Motion Simulations: Recent Progress on Validation of Methods and Planning the Next Steps: This workshop held in connection with the 2013 annual SCEC meeting in Palm Springs focused on the validation of methods for ground motion simulations and on the development of forward simulations for engineering applications, using methods implemented on the SCEC BroadBand Platform (BBP). The objectives were to inform, spur discussions and collect feedback for future development. The session was organized around three main topics: (1) Summary of the first phase of the validation exercise (against recorded events and ground motion prediction equations) and presentation of evaluation results, (2) Discussion on parameterization of new scenarios and review of preliminary forward simulation results, and (3) Discussion of the development plans for the next few years: additional methods and improvements, scientific problems and computational issues to resolve, refinement of evaluation criteria, etc. Conveners: Norm Abrahamson and Christine Goulet.

b. Testing Statistical Models of Small-scale heterogeneities: Shaw et al. (2013) and Savran et al. (2013) analyzed Vs30 and borehole data from the Los Angeles area and constrained heterogeneity spectrum for the basin (see USR discussion). The constraints were used to generate statistical models of the small-scale medium complexity required to simulate high frequencies. These models were incorporated into the CVM 4.0, and used in 0-2.5 Hz simulations of the Chino Hills earthquake to test the effects on the ground motions (Savran et al., 2013). They found amplification/de-amplification of PGVs by up to a factor of 2. Horizontal versus vertical anisotropy of the heterogeneities and the correlation length significantly affect ground motions. The Hurst exponent had less effect on the simulations. Such results highlight the importance of incorporating fine-scale velocity structure for strong ground motion simulations.

c. CyberShake: CyberShake is a SCEC project to develop physics-based probabilistic seismic hazard analysis (PSHA). The CyberShake approach uses full 3D wave propagation simulations to forecast ground motions that will be produced by specific ruptures. CyberShake is expected to produced significantly more accurate estimates for many sites than commonly used empirical-based ground motion decay attenuation relationships. During the past year, probabilistic seismic hazard curves were calculated using CVM-S and CVM-H with the RWG V3.0.3 SGT code and AWP-ODC-SGT, and the Graves and Pitarka

(2010) rupture models. The goal is to calculate the same Southern California site list (286 sites) in previous CyberShake studies to produce comparison curves and maps, and understand the impact of the Strain Green Tensor (SGT) codes and velocity models on the CyberShake results.

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. This past year's accomplishments include:

- Restructuring the Ground Motion Simulation Validation working group to focus on three classes of validation: nonlinear MDOF buildings, Geotechnical Systems, and SDOF oscillators.
- Evaluating the proposed validation methodologies using newly produced ground motions from the Broadband Platform validation project (discussed in the Ground Motion Prediction section).
- Comparing analysis responses to simulated vs. recorded ground motions for historical earthquakes and station locations.
- Adjusting validation methodologies to address incomplete treatment of near-surface site conditions in the simulation methodologies.
- Evaluating testing methodologies for the specific applications of building code analyses and landslide displacement analysis.

a. Engineering Partnerships: Cybershake results are used by the USGS's National Seismic Hazard Mapping Program in its 2014 revisions. A Committee for Utilization of Ground Motion Simulations (UGMS) was established to evaluate use of CyberShake simulations for development of long-period design hazard maps in Los Angeles, with heavy participation by engineering professionals and building code developers. A number of outreach sessions to engineering professionals and researchers were established, including the 2013 Consortium of Organizations for Strong Motion Observation Systems technical session, a special session at the 10th National Conference on Earthquake Engineering, and the Structural Engineers Association of California's Buildings at Risk summits in Los Angeles and San Francisco.

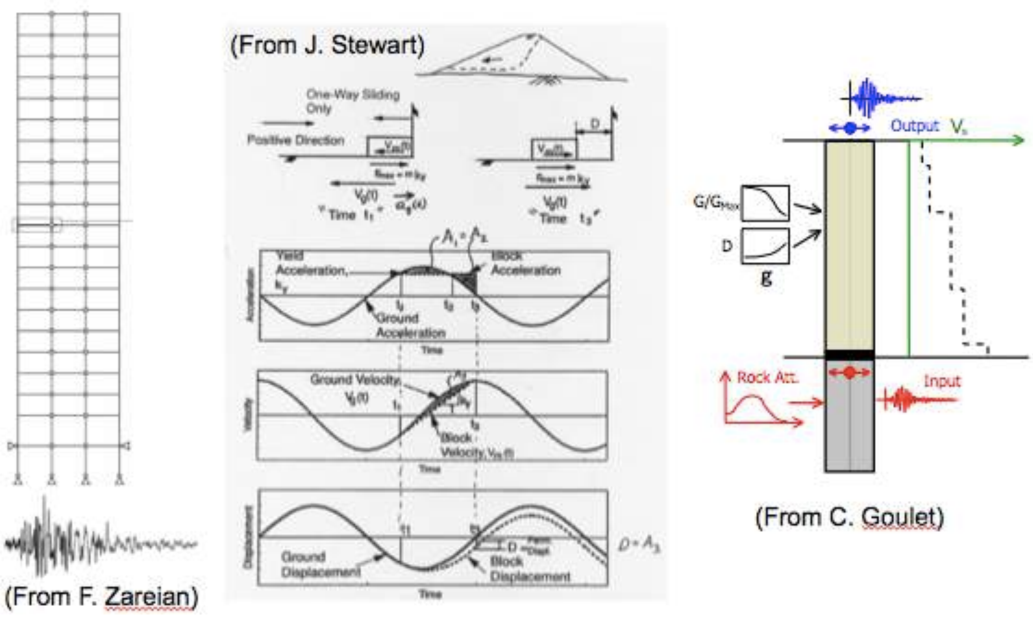

Figure 3.20. Validation objectives GMSV target applications for validation.

b. Ground Motion Simulation Validation: A Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV) was active in the past year. Via individual projects and a number of coordination workshops, the TAG proposed and implemented a number of testing/rating methodologies for evaluating the usefulness of simulated ground motions for a number of applications. Informative metrics identified in the past year include directional polarization of structural responses (Figure 3.20), and significant duration as an indicator of seismic demands in slope stability analyses. This work involved both ground motion modelers and engineering users, and is also coordinated with the BroadBand Platform Validation activities discussed in the Ground Motion Prediction section.

12. Working Group on California Earthquake Probabilities (WGCEP)

In October 2013, the Working Group on California Earthquake Probabilities (WGCEP) published the long-term, time-independent, component of the Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) (http://pubs.usgs.gov/of/2013/1165/). The primary goals for this earthquake-rate model, which constitutes authoritative estimates of the magnitude, location, and time-averaged frequency of potentially damaging earthquakes, have been to relax fault-segmentation assumptions and to include multi-fault ruptures (both of which were limitations of the previous model -- UCERF2). In other words, the conceptual breakthrough for UCERF3 has been the recognition that faults are not isolated, as previously assumed, but interconnected in a broad network or “fault system”. Several recent earthquakes demonstrated this fact by rupturing beyond previously inferred fault boundaries (e.g., the 2010 *M*7.2 El Mayor-Cucapah, 2011 *M9* Tohoku, Japan, and the 2012 *M*8.6 Sumatra events).

Success with these goals was achieved through a new “grand inversion” platform, which solves for the rate of all earthquakes simultaneously, while also using a broader range of data constraints. This allowed correction of the apparent UCERF2 over-prediction of *M*6.5-7 earthquake rates, as well as inclusion of types of multi-fault ruptures seen recently in nature. The approach is conceptually simple and extensible with respect to adding other constraints. Without invoking segmentation, however, the problem is inherently underdetermined in terms of solving for the rate of every possible rupture (solutions are non-unique). We therefore developed a multi-threaded simulated-annealing algorithm, which not only allows us to sample the null space efficiently, but also to sample a range of models given overall data uncertainties. As such, our approach is more derivative than the prescriptive nature of previous models (e.g., magnitude-frequency distributions are now derived rather than assumed). This also means that individual solutions are more difficult to understand, which necessitated the development of a variety of analysis tools.

Virtually all datasets were updated from UCERF2, and a number of new key components were developed as well. These include four new deformation models (which provide fault slip rates): one based on geologic data, and three kinematically consistent models that also include GPS observations. These models provided slip rates on faults where none previously existed, thereby producing some of the largest hazard changes relative to UCERF2. The deformation models also constitute one of the largest epistemic uncertainties, with the other important contributors being a new smoothed-seismicity algorithm, two new scaling relationships, and alternative values for the total regional rate of $M \geq 5$ events. All these influential options are new, so UCERF3 represents a considerable broadening of epistemic uncertainties, with the complete set producing 1440 alternative models (logic-tree branches). The large number of models, coupled with a need to sample the null space of each, necessitated use of supercomputers. Extensive hazard calculations have not only quantified the influence of each epistemic uncertainty, but have also shown that those associated with model non-uniqueness are completely negligible in comparison.

Multi-fault ruptures imply a potential for larger earthquakes than previously accounted for (e.g., the predicted rate of $M \geq 8$ events has increased by about 40%). However, the total frequency of damaging earthquakes is also reduced (e.g., the rate of $M \geq 6.7$ events has decreased by about 25%), making the overall hazard and risk implications situationally dependent (e.g., the risk to tall buildings and bridges may go up, while that to residential homes might decrease).

UCERF3 is still an approximation of the system that represents a limited range of models. For example, inversions are constrained to stay as close as possible to UCERF2, and Boolean rules are applied with respect to whether ruptures can jump between faults. This means that while UCERF3 is demonstrably better than UCERF2 overall, there may be areas that warrant further site-specific investigations. To this end, the entire framework is available on an open-source platform.

The grand inversion is not free of expert judgment, but it provides a system-level framework for testing hypotheses and formally balancing the influence of different experts. For example, we demonstrate significant challenges with respect to the Gutenberg-Richter hypothesis for individual faults, which may indicate that the hypothesis should be rejected. The report also includes a list of key assumptions and future improvements. Time-dependent components for UCERF3, including both elastic rebound effects and spatiotemporal clustering (aftershocks) are under development and will be published in the future.

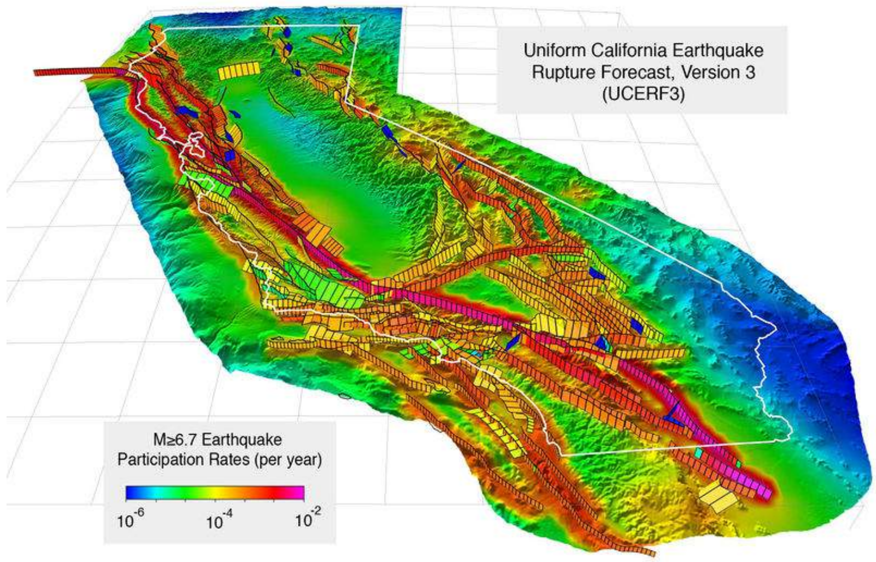

Figure 3.21. 3D perspective view of California, showing the average long-term rate at which different areas of the state participate in M≥6.7 earthquake ruptures. Black rectangles represent explicitly modeled faults (for UCERF3 Fault Model 3.1). Ruptures associated with the Cascadia megathrust are not shown.

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

The Collaboratory for the Study of Earthquake Predictability (CSEP) provides a controlled and transparent research infrastructure for the prospective and blind evaluation of earthquake forecasting and prediction methods. This past year's accomplishments include:

- First results from the RELM experiment of prospective five-year forecasts for California.
- Software support for generating and evaluating ensemble models of RELM forecasts to assess whether combinations of forecasts lead to greater predictability.
- Installation of UCERF2 for evaluation against existing RELM models and initial results of UCERF2's performance.
- Installation of 21 new forecasting models for the California testing region. These include twelve 1-day models, three 3-month models, three 1-year models, and three 5-year models.
- Software support for very-short-term predictability experiments for 30-minute forecasts, and installation of one 30-minute forecasting model (an ETAS model).
- A prototype experiment to evaluate external forecasts and predictions (EFPs), i.e. those generated outside of CSEP that are based on electro-magnetic or other precursory data.
- Software support for automatically importing the PDE earthquake catalog for CSEP experiments such as evaluating EFP and other experiments.
- Retrospective testing of time-dependent models that are used for operational forecasts for the Canterbury, New Zealand, region.
- Installation of one global forecasting model at high resolution (0.1 by 0.1 degrees) to serve as a reference model against EFP and other experiments.
- Improved software support for polygon-based forecasting and testing.
- Software releases of the CSEP cyber-infrastructure on a quarterly basis to all testing centers (New Zealand, Europe, Japan, China).

a. Results from the Regional Earthquake Likelihood Models (RELM) Experiment: The first major prospective and comparative earthquake forecasting experiment that CSEP hosted concluded, and CSEP organized a workshop to analyze and interpret the results (Figure 3.22). The evaluation of the forecasts suggest that a simple smoothed seismicity model based on recent earthquake locations was significantly more informative in forecasting earthquakes M4.95+ from 2007 to 2012 than other models, including geologic, geodetic and kinematic models, and a physics-based simulator. Initial results from a comparison of UCERF2 with the RELM models suggest the observed earthquakes are consistent with the UCERF2 forecast, but that the adaptively smoothed seismicity model generated more informative forecasts. An analysis of ensemble models, created by combining RELM forecasts, showed that Bayesian averaging did not result in better forecasts, while multiplicative models could outperform individual forecasts.

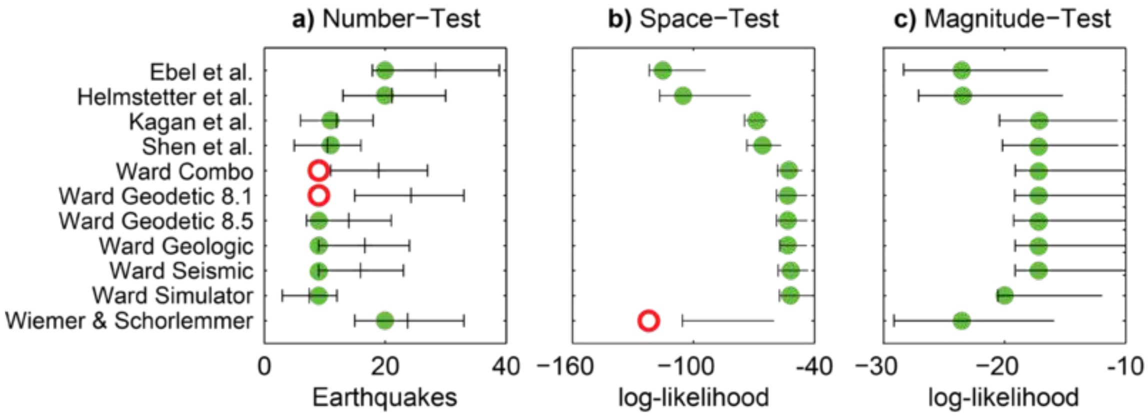

Figure 3.22. Results of consistency tests for RELM mainshock forecasts. Horizontal lines delimit the 95% confidence "pass" region. (a) Results of the two-sided N-test, where the forecast number of target earthquakes is indicated as the middle vertical dash, and the observed number of target earthquakes is indicated by the circle. (b–d) Results of the one-sided L- (S-, M-) test; circles represent the observed space–rate–magnitude (space, magnitude) log-likelihood for each forecast, and the horizontal black lines delineate the top 95% of log-likelihoods from simulated catalogs that are consistent with the forecast [Zechar et al., 2013].

b. Short-Term Earthquake Predictability: To support plans by the USGS to begin operational earthquake forecasting (OEF), CSEP scientists have evaluated the potential probability gain that can be attained by updating forecasts more frequently than every 24 hours. The probability gain increases sharply as the forecast horizon is reduced from 24 hours to 30 minutes (Figure 3.23). CSEP IT staff added support for a 30 minute forecasting group in California, and one ETAS model is now installed, which can be used to benchmark future operational forecasts from the USGS.

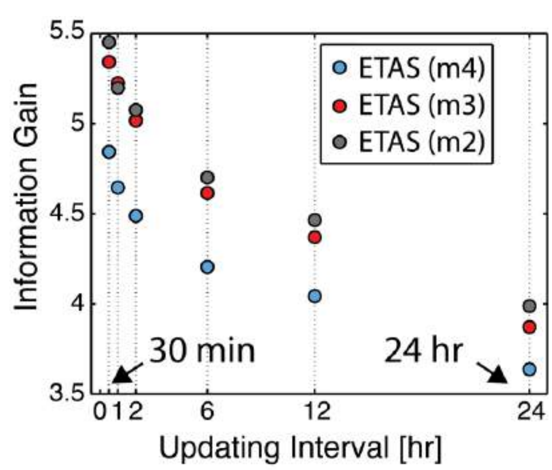

Figure 3.23. Information gain per earthquake of ETAS forecasts as a function of forecast horizon for target earthquakes M4.95+ from 1992 to 2012 in California. Colors indicate three different learning catalogs (M2+, M3+, M4+) that were used to generate forecasts [Werner et al., 2013].

c. Prototype Experiment of External Forecasts and Predictions (EFPs): CSEP organized a workshop in May 2013 to identify and develop prototype experiments to evaluate forecasts and predications that are generated outside of CSEP, such as those based on electro-magnetic precursors or those based on pattern recognition of earthquake chains. A first prototype to evaluate external five-year global earthquake predictions from the algorithm M8 was implemented, along with a new evaluation metric based on the gambling score suitable for evaluating predictions against heterogeneous Poisson reference models.

d. Retrospective Evaluation of Forecasts for the Canterbury, New Zealand, Region: Following the Canterbury, New Zealand, earthquake sequence, an operational earthquake forecast for the region was created by an expert elicitation panel. This forecast informs decisions regarding building standards and urban planning. CSEP scientists evaluated this model retrospectively, both in its final composite form and as individual components of short-term, medium-term and long-term forecasts. The composite model is more informative in retrospective tests than individual components, providing greater confidence in its prospective forecast.

14. Community Modeling Environment (CME)

The Community Modeling Environment (CME) is a collaboratory organized around a structured, iterative, process for improving earthquake ground motion forecasts using physics-based simulations. CME computational tools implement different aspects of the ground motion simulation problem. CME researchers collaborate with many SCEC groups including Unified Structural Representation, WGCEP, Ground Motion, Fault and Rock Mechanics, Ground Motion Prediction, Earthquake Engineering Implementation Interface, and Computational Science. This past year's accomplishments include progress in the following areas:

a. Rupture Forecast Models: Working with USGS and CGS scientists, CME researchers and software staff contributed to development of UCERF3 models. The CME software group extended OpenSHA software to include significant new complexities in fault geometries, and source complexities in rupture propagation models required by UCERF3 [Field, Dawson et al. 2012]. As part of this UCERF3 development work, CME researchers ran simulated annealing research calculations on XSEDE supercomputer Stampede, making use of large, shared, NSF-funded scientific computing resources.

b. Wave Propagation Models: CME ground motions modeling groups ran deterministic wave propagation simulations above 4Hz and compared simulation results to observations. A CME research group from CMU performed a set of simulations for the Mw 5.4 2008 Chino Hills, California earthquake using the various Southern California Velocity Models (Taborda and Bielak, 2013b,c,d, 2014) designed to produce a valid representation of the ground motion up to a maximum frequency of 4 Hz. As part of the validation they compared the results of simulations of the Chino Hills earthquake with 336 seismic records of the earthquake. The quality of the match between the actual records and the simulated synthetics was measured in terms of a commonly used engineering-oriented goodness-of-fit criterion. Recent changes to the physics-based wave propagation codes includes support for simulation volumes with topography, frequency dependent attenuation (Q) models, introduction of Drucker-Prager plasticity, and new implementations of wave propagation models in the Cuda programming languages that can utilized the processing efficiency of GPUs and MICs which currently seems needed to support 10Hz deterministic simulations.

CME researchers performed software development for the Broadband Platform (BBP), as part of a collaborative scientific and engineering activity evaluating use of simulations in seismic hazard evaluations (Figure 3.24). The BBP contains carefully evaluated scientific software, and provides a framework to run large numbers of simulations. The SCEC BBP was expanded to include three (3) new ground motion simulation methods (UNR, UWO, and U of Tokyo). We added new BBP capabilities to support evaluation five alternative ground motion simulation methods under consideration for use in seismic hazard studies for Northern California, Southern California, and Arizona. Our CME BBP activities included software development, running simulations, and releasing all recent BBP software improvements as Broadband Platform v13.9, an open-source software distribution available for download from a SCEC web site.

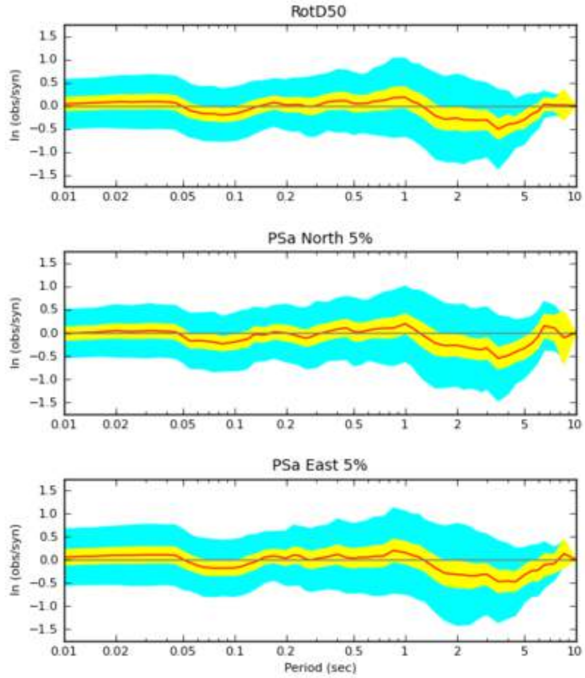

Figure 3.24. Broadband Platform Goodness of fit bias plots comparing peak acceleration from simulated recorded data across a range of frequencies relevant to engineering. These plots compare results for 40 stations using the Graves & Pitarka method against Loma Prieta (1989) earthquake data.

CME researchers calculated four new CyberShake hazard models [Callaghan *et al*., 2013)] using NSF and XSEDE resources Blue Waters and Stampede. The models were computed using different codes (AWP-ODC, and RWG) and different velocity models (CVM-S4 and CVM-H11.9) as shown in Figure 3.25.

CME researchers generalized the formulation of PSHA to accommodate simulation-based models (Wang and Jordan, 2012), and from this developed a ground motion analysis method called Averaging-Based Factorization, which allows CyberShake hazard models to be decomposed into components that can be quantitatively compared with each other and with empirical hazard models, such as the Next Generation Attenuation (NGA) ground motion prediction equations (Wang and Jordan, 2013). These comparisons were used to examine the dependences of basin effects, directivity effects, and directivity-basin coupling on the structure of the pseudo-dynamic rupture models and the Community Velocity Models used in the large-scale simulations, including the CyberShake Study 13.4 run in April 2013 (Wang et al., 2013).

c. Dynamic Rupture Models: CME researchers use dynamic rupture models to investigate basic properties of earthquake rupture physics, and to generate earthquake source descriptions that contain the high frequencies observed in real earthquakes. CME dynamic rupture model simulations are used to evaluate alternative friction laws, investigate supershear ruptures, investigate the impact of complex (non-planar) fault geometries, evaluate the rough fault generation of high frequency motions, and the moderation of strong ground through plasticity of the earth.

CME researchers developed rough fault model simulations (Withers et al., 2013) using the SORD code as a tool for dynamic simulation of geometrically and physically complex ruptures. To do so, we integrated high-speed frictional weakening (in a rate- and state-dependent formulation) into the code. This integration was done using a method that time-staggers the state and velocity variables at the split nodes, producing a stable, accurate and very efficient solution scheme. We also added the Drucker-Prager formulation of pressure-dependent plastic yielding into SORD, with added visco-plastic terms to suppress strain localization. The resulting code was successfully tested using SCEC rupture dynamics benchmarks. We also implemented and successfully tested a scheme for the generation of SORD meshes for power-law rough faults.

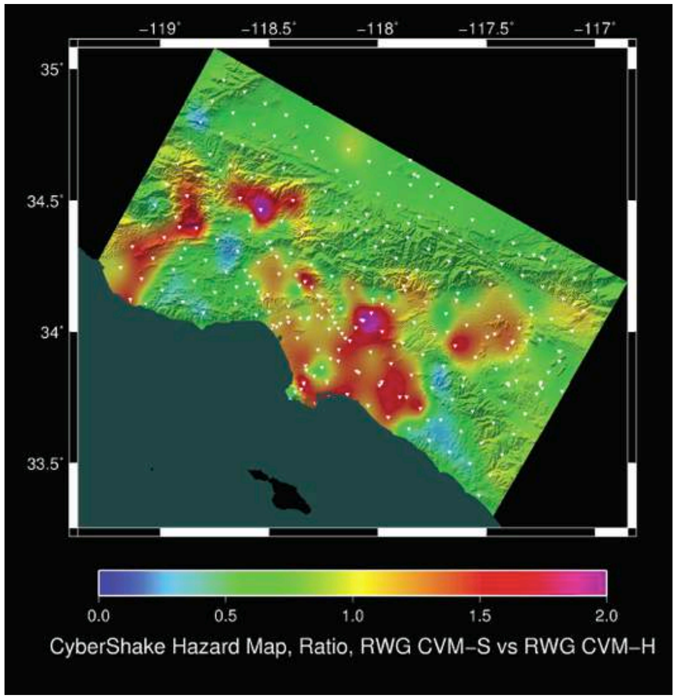

Figure 3.25. Ratio of CyberShake hazard assuming CVM-SCEC and CVM-Harvard. Blues and greens are lower CVM-SCEC hazard, oranges and reds higher, showing significant hazard differences for the alternative southern California 3D velocity models.

d. Scientific Software: CME researchers develop new software, run existing SCEC scientific software on large research calculations, and integrate SCEC software with the HPC environments available from USC, NSF, and DOE for SCEC research. The CME software group released Broadband Platform v13.9, as open-source scientific software, which includes updated ground motion models, and new goodness-of-fit algorithms designed to validate the software, and to establish its usability for engineering applications.

The CME software group integrated the updated CVM-S4.26 model into the Unified Community Velocity Model (UCVM) software (Gill et al., 2013), and released UCVM v13.9 as open-source scientific software available to the seismological community for download from a SCEC website. The SCEC UCVM software provides a framework for managing seismic velocity models used in earthquake ground motion simulations. We used the UCVM software to support our CyberShake 13.4 Study. We used UCVM to support Hercules high frequency ground motion simulation using Blue Waters.

CME researchers developed highly parallel Cuda-language wave propagation code called AWP-ODC-GPU (Cui et al., 2012) that achieves sustained Petaflops [Cui et al., 2013) and was used to run a 10Hz deterministic ground motion simulation (Withers et al., 2013) for a high frequency earthquake rupture produced by a dynamic rupture on a rough fault (Shi et al., 2012), in a velocity model containing small scale heterogeneities (Olsen et al., 2013).

CME researchers developed CPU/GPU versions of the wave propagation code AWP-ODC-GPU, and a reciprocity-based version called AWP-ODC-GPU-SGT. A CPU/GPU version of Hercules is also under development including researchers from USC, CERI, and CMU. These codes are aimed at use on the largest and newest heterogeneous supercomputers including NSF Blue Waters and DOE Titan. While this code development is preliminary, these significant performance gains shown by our GPU algorithms opens new possibilities for higher resolution ground motion simulations in the near future.

SCEC developed a version of the AWP-ODC-GPU software to calculate strain Green tensors (SGT) for use in CyberShake. We tested this code on Blue Waters and developed an innovative co-scheduling approach that will let us run our parallel SGT CyberShake processing on Blue Waters GPUs, while we run the serial post-processing jobs on Blue Waters CPUs.

B. Communication, Education and Outreach Accomplishments

Through its engagement with many external partners, SCEC CEO delivers research and educational products to the Center's many audiences, including the general public, government, business, academia, students, practicing engineers, and the media. The theme of the CEO program during SCEC4 is *Creating an Earthquake and Tsunami Resilient California.* This includes: increased levels of preparedness and mitigation; routine training and drills; financial preparedness; and other ways to speed recovery. In particular, we are preparing Californians for making decisions in response to changing seismic hazards, in anticipation of operational earthquake forecasts and earthquake early warning. Although tsunami research is not a focus of SCEC, tsunami education and preparedness is an activity of SCEC CEO and ECA.

This theme will be addressed within four interconnected thrust areas. The *Implementation Interface* connects SCEC with engineering partners in research and practice, as well as other technical audiences. The *Public Education and Preparedness* thrust area educates people of all ages about earthquakes, and motivates them to become prepared. The *K-14 Earthquake Education Initiative* seeks to improve earth science education and school earthquake safety. Finally, the *Experiential Learning and Career Advancement* program fosters and sustains careers in science and engineering.

A SCEC CEO Strategic Plan with metrics and milestones for activities within each thrust area was reviewed and revised by the new CEO subcommittee of the Advisory Council in 2013 (see Appendix B for 2013 accomplishments relative to these milestones). The group has helped simplify and prioritize the proposed metrics to align with budget and staffing realities.

1. Implementation Interface

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

a. Research Engineering Partnerships

These activities are coordinated as a SCEC research focus group, managed by representatives on the planning committee. SCEC has produced a large body of knowledge about the seismic hazard in California that enhances the seismic hazard maps currently used in building codes and engineering risk assessments. For example, Cybershake results were used by the USGS's National Seismic Hazard Mapping Program in its 2013 revisions. Further details of recent activities are described in §III.A.11 above. In 2013 SCEC greatly exceeded our milestone for number of engineers attending the SCEC Annual Meeting and other workshops, but structures for assessing other metrics still need to be set up, in 2014.

b. Activities with Technical Audiences

The Implementation Interface also involves interactions with technical audiences that make decisions based on understanding of earthquake hazards and risk, including practicing engineers, geotechnical consultants, building officials, emergency managers, and financial institutions. SCEC, ECA, and our partners are planning training sessions for practicing engineers and building officials to introduce new technologies (including time-dependent earthquake forecasts), discuss interpretation of simulation records, and provide a forum for SCEC scientists to learn the needs of practicing professionals.

The key activity of this area in 2013 was the third annual *Buildings at Risk* Summit held in October in Los Angeles and also San Francisco for the first time (as "precursors" to the Great California ShakeOut). This is a significant partnership of the Structural Engineers Association of Southern California, SCEC, ECA, CalOES, and other partners that brought together over 200 research and practicing engineers, scientists, government leaders, building code officials, and others to learn and discuss earthquake risk reduction strategies. Our levels of participation greatly exceed our milestones for 2013, but other metrics need further development to be tracked better.

2. Public Education and Preparedness

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

a. Earthquake Country Alliance (ECA)

The ECA public-private statewide partnership is the primary organizational structure within the Public Education and Preparedness thrust area. In September 2011 the relationship between SCEC and the ECA (managed by SCEC since its inception in Southern California in 2003) was formalized via a memorandum of understanding specifying SCEC as the administrative headquarters and SCEC'S Associate Director for CEO as ECA's Executive Director. SCEC remains very involved within the southern California regional effort, including the ECA Speakers Bureau that held monthly trainings at SCEC's facilities.

ECA 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* (revised extensively in 2013), *www.shakeout.org*, *www.dropcoverholdon.org*, and *www.terremotos.org*), and manages the printing of the "Putting Down Roots" publication series statewide.

In 2013 SCEC received $150K of funding (along with $260K more for national ShakeOut support) from FEMA to administer ECA activities, including monthly calls of 8-10 committees, funding for activities of each regional alliance, and a leadership retreat of the Steering Committee and key partners.

Because of the growth of the ShakeOut and its other activities, ECA has received national recognition. In fall, 2011 ECA was recognized by FEMA with the "Awareness to Action" award, which resulted in SCEC's Associate Director for CEO Mark Benthien being named a "Champion of Change" by the White House in early 2012. In April 2012, ECA also received the "Overall National Award in Excellence" at the quadrennial National Earthquake Conference in Memphis.

b. ShakeOut Earthquake Drills

A major focus of the CEO program since 2008 has been organizing the *Great California ShakeOut* drills and coordinating closely with ShakeOut drills in other states and countries. The purpose of the Shakeout is to motivate people to practice how to protect ourselves during earthquakes and to get prepared at work, school, and home. ShakeOut is based on 30 years of social science research about why people choose to get prepared.

The ShakeOut began in southern California in 2008, to involve the general public in a large-scale exercise based on an earthquake on the San Andreas Fault (the "ShakeOut Scenario"). SCEC developed advanced simulations of this earthquake used for loss estimation and to visualize shaking throughout the region. In addition, SCEC hosted the ShakeOut website (*www.ShakeOut.org)* and created a registration system so that participants could be counted. In 2008 more than 5.4 million southern Californians participated. In 2013 more than 9.6 million participated statewide.

In addition to its continued lead role in organizing the California ShakeOut, SCEC now manages a growing network of Official ShakeOut Regions spanning 44 US states and territories and several other countries (Box 3.1). In 2013 more than 24.7 million people participated in 23 Official ShakeOut Regions worldwide. Many millions more see or hear about the ShakeOut via the news media. SCEC manages the websites of every ShakeOut except those in Japan.

Box 3.1. Growth of ShakeOut Drills

2008: 5.4 million
Southern California

2009: 6.9 million
California, New Zealand West Coast

2010: 7.9 million
California, Nevada, Guam

2011: 12.5+ million
CA, NV, GU, OR, ID, BC, and Central US (AL, AR, GA, IN, IL, KY, MI, MO, OK, SC, TN)

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

2013: 24.7 million
All above except New Zealand, plus:
Rocky Mountain region (CO, WY, MT), HI, OH (now in the Central U.S.), WV & DE (now in the Southeast region), Northeast region (CT, PA, MA, ME, NH, NJ, NY, PA, RI), American Samoa, U.S. Virgin Islands, Commonwealth of Northern Marianas Islands. Charlevoix region of Quebec, and expansion across Japan.

Extensive surveys have been done after each ShakeOut and the results of these surveys are providing insights into what participants are learning and improving in terms of their level of preparedness. The ECA Evaluation Committee is also encouraging additional social science research.

c. Putting Down Roots in Earthquake Country

This 32-page handbook has provided earthquake science, mitigation, and preparedness information to the public since 1995. *Roots* was first updated in 2004, when the *Seven Steps to Earthquake Safety* was created to organize the handbook's preparedness content. Since then five additional revisions and printings have produced 3.5 million copies. The first Spanish version of *Roots* was produced in 2006. The 2011 version included new tsunami science and preparedness content, based on content created for the 2009 version of *Living on Shaky Ground*. This is a similar publication of the Redwood Coast Tsunami Workgroup that now also includes the SCEC/ECA *Seven Steps to Earthquake Safety.* The steps were revised subtly in summer 2012 and are featured within the new ECA website (launched in summer 2013) and also by the California Earthquake Authority and American Red Cross in a new marketing effort focused around the "Traveling Red Table" which promoted ShakeOut and other preparedness messaging.

The booklet has spawned the development of region specific versions for the San Francisco Bay Area, Nevada, Utah, Idaho, and the Central U.S. (totaling an additional 4 million copies). SCEC and its partners also have developed a 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. All booklets are available on the ECA website (*www.earthquakecountry.org/roots*).

In 2013 the California Earthquake Authority and California Office of Emergency Services have supported the development of the latest 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 will be produced for 8-10 regions of the state.

d. ECA Education and Public Information centers (EPIcenters)

SCEC CEO has developed exhibits and partnered with information education venues for many years. The expansion of these partnerships, especially with the San Bernardino County Museum (SBCM) led SCEC to create the ECA Earthquake Education and Public Information Centers (ECA EPIcenters) network which includes museums, science centers, libraries, universities, parks, and other places visited by a variety of audiences including families, seniors, and school groups. Over 65 organizations now participate and have implemented a variety of activities including displays and talks related to the ShakeOut (60 in California, 2 in Oregon, 1 in Maine, 1 in Vermont, 1 in Connecticut, and 1 in Arizona). Growth has been enhanced through the collaboration with the Cascadia EarthScope Earthquake Education and Tsunami Education Program (CEETEP) and the EarthScope Interpreters workshop. Via the EPIcenter project SCEC continues strong relationships with EarthScope, UNAVCO, IRIS, and has developing relationships with the NASA-Jet Propulsion Laboratory, and through our Native California is Earthquake Country Project the Bureau of Indian Affairs. The following are highlights of 2013 activities:

- SBCM Hall of Geological Wonders Learning Treks Program (GeoTreks): The visitor is invited to stand on the San Andreas fault at Pallett Creek. Over the last two years SBCM and SCEC interns created the prototype of a field guide series, *The San Bernardino County Museum Discover Your Backyard Field Guides,* which interprets Pallett Creek in Valyermo, CA, widely known as "the Rosetta Stone of Paleoseismology". A re-excavated "trenchcrop" at Pallett Creek provides the basis for the field guide, which includes basic geological background as well as lithologic and chronologic data about earthquake events as revealed at the outcrop. In 2013 SCEC and the San Bernardino County Museum also hosted day trips to the San Andreas fault as part of the California Science Education Conference and for the NASA-JPL InSight Vital Signs of the Planet Professional Development Program.
- Active Earth Monitor – San Andreas Fault Content Set (with IRIS and EarthScope): This online resource is one in a series of products from EarthScope workshops for park and museum interpreters. The product will be online (finally) in 2014.
- Citizen Science with the Quake-Catcher Network: This project facilitated the installation and marketing of QCN sensors in museums and other venues. Collaborators include USGS, SBCM, Stanford, and NEES. SCEC also supported a new "Quake Catcher" game for the Kinect video game system by a team led by Debi Kilb at SIO. SCEC has expanded the Quake Catcher Network of low-cost seismic sensors installed at over 19 EPIcenter locations in California and Oregon (as well as installations at

15 schools). 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. SCEC is collaborating with the USGS, Stanford, NEES, and the California Geological Survey, and various members of the EPIcenter network to establish a QCN professional development program for science educators.

- Other Locations: Examples of other recent activities include an exhibit at the California State University Los Angeles Department of Geological Sciences, featuring a computer screen showing recent worldwide and local earthquakes and a display of the Seven Steps to Earthquake Safety. New EPIcenter exhibits have also recently been completed at the California Academy of Sciences, San Francisco, and the earthquake themed highway rest stop in Marston, MO. Ongoing projects include the Hatfield Marine Science Center in Newport, OR, the Wallace Creek Interpretive Trail, the Earthquake Information Centers at Rancho Mirage Public Library, and The Science Spectacular Earthquake Program at the California Science Center.

e. Media Relations

SCEC has developed extensive relationships with the news media and is increasingly called upon for interviews by local, national, and international reporters and documentary producers. As a result the demand on SCEC scientists after a large California earthquake or elsewhere will be even greater than in previous earthquakes. An important component to this effort will be media and risk communication training for the SCEC Community. The first such offering was held at the 2012 SCEC Annual Meeting. Social media capabilities have been greatly expanded in 2013, see *twitter.com/scec* and *facebook.com/scec*.

3. K-14 Earthquake Education Initiative

The primary goal of this new Initiative is to educate and prepare California students for living in earthquake country. This includes improved earth science education as well as broadened preparedness training. The science of earthquakes provides the context for understanding why certain preparedness actions are recommended and for making appropriate decisions; however earthquake science and preparedness instructions are usually taught in a manner that lacks this context. SCEC's approach is to facilitate learning experiences and materials for use after large earthquakes worldwide and also the ShakeOut drill, and to develop learning materials that complement traditional standards-based instruction with regional earthquake information. The following are activities in this area in 2013:

- "Vital Signs of the Planet": Starting in 2013 SCEC has a 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 single geophysical lander on Mars to study its deep interior in 2016. 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. This program continues and expands the Cal State San Bernardino/EarthScope RET program that SCEC has developed with Sally McGill since 2009. In 2013, thirteen science educators and four students participated in the Vital Signs program and their posters were displayed at the 2013 SCEC Annual meeting. All of the teachers participated in 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.
- "Native California is Earthquake Country!" Initiative. SCEC is working with the Sherman Indian High School in Riverside, CA, to develop earthquake awareness and preparedness messaging, beginning with translation of "Drop, Cover, and Hold On" into many Native American languages. Products developed in 2013 include a "Native California is Earthquake Country" poster that was initially distributed and displayed in classrooms and dormitories at the school. Distribution has expanded to Native American cultural centers, administrative buildings, and schools throughout California. This engagement program is expanding participation in the ShakeOut, build more diverse array of EPIcenters, and create new avenues of collaboration.
- Professional Development. SCEC hosted a workshop for science educators as part of the 2013 SCEC Annual Meeting. The workshop was held at the San Bernardino County Museum. Additionally

SCEC partnered with CEETEP and the EarthScope Interpreter Workshops and SCEC materials were presented at 3 additional workshops in 2013.

- 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. The kit is distributed nationwide.
- California Science Teachers Association*:* SCEC participates each year in national and statewide science educator conferences to promote innovative earthquake education and communicate earthquake science and preparedness. SCEC and SBCM hosted a whole-day field course to the San Andreas fault as part of the 2013 California Science Education Conference in Palm Springs, CA, and SCEC and the California Geological Survey have shared a booth in the exhibit hall.

4. Experiential Learning and Career Advancement (ELCA)

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

The ELCA program in SCEC4 is built on the foundation of our long-established UseIT and SURE internship programs that challenge undergraduates with difficult, real-world problems that require collaborative, interdisciplinary solutions:

1) 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. 257 internships have been supported since 1994. In 2013, SURE had 10 Interns from institutions across the country, including community colleges.
2) The ***Undergraduate Studies in Earthquake Information Technology (UseIT)*** internship brings together undergraduates from many majors and from across the country in an NSF Research Experience for Undergraduates Site at USC. The eight-week program develops and enhances computer science skills while teaching the critical importance of collaboration for successful learning, scientific research and product development. UseIT interns tackle a scientific "Grand Challenge" that entails developing software and resources for use by earthquake scientists or outreach professionals, including SCEC-VDO. 244 students have participated since 2002. The 2013 UseIT Program had 24 Interns representing 10 institutions, and worked on the Grand Challenge to *Develop SCEC-VDO and GIS tools for exploring the new Uniform California Earthquake Rupture Forecast, Version 3.3, and use the UCERF3.3 to produce visualizations of the earthquake hazard in Southern California for public education during the 20th Anniversary of the 1994 Northridge earthquake.*

In addition to our undergraduate internships, we are exploring additional funding for master's level internships that provide unique opportunities. Students may participate in the UseIT program as mentors, conduct research projects with scientists at SCEC institutions (different than their own), and participate in CEO activities such as media relations, curricula development, and program evaluation (in 2013 CEO involved 4 masters students and 1 PhD student in its activities).

The final element of the ELCA program is career advancement opportunities for early-career researchers, including post-docs, young faculty, and research staff. In addition to employment opportunities that are shared via SCEC's email list, SCEC also appoints early career researchers to SCEC leadership positions, especially the planning committee, which provides significant opportunities for career advancement. In 2013, SCEC supported a presentation of Emmett McQuinn at the California Science Education Conference and Dr. Danielle Sumy (Cochran and de Groot Postdoc) presentations at the SCEC Education Workshop at the San Bernardino County Museum.

C. Honors and Awards

Compilation of responses by our members regarding national awards garnered by individuals or organizations within the SCEC Community:

- Whitney Behr (UT Austin) awarded 2013 Subaru Outstanding Woman in Science Award by the Geological Society of America.
- James Evans (Utah State) awarded 2013 AAPG Foundation Professorial Award.
- Thomas Jordan (USC) awarded 2014 GSA Presidential Medal.
- SCEC Community Modeling Environment Collaboration awarded 2013 High Performance Computing Innovation Excellence Award.
- Jacobo Bielak (CMU) elected 2013 U.S. Association for Computational Mechanics Fellow.
- Dennis Mileti (NHRAIC Emeritus) awarded 2012 Outstanding Contribution Award to Disaster Research and Management from the World Conference on Disaster Management.
- James Rice (Harvard) awarded
    - 2012 Honorary Doctoral Degree, Université Joseph Fourier (scientific division, University of Grenoble), for "*Géophysique, mécanique des solides*".
    - 2012 Louis Néel Medal of the European Geosciences Union in the areas of rock magnetism, rock physics and geomaterials, for "*seminal contributions to our fundamental understanding of strain localization, poromechanics and friction and his elegant and systematic studies have elucidated fault mechanics and the coupling with hydrologic and thermal processes during all phases of the earthquake cycle*".
    - 2012 Walter H. Bucher Medal by the American Geophysical Union.
    - 2013 Harry Fielding Reid Medal of the Seismological Society of America.
    - 2013 George Irwin Gold Medal of the International Congress on Fracture (ICF), intended for "*a senior researcher whose pioneering contributions have had lasting impact on engineering applications of fracture theories*".
- Gregory Beroza (Stanford) to be awarded 2014 Gutenberg Medalist of the European Geosciences Union in recognition of "outstanding contributions to Seismology".
- Eric Dunham (Stanford) awarded
    - 2012 Sloan Foundation Fellowship in Physics
    - 2013 NSF CAREER grant
- Bradford Hager awarded 2013 Inge Lehmann Medal from the American Geophysical Union.
- Roland Burgmann (UC Berkeley), Joan Gomberg (USGS), Irina Artemieva (U Copenhagen), Herb Dragert (UNAVCO), Kazushige Obara (ERI Tokyo), Eric Rignot (NASA JPL), An Yin (UCLA) elected 2013 American Geophysical Union Fellows.
- Sandy Seal (UCSB) recognized in 2013 for Outstanding Contributions to STEM Education by Henry Cuellar, Congressman of the 28th District in Texas.
- SCEC Researchers received 2012 Claire P. Holdredge Award from the Association of Engineering Geologists for a publication that is adjudged to be an outstanding contribution to the Engineering Geology profession: Rockwell, T., E. Gath, T. Gonzalez, C. Madden, D. Verdugo, C. Lippencott, T. Dawson, L.A. Owen, M. Fuchs, A. Cadena, P. Williams, E. Weldon, and P. Franceschi, 2010, Neotectonics and paleoseismology of the Limón and Pedro Miguel faults in Panamá: Earthquake Hazard to the Panama Canal; Bulletin of the Seismological Society of America, Vol. 100, No. 6, pp. 3097-3129, doi: 10.1785/0120090342.
- Andrew Meigs (Oregon State), Thomas Brocher (USGS) elected 2013 Geological Society of America Fellows.
- Elizabeth Cochran (USGS) was a 2013 Finalist for the World Technology Awards in the Environment category, for her work on the Quake Catcher Network.
- Rowena Lohman (Cornell) recognized by AGU in 2013 for outstanding scientific accomplishements in the field of geodesy by a young scientist.
- Julia Morgan (???) received 2013 Paul G. Silver Award for Outstanding Scientific Service, in the development of collaborative and interdisciplinary research on continental margins.

- Rober King (MIT) received 2013 Ivan I. Mueller Award for distinguished service and scientific leadership in the development of geodetic GPS positioning.
- John Labrecque (NASA) received 2013 AGU Union Medal promoting the international observation networks that are so critical to modern space geodesy.
- Thorsten Becker (USC) awarded 2013 Alexander von Humboldt Foundation Research Award.
- Lee McAuliffe (USC) received 2013 GSA Student Paper Award.
- Robert Yeat's book, Active Faults of the World (Cambridge University Press, 2012), received the Mary B. Ansari Best Reference Work Award for 2012 from the Geoscience Information Society.
- Peter Bird (UCLA) received 2013 George P. Woollard Award from Geophysics Division of the Geological Society of America.
- Cliff Thurber (UW Madison) elected outstanding reviewer of the year 2013 by the Geophysical Journal International's Editorial Board.

IV. SCEC Goals and Objectives

A. 2014 Science Collaboration Plan

1. Disciplinary Activities

The Center will sustain disciplinary science through standing committees in Seismology, Geodesy, 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 include the following tasks:

a. Seismology

Objectives. The objectives of the Seismology group are to gather data on the range of seismic phenomena observed in southern California and to integrate these data into physics-based models of fault slip. Of particular interest are proposals that foster innovations in network deployments, data collection, real-time research tools, and data processing. Proposals that provide community products that support one or more of the 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 the ANSS and NEES projects, that would augment existing and planned network stations with downhole and surface instrumentation to assess site response, nonlinear effects, and the ground coupling of built structures.
- 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 in 2014

- ***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 time-dependent geodetic data product for southern California that leverages the complementary nature of GPS and InSAR time series data. The resulting product will consist of well-constrained, temporally and spatially dense horizontal and vertical displacement time series that can be used in meeting a variety of SCEC4 objectives. This will require development of optimal methods for combining GPS and InSAR data, characterizing seasonal/hydrologic/anthropogenic signals, incorporating new data, and accounting for earthquake effects as needed. Proposals should demonstrate coordination with the overall activities and timeline of the CGM project including group efforts to compile GPS data and compare InSAR analysis techniques. More information can be found here: *http://collaborate.scec.org/cgm*.
- **Analysis of geodetic data to address specific SCEC4 research targets.** Studies addressing geodetic/geologic slip rate discrepancies, assessing the role of lower crust/upper mantle processes in driving fault loading, developing more physically realistic deformation models, providing input to the development of Community Stress Models, and constraining physics-based models of slow slip and tremor are encouraged, as are studies that pursue integrated use of geodetic, geologic, seismic, and other observations targeting special fault study areas. Proposals that include collection of new data should explicitly motivate the need for such efforts. Resulting data should be provided for inclusion in the CGM. In compliance with SCEC's data policy, data collected with SCEC funding must be made publicly available upon collection by archiving at an appropriate data center. 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. 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.***

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 VIII, 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 newly available Ventura lidar data sets to better define fault traces, fault activity, and geologic structure.
- Improve the statewide community fault model in areas of inadequate fault representations or where new data is available, such as using high-resolution topographic data sets to better define fault traces, spatial uncertainty, and stochastic heterogeneity of fault geometry (Problem 4c).
- Quantifying along-strike variations in fault roughness, complexity, strain localization, and damage in relation to the rupture propagation processes, including evaluation of the likelihood of multi-fault ruptures (Problem 4b).
- Validation of ground motion prediction through analysis and dating of precariously balanced rocks and other fragile geomorphic features (Problem 6).

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

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

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

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

Priorities for Earthquake Geology

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

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 HPC labs/centers as well as the vendor community in crosscutting efforts enabling SCEC petascale 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 HPC 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 computing resources 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.
- The computer resources you plan to use to perform your simulations.

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

Example Research Strategies

- Porting and optimization of high performance codes, required to reach SCEC research goals, on new architectures, and utilize advanced high performance computing programming techniques such as hybrid MPI/OpenMP, MPI/CUDA, PGAS, and auto-tuning.
- 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 simulators that can resolve the faulting processes across the range of scales required to investigate stress-mediated fault interaction, including those caused by dynamic wave propagation, generate synthetic seismicity catalogs, and assess the viability of earthquake rupture forecasts.
- Tools and algorithms for uncertainty quantification in large-scale inversion and forward-modeling studies, for managing I/O, data repositories, workflow and data analysis.

- 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 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.
- 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 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 enhanced ground motion 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.
- Engineering applications
  - Facilitate the "rupture-to-rafters" modeling capability to transform earthquake risk management into a Cyber Science and Engineering discipline.

2. 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 and (2) developing methods to represent smaller scale features, such as the detailed representations needed for the special fault study areas and stochastic variations of seismic velocities and attenuation structure.

- ***Community Velocity Model (CVM).*** Improve the current SCEC CVMs, with emphasis on more accurate representations of Vp, Vs, density, attenuation, and basin structure. Generate improved mantle Vp and Vs models, as well as more accurate descriptions of near-surface properties that can be incorporated into the models' geotechnical layers. Perform 3D waveform tomographic inversions and ambient noise analysis for evaluating and improving the CVMs. Develop and apply procedures (i.e., goodness-of-fit measures) for evaluating the existing and future models with data (e.g., waveforms, gravity) to distinguish alternative representations and quantify model uncertainties; apply these methods for well-recorded earthquakes in southern California to delineate areas where CVM updates are needed. Develop databases, models, and model building tools that will help facilitate expansion of the CVMs to statewide and plate-boundary scale velocity representations. These efforts should be coordinated with the SCEC CME special project.

- ***Community Fault Model (CFM).*** Improve and evaluate the CFM and statewide CFM (SCFM), placing emphasis on defining the geometry of major faults that are incompletely, or inaccurately, 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 heterogeneity. Evaluate the CFM with data (e.g., seismicity, seismic reflection profiles, geologic slip rates, and geodetic displacement fields) to distinguish alternative fault models. Update the CFM-R (rectilinear fault model) to reflect improvements in the CFM. Work on the statewide CFM in regions outside the SCEC CFM should be coordinated with the appropriate agencies (e.g., USGS for central and northern CA).
- ***Unified Structural Representation (USR).*** Develop better IT mechanisms for delivering the USR, particularly the CVM parameters and information about the model's structural components, to the user community for use in generating and/or parameterizing numerical models. Generate maps of geologic surfaces compatible with the CFM that may serve as strain markers in crustal deformation modeling and/or property boundaries in future iterations of the USR.

b. Fault and Rupture Mechanics (FARM)

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

Priorities for FARM in 2014

- Investigate the relative 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; collaboration with the Technical Activity Group (TAG) on Source Inversion Validation (SIV) is encouraged.
- Develop realistic descriptions of heterogeneity in fault geometry, rock properties, stresses and strains, and tractable ways to incorporate heterogeneity in numerical models of single dynamic rupture events and multiple earthquake cycles (3e, 3f, 4b, 4d, 6b). Test dynamic rupture modeling that incorporates these heterogeneities first by verifying the computational algorithms with benchmark exercises of the

Dynamic Rupture Code Verification Technical Activity Group (TAG), then by comparing the results with geological and geophysical observations.

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

c. Stress and Deformation Over Time (SDOT)

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

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

Projects Solicited for SDOT

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

the heat flow paradox, stress and strain transients, fault system evolution, as tied in with stress and deformation measurements across scales.

- Development of models of interseismic and earthquake cycle deformation, including efforts to estimate slip rates on southern CA faults, fault geometries at depth, and spatial distribution of slip or moment deficits on faults. Assessments of potential discrepancies of models based on geodetic, geologic, and seismic data. Development of deformation models (fault slip rates and locking depths, off-fault deformation rates) in support of earthquake rupture forecasting.
- Research into averaging, simplification, and coarse-graining approaches across spatio-temporal scales, addressing questions such as the appropriate scale for capturing fault interactions, the adequate representation of frictional behavior and dynamic processes in long-term interaction models, fault roughness, structure, complexity and uncertainty. Modeling approaches may include analytical or semi-analytical methods, spectral approaches, boundary, finite, or distinct element methods, and a mix of these, and there are strong links with all other SCEC working groups, including FARM, Earthquake Simulators, and USR.

d. Earthquake Forecasting and Predictability (EFP)

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

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

For research strategies that plan to utilize the Collaboratory for the Study of Predictability (CSEP), see Section XI 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 in 2014

- Support the development of statistical or physics-based real-time earthquake forecasts.
- Utilize and/or evaluate the significance of earthquake 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.

Research Topics in GMP

- Developing and/or refining physics-based simulation methodologies, with particular emphasis on high frequency (1-10 Hz) 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.
- Waveform modeling of past earthquakes to validate and/or refine the structure of the Community Velocity Model (CVM) (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, and development and validation of improved (possibly frequency-dependent) attenuation (intrinsic or scattering) models in physics-based simulations (in collaboration with USR).
- 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 simulation methodologies used to simulate ground motions.
- 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. 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. Comparison of synthetic ground motions from deterministic and stochastic approaches to data for overlapping bandwidths. Close collaboration with the Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV).

f. Southern San Andreas Fault Evaluation (SoSAFE)

The SCEC Southern San Andreas Fault Evaluation (SoSAFE) Project aims to increase knowledge of slip rates, paleoearthquake ages, and slip distributions of past earthquakes, for the past two thousand years on the southern San Andreas fault system. From Parkfield to Bombay Beach, and including the San Jacinto fault, the objective is to obtain new data to clarify and refine relative hazard assessments for each potential source of a future 'Big One'.

Priorities for SoSAFE in 2014

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

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

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

g. Earthquake Engineering Implementation Interface (EEII)

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

Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV). A TAG focused on validation of ground motion simulations for use in engineering applications is developing and implementing testing/rating methodologies, via collaboration between ground motion modelers and engineering users. The workshops and research of this TAG to date have identified the efforts below as potential priority activities in this area. See the Ground-Motion Prediction (GMP) and the Community Modeling Environment (CME) sections of the Collaboration Plan for related research priorities. Proposals on these topics will be reviewed with all other SCEC proposals in January of 2014. Interested researchers are invited to contact Dr. Nicolas Luco (nluco@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 approximately two coordination workshops.

- Develop validation methodologies that use elastic and inelastic response spectra, and/or other 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 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.
- Develop validated and efficient methods for either i) adjusting ground motion time series simulated by the Broadband Platform to account for the local site conditions at historical earthquake stations; or ii) de-convolving recorded ground motion time series to a reference site condition corresponding to that for simulated ground motions.

Improved Hazard Representation

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

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 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 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 Broadband Platform.
- Compare simulated versus recorded ground motions for different models of the regional geologic structure.

Collaboration in Structural Response Analysis

- Tall Buildings and Other Long-Period Structures. Enhance the reliability of simulations of long period ground motions in the Los Angeles region using refinements in source characterization and seismic velocity models, and evaluate the impacts of these ground motions on tall buildings and other long-period structures (e.g., bridges, waterfront structures). Such projects could potentially build on work done in the PEER TBI Project.

- End-to-End Simulation. Interactively identify the sensitivity of structural response to ground motion parameters and structural parameters through end-to-end simulation. Buildings of particular interest include non-ductile concrete frame buildings.
- Reference Buildings and Bridges. Participate with PEER investigators in the analysis of reference buildings and bridges using simulated broadband ground motion time histories. The ground motions of large, rare earthquakes, which are poorly represented in the NGA strong motion 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.

3. Special Projects and Initiatives

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

a. Working Group on California Earthquake Probabilities (WGCEP)

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

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

- Evaluate fault models in terms of the overall fault connectivity at depth (important for understanding the likelihood of multi-fault ruptures) and the extent to which faults represent a well-define surface versus a proxy for a braided deformation zone.
- Evaluate existing deformation models, or develop new ones, in terms of applicability of GPS constraints, categorical slip-rate assignments (based on “similar” faults), applicability of back-slip methods, and other assumptions. Of particular interest is the extent to which slip rates taper at the ends of faults and at fault connections.
- Evaluate the UCERF3 implication that 30% to 60% of off-fault deformation is aseismic.
- Help determine the average along-strike slip distribution of large earthquakes, especially where multiple faults are involved (e.g., is there reduced slip at fault connections?).
- Help determine the average down-dip slip distribution of large earthquakes (the ultimate source of existing discrepancies in magnitude-area relationships). Are surface slip measurements biased with respect to slips at depth?
- Develop a better understanding of the distribution of creeping processes and their influence on both rupture dimension and seismogenic slip rate.
- Contribute to the compilation and interpretation of mean recurrence-interval constraints from paleoseismic data and/or develop site-specific models for the probably of events going undetected at a paleosiesmic site.
- Develop ways to constrain the spatial distribution of maximum magnitude for background seismicity (for earthquakes occurring off of the explicitly modeled faults).
- Address the question of whether small volumes of space exhibit a Gutenberg Richter distribution of nucleations (even on faults).
- Develop improved estimates (including uncertainties) of the long-term rates of observed earthquakes for different sized volumes of space.
- Refine our magnitude completeness estimates (as a function of time, space, and magnitude). Develop such models for real-time applications (as will be needed in operational earthquake forecasting).
- Develop methods for quantifying elastic-rebound based probabilities in un-segmented fault models.
- Help quantify the amount of slip in the last event, and/or average slip over multiple events, on any major faults in California (including variations along strike).
- Develop models for fault-to-fault rupture probabilities, especially given uncertainties in fault endpoints.
- 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?
- Is there 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 the behavior of physics-based earthquake 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 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 with 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? Contributions may include:

- 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;
- Developing seismicity forecasting models based on the Coulomb stress hypothesis that can be tested retrospectively and prospectively within CSEP;
- Developing methodology for forecasting focal mechanisms and assessing the skill of such forecasts;
- Expanding the range of physics-based models to test hypotheses that some aspects of earthquake triggering are dominated by dynamic rather than quasi-static stress changes and that slow slip event activity can be used to forecast large earthquakes;
- Working to develop testable fault-based forecasting models;
- Developing CSEP experiments for prospectively testing 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;
- Using catalogs generated by physics-based earthquake simulators as synthetic laboratories to quantify the predictability of simulated earthquakes given uncertain initial conditions (see also the WGCEP section);
- Developing forecasting strategies and CSEP testing methodology to test simulator-generated forecasts against observations prospectively (see also the WGCEP section);
- Evaluating hypotheses critical to forecasting large earthquakes, including the characteristic earthquake hypothesis, the seismic gap hypothesis, and the maximum-magnitude hypothesis;
- Developing experiments to test external forecasts and predictions (generated outside of CSEP) that are registered and evaluated prospectively within CSEP;
- Reducing testing latency by reducing the updating interval of short-term forecasting models (e.g., STEP and ETAS) to explore the potential information gain in aftershock sequences. Most desirable is testing on an event by event basis to adapt the testing frequency to the seismic activity;
- Supporting Operational Earthquake Forecasting efforts by developing testing procedures that explicitly recognize that real-time catalogs are incomplete and have larger errors in source parameters;
- Establishing seismicity-based reference models within CSEP as norms against which the skill of candidate models can be evaluated;
- Developing methods for forming optimal hybrid (or ensemble) models from a variety of existing probability-based or alarm-based forecasting models;
- Intensifying the collaboration with Japan and New Zealand with a special emphasis on the effect of the Darfield and Tohoku earthquakes, and using data collected from these sequences to retrospectively calibrate and prospectively test improved forecasting models; or
- Conducting workshops to facilitate international collaboratories.

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

c. Community Modeling Environment (CME)

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

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

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

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

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

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

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

NSF has funded a new effort within SCEC to broaden and deepen our collaborations with Japanese earthquake scientists. A particular emphasis will be to broaden the participation of early career scientists. Collaborative research funded through VISES should have relevance for research questions of concern to the SCEC core program. Examples of relevant research activities include testing earthquake forecast models, numerical simulation of earthquake ground motion to high frequencies, ground motion simulation using dense networks of high-dynamic range sensors, and geodynamical studies of fault interaction and deformation. Travel support to Japan for early career scientists developing collaborations with colleagues in Japan is a priority for funding under the VISES program.

Note: Funding for successful proposals for travel to Japan will be handled from the SCEC office. Your proposed budget should not include overhead.

e. National Partnerships through EarthScope

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

B. 2013 Communication, Education and Outreach Goals and Objectives

SCEC's CEO program addresses the third element of SCEC's mission: Communicate understanding of earthquake phenomena to the world at large as useful knowledge for reducing earthquake risk and improving community resilience. The programs and resources being implemented in SCEC4 provide an expanded capacity for accomplishing this overall goal. See §III.B for descriptions of each thrust area of the CEO program and current activities of each.

A SCEC CEO Strategic Plan with metrics and milestones (see Appendix B) and this plan was reviewed by a new CEO subcommittee of the Advisory Council in 2013. Currently we are working on a structure for monitoring and tabulating our progress towards the range of milestones that were proposed. This report summarizes planned activities in 2014 in terms of the proposed metrics.

1. The Implementation Interface

a. Research Engineering Partnerships

As these activities are coordinated as a SCEC research focus group and managed by representatives on the planning committee, see §IV.A.2.g for activities in 2014. This is an area that will have special focus in 2014 in terms of how to track participation and collaborations with engineers, as several metrics have not been tracked yet. Activities to be coordinated, with metrics to be assessed in 2014 include:

- # of research engineers attending SCEC Annual Meeting and other SCEC research workshops;
- # of documented uses (citations, reports) of SCEC simulation models and other SCEC products in engineering research and risk assessments;
- # of SCEC projects and collaborations involving research engineers;
- # of partnerships with engineering and risk modeling organizations (with MOUs or other written partnership);
- # of jointly-funded research projects with partner organizations.

b. Activities with Technical Audiences

To understand SCEC's effectiveness in this area, we are developing structures to document the 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. Assessing these activities and metrics will be another high priority in 2014:

- # of practicing engineers, geotechnical consultants, building officials, emergency managers, financial institutions, and insurers attending SCEC Annual Meeting and other SCEC research workshops;
- # of practicing engineers, geotechnical consultants, building officials, emergency managers, financial institution representatives, and insurers in the ECA (statewide);
- # of training sessions and seminars for practicing engineers, building officials, etc. (organized by SCEC or co-sponsored). The key example of this will be the third annual *Buildings At Risk* Summit in partnership with the Structural Engineers Association of Southern California and other organizations;
- # of online activities such as webinars, trainings, and filmed presentations (each year). These will likely be done with FEMA, EERI, NEES, and other partners;
- # of SCEC researchers (including students) participating in engineering/building code/etc. workshops and other activities (hosted by SCEC or other organizations) (again, such as the *Buildings At Risk* Summit);
- # of documented technical (not research) uses of our models and informational resources (downloads, citations, etc.);
- # of documented uses of SCEC tools/information in developing or conforming to building codes, guidelines, and standards.

2. Public Education and Preparedness

a. Earthquake Country Alliance

In 2014 ECA will continue the progress made since 2012 to establish its leadership structures, including sector-based committees that may be coordinated with partner organizations. For example, the Business Committee may be transitioned to a partnership with the Business and Industry Council on Emergency Planning and Preparedness (BICEPP) or similar organizations that already have extensive connections and activities. FEMA now provides direct funding via a cooperative agreement for supporting these committees (conference calls, development of materials, etc.), for activities of each regional alliance, for leadership meetings, media relations, and for USC students who support California ShakeOut recruitment, data management, and content development.

Overall five-year ECA goals will determine priorities in 2014:

- *Create a Network:*Further develop the awareness of, engagement in, and support for the ECA among internal audiences
- *Working Together:* Cultivate collaboration among stakeholder Alliance members
- *Continued Engagement of the Already Prepared:* 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
- *Get the Rest of California Prepared:* Expand the community of earthquake / tsunami-ready Californians by reaching out to those who are not yet engaged in earthquake/tsunami readiness activities

Metrics for ECA activities in 2014:

- # of registered ECA Associates;
- # of participants of functional and sector committees;
- # of Strategic Organizational Partners with MOUs;
- # of partner organizations that link to ShakeOut & ECA website;
- # of resources (documents, online tools, etc.) to be used during disaster events to assist with information sharing between experts;
- # of new resources/programs for communities that have not yet been engaged;
- # of ECA curricular resources for use by schools, colleges, and free-choice learning institutions to teach about earthquakes and preparedness;
- # Amount of new funding (grants, donations) for ECA and its activities;
- # of unique visitors to ECA websites.

b. ShakeOut Earthquake Drills

Now that the ShakeOut concept has matured (2013 was the 6th annual drill in California), with additional Official ShakeOut Regions across the country and around the world and more to come, SCEC will develop resources for these regions and others to come to maintain the sustainability of its management of websites for all drills, such that each ShakeOut can manage its own recruitment, media engagement etc.

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. Planning for these aspects will continue in 2014. Also, the Shakeout drills will continue to be an annual exercise of SCEC's post-earthquake response plan.

Extensive surveys have been done after each ShakeOut and will be reported on in 2014; the results of these surveys will provide additional indicators and metrics to monitor in order to assess the effectiveness of the ShakeOut in terms of what was learned, plans improved, and mitigation conducted. The following metrics and milestones are basic aspects of ShakeOut participation and will be monitored in 2013:

- # California ShakeOut Participants;
- # California ShakeOut individual/family registrants;
- # Participants in other U.S. ShakeOuts;
- # Participants in international ShakeOuts (BC, New Zealand, Japan, Central Asia, etc.): While SCEC will be coordinating with ShakeOut Organizers in other countries, and in some cases hosting the websites for the drills, international participation is beyond SCEC's direct influence so this will not have set milestones;
- # of ShakeOut drill franchises: SCEC will report the number of franchises but while we support many we do not actively promote new ShakeOuts as a goal (more is not necessarily better), so specific milestones are not appropriate. For example, at some point multiple ShakeOuts might be combined, reducing the overall total distinct drills.

c. *Putting Down Roots in Earthquake Country* Publication Series

Over the past 8 years this handbook has had several science content updates, new versions, and translations that have expanded its reach. In 2014 experts that specialize in communicating in multiple languages and via culturally appropriate channels, including development of materials for low-literate or visually impaired audiences, will be engaged to adapt a simpler set of publications in the *Roots* series that are also for smaller regions of California to allow customization of the hazard information as well (*Staying Safe Where the Earth Shakes).*

While *Roots* 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. Activities and metrics for 2014:

- Update and improve So Cal booklet with new science and preparedness information;
- Inclusion of updated earthquake forecasting information (UCERF3, etc.);
- # of area-specific supplements (inserts or online, potentially tied to ShakeOut Areas);
- # of CA versions in different languages or for other audiences;
- # of booklets (Roots, supplements, multi-language versions) distributed;
- Evaluation activities (status will be reported, results may be in following year).

d. Earthquake Education and Public Information centers (EPIcenters)

As the EPIcenter network grows in 2013 and beyond, 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. We are also gaining interest from museums and other venues outside of California and in 2014 will determine how to handle these in terms of ECA being a California-based organization.

A key activity in 2014 will continue to be SCEC's collaboration with the USGS, Stanford, and several members of the EPIcenter network to develop a QCN professional development program for science educators which could 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 would like to build community among those teachers and using their local museum, science center, etc. as a hub for this engagement.

Additionally, in partnership with EarthScope and Open Topography, an updated version of the Wallace Creek Interpretive Trail website (originally developed 1999-2001) will debut in 2014. The new site offers an updated web interface, LiDAR images and movies, links to recent research in the region, and many new education activities developed by SCEC Interns and faculty at Arizona State University.

Metrics for EPIcenter activities:

- # of museums and other free-choice learning venues in California and elsewhere;
- # of national organizations (e.g. research organizations, museum associations, etc.) involved;

- # of SCEC-developed exhibits, interpretive trails, or programs in use;
- # of field trip guides or SCEC Seismic Sites updated or created;
- # of EPIcenter field trips or other professional development field experiences;
- # of EPIcenters using network materials (including materials from national organizations and the ShakeOut).

e. Media Relations

In 2014 SCEC will greatly revamp its Media Relations capabilities and level of engagement with local and national news media. We will also establish new coordination among media relations personnel from SCEC institutions. New content management software for SCEC's web pages will allow members of the community to create online summaries of their research, along with video recordings of presentations, as part of a new experts directory. SCEC will partner with USGS, Caltech, and other partners to offer annual programs that educate the media on how to report earthquake science, including available resources, appropriate experts, etc. SCEC (and the ECA) will also increase the availability of multi-lingual resources (materials, news releases, experts, etc.) to more effectively engage all media, including foreign media. Summer and school-year journalism or communications interns will be offered to assist CEO staff in developing these technologies and resources. Media relations metrics are:

- # of traditional news advisories and releases;
- # of traditional news stories (online, print, radio, TV);
- # of podcasts (audio and/or video);
- # of virtual news conferences / webinars;
- # of people in SCEC Experts directory (with summaries/videos/etc.);
- # of experts identified, trained (if necessary) and available for interviews in languages other than English;
- # of social media posts/followers/etc.;
- # of non-English news advisories/releases (by language);
- # of media and risk communication training seminars for SCEC community (and # of participants);
- # of programs to educate the media on how to report earthquake science (and number of participants).

3. K-14 Earthquake Education Initiative

This thrust area organizes SCEC's activities in curricula development and teacher professional development, and connects to other CEO activities such as internships for community college students. Highlights include:

- The GPS summer RET program is now supported with NASA funding ($350K over sever years) as part of the InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission that will place a single geophysical lander on Mars to study its deep interior. SCEC will adapt standards-aligned materials (provided by InSight) to help teachers work with comparative planetology concepts within the current educational environment. In addition SCEC will promote InSight in the EPIcenter Network.
- SCEC CEO will be participating in the planning of the 2014 California Science Education Conference. Additionally, SCEC will participate in finding speakers and planning a field trip along the San Andreas Fault (in partnership with the San Bernardino County Museum).
- Web resources for SCEC's Plate Tectonics Puzzle Map will be developed to facilitate online ordering and access to resources such as activities, plate replacement templates, links to online resources, etc.
- Videos, posters, and other materials will be developed further with our partnership with Sherman Indian High School.

Metrics for K-14 activities:

- # of event-based or "place-based" local/regional education opportunities;
- # of educational materials improved or created to provide information about local earthquake hazards and relevance for learning about earthquakes;
- # of follow-up activities over the long-term to help implement the content;
- # of teacher workshops offered to introduce these resources to educators;
- # of participating educational and research organizations in the initiative;
- # of new learning experiences and materials for use after large earthquakes.

4. Experiential Learning and Career Advancement (ELCA)

In 2014 we will leverage SCEC's intern programs to provide additional learning and career opportunities in a continuum beginning in high school, throughout college, and into careers in science and education. These activities will connect with other activities of SCEC CEO and develop partnerships with other organizations, including SCEC institutions.

SCEC involved more than 50 interns each year during SCEC3, through extensive leveraging of stipend support from mentors and institutions. However funding for travel and other program expenses has not increased. We are developing ways to provide experiences to as many students as possible, but increasing expenses beyond stipends likely means a more selective program that may grow more slowly. Metrics for the intern programs include:

- # of participants (each summer) in SCEC undergraduate internship programs, based on current funding levels and potential leveraging;
- # of students involved in academic-year research or outreach projects (SCEC/ShakeOut/etc.);
- % of undergraduate interns who are women / % under-represented minorities;
- # of intern alumni in graduate school or having graduate degrees;
- # of intern alumni in STEM professions or internships.

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

Additional ELCA metrics:

- # of high school students provided research, education or outreach experiences;
- # of master's level opportunities;
- # of early career researcher presentations supported;
- # of employment or internship opportunities that are shared via SCEC email or website;
- # of early career researchers active in SCEC (criteria TBD);
- # of early career researchers in SCEC leadership positions (planning committee, etc.);
- % of women/underrepresented minorities in SCEC leadership positions.

V. Publications

This section lists the publications recorded in the SCEC community database between November 2012 to November 2013. Each publication is preceded by its SCEC publication number.

A. Journal Articles (138 total)

1665 Aagaard, B. T., M. G. Knepley, C. A. Williams (2013). A Domain Decomposition Approach to Implementing Fault Slip in Finite-Element Models of Quasi-static and Dynamic Crustal Deformation. *Journal of Geophysical Research: Solid Earth*, 118, p. 3059–3079, DOI: 10.1002/jgrb.50217.

1694 Agnew, D. C. (2013). Realistic Simulations of Geodetic Network Data: The Fakenet Package. *Seismological Research Letters*, 84, p. 426-432, DOI: 10.1785/0220120185.

1846 Akciz, S. O., Grant Ludwig, L., Zielke, O. and Arrowsmith, J R. (2013). 3D investigation of a 5m deflected channel along the San Andreas fault in the Carrizo Plain. *Bulletin of the Seismological Society of America*, under review.

1544 Akciz, S. O., L. Grant Ludwig, O. Zielke, and J R. Arrowsmith (2013). Post-1857 fracturing and deflection of an apparent offset channel along the San Andreas Fault in the Carrizo Plain. *Bulletin of the Seismological Society of America*, under review.

1533 Anooshehpoor, A., J. N. Brune, J. Daemen, and M. D. Purvance (2013). Constraints on Ground Accelerations Inferred from Unfractured Hoodoos near the Garlock Fault, California. *Bulletin of the Seismological Society of America*, 103, p. 99-106, DOI: 10.1785/0120110246.

1695 Aurélie Guilhem, Roland Bürgmann, Andrew M. Freed, Tabrez S. Ali (2013). Testing the Accelerating Moment Release (AMR) Hypothesis in Areas of High Stress. *Geophysical Journal International*, 195, p. 785-798, DOI: 10.1093/gji/ggt298.

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

1519 Baltay, A. S., T. C. Hanks and G. C. Beroza (2013). Stable Stress Drop Measurements and their Variability: Implications for Ground-Motion Prediction. *Bulletin of the Seismological Society of America*, 103, DOI: 10.1785/0120120161.

1627 Barall, M. (2012). Data Transfer File Formats for Earthquake Simulators. *Seismological Research Letters*, 83, p. 991-993, DOI: 10.1785/0220120040.

1530 Barbour, A. J. and D. C. Agnew (2012). Detection of Seismic Signals using Seismometers and Strainmeters. *Bulletin of the Seismological Society of America*, 102, p. 2484-2490, DOI: 10.1785/0120110298.

1818 Barnhart, W. D., and R. B. Lohman (2013). Characterizing and estimating noise in InSAR and InSAR time series with MODIS. *Geochemistry, Geophysics, Geosystems*, 14, DOI: 10.1002/ggge.20258.

1800 Barrett, S. A. and G. C. Beroza (2013). An Empirical Approach to Subspace Detection. *Seismological Research Letters*, submitted.

1823 Bennett, S.E.K., and M.E. Oskin (2013). Oblique rifting ruptures continents: example from the Gulf of California shear zone. *Geology*, accepted.

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

1646 Blisniuk, K., M.E. Oskin, K. Fletcher, T. Rockwell, and W. Sharp (2012). Assessing the Reliability of U-series and 10Be dating techniques on Alluvial Fans in the Anza Borrego Desert, California. *Quaternary Geochronology*, 13, p. 26-41, DOI: 10.1016/j.quageo.2012.08.004.

1847 Blisniuk, K., Oskin, M., Meriaux, S., Rockwell, T., Finkel, R., and Ryerson, F. (2013). Stable, rapid rate of slip since inception on the San Jacinto fault. *Geophysical Research Letters*, 40, p. 4209-4213, DOI: 10.1002/grl.50819.

1752 Brodsky, E. E. and L. J. Lajoie (2013). Anthropogenic Seismicity Rates and Operational Parameters at the Salton Sea Geothermal Field. *Science*, 341, p. 543-546, DOI: 10.1126/science.1239213.

1848 Brooks, B., Glennie, C., Hudnut, K., Ericksen, T., and Hauser, D. (2013). Mobile laser scanning applied to the Earth sciences. *Eos, Transactions, American Geophysical Union*, 94, p. 313-315.

1844 Chao, K., Z. Peng, H. Gonzalez-Huizar, C. Aiken, B. Enescu, H. Kao, A. A. Velasco, K. Obara and T. Matsuzawa (2013). Global search of triggered tremor following the 2011 Mw9.0 Tohoku-Oki earthquake. *Bulletin of the Seismological Society of America*, 103, p. 1551-1571, DOI: 10.1785/0120120171.
1687 Chen, K.H., Bürgmann, R., and Nadeau, R.M. (2013). Do earthquakes talk to each other?: Triggering and interaction of repeating sequences at Parkfield. *Journal of Geophysical Research*, 118, p. 165-182, DOI: 10.1029/2012JB009486.
1775 Chen, X., and P. M. Shearer (2013). California foreshock sequences suggest aseismic triggering process. *Geophysical Research Letters*, 40, DOI: 10.1002/grl.50444.
1689 Cooke, M. L., M. T. Schottenfeld and S. W. Buchanan (2013). Evolution of Fault Efficiency at Restraining Bends within Wet Kaolin Analog Experiments. *Journal of Structural Geology*, DOI: 10.1016/j.jsg.2013.01.010.
1683 Cotton, F., R. Archuleta, and M. Causse (2013). What is sigma of the stress drop?. *Seismological Research Letters*, 84, p. 42-48, DOI: 10.1785/0220120087.
1850 Crowell, B. W., D. Melgar, Y. Bock and J. Haase (2013). Earthquake Early Warning with Seismogeodesy: Example of the 2011 Mw 9.0 Tohoku-oki Earthquake. *Geophysical Research Letters*, under review.
1749 Crowell, B. W., Y. Bock, D. T. Sandwell, and Y. Fialko (2013). Geodetic Investigation into the Deformation of the Salton Trough. *Journal of Geophysical Research: Solid Earth*, 118, p. 5030–5039, DOI: 10.1002/jgrb.50347.
1828 DeBock, D. Jared and Abbie B. Liel (2013). A Comparative Evaluation of Probabilistic Regional Seismic Loss Assessment Methods, Using Scenario Case Studies. *Journal of Earthquake Engineering*, under review.
1812 Denolle, M. A., E. M. Dunham, G. A. Prieto, and G. C. Beroza (2013). SAVELA: A Virtual Earthquake Experiment Applied to Los Angeles. *Science*, under review.
1642 Denolle, M. A., E. M. Dunham, G. A. Prieto, and G. C. Beroza (2012). Ground Motion Prediction of Realistic Earthquake Sources Using the Ambient Seismic Field. *Journal of Geophysical Research*, 118, DOI: 10.1029/2012JB009603.
1644 Dominguez, L. A., and P. M. Davis (2013). Seismic Attenuation in the Middle America Region and the Frequency Dependence of Intrinsic Q. *Journal of Geophysical Research*.
1839 Dong, S., G. Ucarkus, S. Wesnousky, J. Maloney, G. Kent, and N. Driscoll (2013). Strike-slip Faulting along the Wassuk Range of the northern Walker Lane, Nevada. *Geosphere*, submitted.
1852 Donovan, J., and T. H. Jordan (2013). Forecasting the Rupture Directivity of Large Earthquakes: Constraints from Observations and Earthquake Simulators. *Seismological Research Letters*, 84.
1791 Duputel, Z., P. S. Agram, M. Simons and S. E. Minson (2013). Accounting for prediction error when inferring subsurface fault slip. *Geophysical Journal International*, submitted.
1796 Erickson, B. A., and E. M. Dunham (2013). An Efficient Numerical Method for Earthquake Cycles in Heterogeneous Media: Alternating Sub-basin and Surface-rupturing Events on Faults Crossing a Sedimentary Basin. *Journal of Geophysical Research*, submitted.
1692 Fang, Z. and E. M. Dunham (2013). Additional Shear Resistance from Fault Roughness and Stress Levels on Geometrically Complex Faults. *Journal of Geophysical Research*, 118, p. 3642-3654, DOI: 10.1002/jgrb.50262.
1697 Fletcher, J.M., O. J. Teran, T. K. Rockwell, M. Oskin, K. W. Hudnut, K. J. Mueller, R. M. Spelz, S. O. Akciz, E. Masana, G. Faneros, A. Morellan, J. Stock, A. Elliott, P. Gold, J. Liu-Zeng, A. Gonzalez, D. Lynch (2013). Assembly of a large earthquake from a complex fault system: surface rupture kinematics of the April 4, 2010 El Mayor-Cucapah Mw7.2 earthquake. *Geosphere*, submitted.
1655 Gabriel, A. A., J.-P. Ampuero, L. A. Dalguer, and P. M. Mai (2013). Source Properties of Dynamic Rupture Pulses with Off-fault Plasticity. *Journal of Geophysical Research*, 118, p. 4117-4126, DOI: 10.1002/jgrb.50213.
1767 Gabuchian, V., A.J. Rosakis, N. Lapusta, and D.D. Oglesby (2013). Experimental investigation of strong ground motion due to thrust-fault earthquakes. *Journal of Geophysical Research: Solid Earth*, submitted.

1698 Galasso, C., F. Zareian, I. Iervolino, and R.W. Graves (2012). Validation of Ground-Motion Simulations for Historical Events Using SDoF Systems. *Bulletin of the Seismological Society of America*, 102, p. 2727–2740, DOI: 10.1785/0120120018.

1699 Galasso, C., P. Zhong, F. Zareian, I. Iervolino, R. W. Graves (2013). Validation of ground-motion simulations for historical events using MDoF systems. *Earthquake Engineering & Structural Dynamics*.

1732 Geng, J., Y. Bock, D. Melgar, B. W. Crowell, and J. Haase (2013). A new seismogeodetic approach applied to GPS and accelerometer observations of the 2012 Brawley seismic swarm: Implications for earthquake early warning. *Geochemistry, Geophysics, Geosystems*, 14, p. 2124-2142, DOI: 10.1002/ggge.20144.

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1673 Gold, P. O., Oskin, M. E., Elliott, A. J., Hinojosa-Corona, A., Taylor, M. H., Kreylos, O., and Cowgill, E. S. (2013). Coseismic slip variation assessed from terrestrial lidar scans of the El Mayor-Cucapah earthquake surface rupture. *Earth and Planetary Science Letters*, 366, p. 151-162.

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B. Thesis/Dissertation (1 total)

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VI. Appendices

A. Science Milestones

NSF has requested that we submit an annualized list of milestones as part of a revised SCEC4 plan for 2012-2017. According to NSF instructions, these milestones are based on the six fundamental problems in earthquake physics described in the SCEC4 proposal (Table 3.1). 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, 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. Assess field evidence for the importance of specific resistance mechanisms during fault rupture, and plan fieldwork to collect new diagnostic data. Develop laboratory experiments that explore novel weakening mechanisms. Standardize observations from key earthquakes for the testing of different methods of finite-fault source inversion, and set up standardized inverse problems as cross-validation exercises. **[III, VI]**

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]**

Year 2 (2013-2014)

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, V]**

5. Community Stress Model. Populate the CSM data system with existing observational and model-based constraints. Begin coordination efforts with developers of the CGM and earthquake models. Investigate the variations in directions and magnitudes of the stresses and stressing rates predicted by different existing models. **[I, II, IV]**

6. Special Fault Study Areas. Solicit SFSA Science Plan(s) from the SCEC community and post Science Plan(s) for 2014 RFP on the website. Re-examine requirements for SFSA Science Plans. Evaluate whether SCEC should increase the number of SFSA-oriented studies in the SCEC base program. **[I-VI]**

7. Ground Motion Simulation Validation. Develop a list of metrics identified by earthquake scientists and engineers as needed to validate ground motion predictions for application to seismic hazard analysis and earthquake engineering. Use the observed ground motions of well-recorded California earthquakes to evaluate existing ground motion simulation methods and recommend improvements. Establish the Broadband Simulation Platform as a high-performance cyberfacility for ground motion simulation by outside research communities, including earthquake engineers. **[III, VI]**

8. Source Modeling. Develop numerical methods that simultaneously resolve fault zone processes and large-scale rupture, including fault interaction, complex geometries, heterogeneites and multiple fault physics. Assess data available to distinguish source from path/site effects at high frequencies. Develop a methodology for uncertainty quantification in finite-fault source inversion and back-projection source imaging, tested on standardized data sets. **[III, VI]**

9. Time-Dependent Earthquake Forecasting. Assess the capabilities of UCERF3 for time-dependent forecasting through comparisons with earthquake catalogs or synthetic catalogs from earthquake models. Through CSEP and in collaboration with the USGS and CGS, test the suitability of deploying UCERF3 as an operational earthquake forecast. Couple UCERF3 to the Cybershake simulation suite for the Los Angeles region to prototype a time-dependent urban seismic hazard model. **[II, VI]**

10. Progress Report on SCEC4 Problems. Report to the SCEC4 community and Advisory Council on the progress made so far in formulating and testing hypotheses that address the six fundamental problem areas of earthquake physics.

Year 3 (2014-2015)

1. Improved Observations. Archive and make available at the SCEDC waveforms, refined catalogs of earthquake locations and focal mechanisms for the period 1981-2013. Continue cataloging SCEC-supported geochronology analyses available for Southern California. Submit a proposal to NSF/Earthscope that focuses on high-resolution imaging of SFSAs and elsewhere in Southern California. Begin developing catalogs of prehistoric surface rupturing events along major faults in the system. **[I-VI]**

2. Transient Geodetic Signals. Using the first two years of results from Southern California, assess the capability and consistency of the geodetic transient detection procedures. Develop ensemble-based detection procedures that combine the output of multiple detection algorithms. **[II, V]**

3. Community Modeling Environment. Incorporate results from the Salton Seismic Imaging Project into the CVMs. Incorporate stochastic descriptions of small-scale heterogeneities into the upper layers of the CVMs and evaluate the importance of these heterogeneities in ground motion models. Integrate and evaluate a statewide unified CVM suitable for 3D ground motion modeling. Incorporate new information on fault complexity from SFSA projects into the CFM. **[II, III, IV, VI]**

4. Community Geodetic Model. Integrate InSAR and GPS in order to formulate a uniform resolution model for secular surface velocities and associated uncertainties and covariances. Revise or refine the technical specifications of the CGM based on results obtained in years 1 and 2 and input from the CSM and the Geodetic Transient Detection TAG. Define the framework and infrastructure for maintaining CGM. Identify and test algorithms for time-dependent InSAR analysis. **[I, 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-VI]**

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 intergration with back-projection imaging. **[III, VI]**

9. Time-Dependent Earthquake Forecasting. Develop approaches for using computational earthquake-cycle simulation models in forecasting. Employ these models for studying the predictability of large events and constraining seismic cycle parameters (maximum magnitude, inter-event time, etc.). Conduct prospective forecasting experiments in CSEP that test the key hypotheses that underlie time-dependent forecasting methods. **[II]**

10. Progress Report on SCEC4 Problems. Report to the SCEC4 Community and Advisory Council on the progress made so far in formulating and testing hypotheses that address the six fundamental problem areas of earthquake physics and report to SCEC4 community.

Year 4 (2015-2016)

1. Improved Observations. Refine catalogs of prehistoric surface rupturing events along major faults in the system and, if needed, document more events, including paleo-magnitudes, with more robust uncertainty measurements. Initiate the use of GPS data to better constrain 3D motion observed by InSAR, especially in the North/South direction. **[I-VI]**

2. Transient Geodetic Signals. Incorporate the CGM into the transient detection procedures as the reference model for time-dependent geodetic signals. Using the data collected in Southern California and elsewhere on geodetic transients, assess the observational constraints on the spectrum of deformation transients that might be associated with earthquake processes in San Andreas Fault system. **[II, IV, V]**

3. Community Modeling Environment. Develop a prototype CyberShake hazard model for the Los Angeles region based on extensions of UCERF3 and large suites of ground motion simulations up to 1 Hz calculated from improved CVMs. Provide interactive access to this layered seismic hazard model. **[II, III, IV, VI]**

4. Community Geodetic Model. Use SAR data catalogs from previous and current SAR missions to generate LOS displacement time series over Southern California, and conduct comparisons between InSAR and GPS time series results. **[I, V]**

5. Community Stress Model. Integrate the various stress model developed in years 1-3 into a full-scale version of the CSM that includes both time-independent and time-dependent components. 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 example how SFSAs results can be integrated 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, and high-frequency scattering by near-surface heterogeneities. **[VI]**

8. Source Modeling. Incorporate more realistic models of fault-resistance evolution into CFM- and CSM-based simulations of the earthquake cycle. 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 and implications for seismic network design. **[III, VI]**

9. Time-Dependent Earthquake Forecasting. Prototype numerical forecasting earthquake models, and evaluate their utility in developing new versions of a Uniform California Earthquake Rupture Forecast. **[II]**

10. Progress Report on SCEC4 Problems. Report on the progress made so far by SCEC4 investigations of the six fundamental problem areas of earthquake physics. Synthesize the current state of interdisciplinary knowledge in each of these problem areas, and evaluate which among the alternate hypotheses described in the SCEC4 proposal are now favored by the observational data and model-based constraints. This report will be used as input to the SCEC5 proposal. **[I-VI]**

Year 5 (2016-2017)

1. Improved Observations. Archive and make available at the SCEDC waveforms, refined catalogs of earthquake locations and focal mechanisms for the period 1981-2015. Document results from significant earthquakes that occurred during SCEC4. Continue refinement of the catalog of prehistoric surface rupturing events along major faults in the system including realistic uncertainty estimates. Initiate new project for archiving and making available InSAR datasets from Sentinel and ALOS2 acquisitions, which pertain to geological problems being studied by SCEC investigators. Complete comparing InSAR and GPS data to flag any suspect anomalies in GPS data as a first step to resolving discrepancies between GPS and InSAR strain rates. **[I-VI]**

2. Transient Geodetic Signals. Using the data collected in Southern California and elsewhere on geodetic transients during SCEC4, assess the validated and potential utility of geodetic data in time-dependent earthquake forecasting. **[II, IV, V]**

3. Community Modeling Environment. Perform reference calculations and apply goodness-of-fit measures to evaluate a SCEC California statewide CVMs using earthquake waveform data. Calculate statewide CyberShake hazard model based on extensions of UCERF3, the California statewide CVM, and large suites of ground motion simulations up to 1 Hz. Provide interactive and programmable access to this layered seismic hazard model. **[II, III, IV, VI]**

4. Community Geodetic Model. Develop a full-scale version of the CGM that integrates data types and includes both time-independent and time-dependent components. Provide outputs from the CGM that can be used as input to the CSM, transient detectors, and time-dependent earthquake forecasting. **[I, V]**

5. Community Stress Model. Release the final SCEC4 version of the CSM and assess its implications for earthquake physics. Recommend guidelines for future data collection and modeling studies to improve resolution of the CSM. **[I, II]**

6. Special Fault Study Areas. Publish synthesis studies of the SCEC4 SFSAs. Assess the utility of these syntheses in improving seismic hazard models for California. **[I-VI]**

7. Ground Motion Simulation Validation. Complete an evaluation of the simulated ground motions produced by the current versions of the Broadband Platform and the statewide CyberShake model. **[VI]**

8. Source Modeling. Develop realistic broadband kinematic source models of well-recorded earthquake in California that are consistent with source inversion and dynamic rupture modeling. Work with USGS/Golden to migrate improvements in source inversion into operational methods. **[III, VI]**

9. Time-Dependent Earthquake Forecasting. Use earthquake models, the CFM and CSM, and other modeling tools to quantify how fault-system complexities govern the probabilities of large earthquakes and rupture sequences. **[II]**

10. Progress Report on SCEC4 Problems. Conduct a final assessment of SCEC4 investigations of the six fundamental problem areas of earthquake physics, and evaluate the utility of new knowledge in time-independent and time-dependent seismic hazard analysis. **[I-VI]**

B. Communication, Education, and Outreach Strategic Plan (v4.3)

2013-2017: Creating an Earthquake and Tsunami Resilient California

SCEC's Communication, Education, and Outreach (CEO) program is an important complement to 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.

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

SCEC also continues to expand its CEO activities through partnerships with groups in academia and practice. The Earthquake Country Alliance (ECA), created and managed by SCEC, continues to grow and serve as a model for multi-organizational partnerships that we plan to establish within education and among practicing and research engineers. Much of this interaction is virtual, in line with SCEC's "smart and green" Virtual Organization objectives

The metrics and yearly milestones provided 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. While milestones below are expressed (mostly) numerically, additional qualitative assessments for each metric 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.

Area	Performance Metric	2013	2014	2015	2016
1.a: Implementation Interface – Research Engineering Partnerships	*Metrics and Milestones to be reported annually*				
	1.a.001: # of research engineers attending SCEC Annual Meeting and other SCEC research workshops	12 70	15	18	20
	Metrics to be reported annually (without specific targets)				
	1.a.002: # of 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). 2013: not yet assessed			
	1.a.003: # of SCEC projects and collaborations involving research engineers	Given uncertainties in funding and participation we cannot commit to milestones 2013: 16			
	1.a.004: # of 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 2013: 0			
	1.a.005: # of 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 2013: 2			

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.

Area	Performance Metric	2013	2014	2015	2016
1.b: Implementation Interface – Activities with Technical Audiences	*Metrics and Milestones to be reported annually*				
	1.b.001: # of practicing engineers, geotechnical consultants, building officials, emergency managers, insurers, etc. attending SCEC Annual Meeting and other SCEC research workshops (each year)	8 39	12	16	20
	1.b.002: # of practicing engineers, geotechnical consultants, building officials, emergency managers, financial institution representatives, and insurers in the ECA (statewide, cumulative)	30 >100 (members	50	60	70
	1.b.003: # of training sessions, seminars, and field trips for practicing engineers, building officials, etc. (organized by SCEC or co-sponsored) (each year)	1 2	2	4	6
	1.b.004: # of online activities such as webinars, online trainings, and filmed presentations (each year)	1 0	2	3	4
	Metrics to be reported annually (without specific targets)				
	1.b. 005: # of 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) 2013: ~10			
	1.b.006: # of documented technical (not research) uses of our models and informational resources (downloads, citations, etc., cumulative)	As our capacity builds for documenting such use (perhaps quite complicated) we will report results, however milestones cannot be specified initially. Developing pub database for this			
	1.b.007: # of documented uses of SCEC tools/information in developing or conforming to building codes, guidelines, and standards (cumulative)	This is something we will develop the capacity to track, however because this can be limited by the frequency of code updates and other external issues, we cannot estimate milestones. Developing database for this			

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 Emergency Management Agency 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.

Area	Performance Metric	2013	2014	2015	2016
2.a: Public Education and Preparedness – Earthquake Country Alliance	*Metrics and Milestones to be reported annually*				
	2.a.001: # of registered ECA Associates (cumulative)	500 660	600	650	700
	2.a.002: # of participants of functional and sector committees (each year)	60	80	100	100
	2.a.003: # of Strategic Organizational Partners with MOUs (cumulative)	5 2	10	12	16
	2.a.004: # of partner organizations (Associate or strategic orgs) that link to ShakeOut & ECA website	50 230	100	150	200
	2.a.005: # of new resources/programs for cultural/sector communities that have not yet been engaged (each year)	2 4	4	5	5
	2.a.006: # of ECA curricular resources for use by schools, colleges, and free-choice learning institutions to teach about earthquakes and preparedness (cumulative)	6 6	12	14	16
	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 $410K awarded from FEMA in 2013			

	2.a.008: # of unique visitors to each of ECA's websites (including the California ShakeOut site) and social media followers (each year)	This will be reported but milestones will not be specified until trends can be forecasted (the sites are being revised and may have much more traffic than currently) Web traffic being analyzed @shakeOut: 1,381 tweets, 5148 followers facebook.com/greatshakeout: 7,925 likes			
	Metrics to be tracked internally (not reported)				
	2.a.009: # of Associates in each Alliance (cumulative) (initial totals need to be confirmed)	TBD	TBD	TBD	TBD
	2.a.010: # of active functional and sector-based committees (each year)	8 8	10	12	12
	2.a.011: # of people/organizations showcased as "ECA heroes" or "ShakeOut Spotlights", etc.) (each year)	15 0	20	25	25
	2.a.012: # of new tsunami documents and programs (each year)	2 2	3	3	3

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.

Area	Performance Metric	2013	2014	2015	2016
2.b: Public Education and Preparedness – ShakeOut Earthquake Drills	*Metrics and Milestones to be reported annually (see Note above)*				
	2.b.001: # California ShakeOut Participants (each year)	9.5 million 9.6 million	10 million	10.3 million	10.5 million
	2.b.002. # California ShakeOut individual /family registrants (included in 2.b.001 (each year)	50,000 16,513	70,000	100,000	120,000
	2.b.003: # Participants in other U.S. ShakeOuts (each year)	5.0 million 11.3 million	5.5 million	6.0 million	6.5 million
	Metrics to be reported annually (without specific targets)				
	2.b.004: # Participants in international ShakeOuts (BC, Quebec, New Zealand, Japan, Central Asia, etc.) (each year)	While SCEC will be coordinating with ShakeOut Organizers in other countries, and in some cases hosting the websites for the drills, international participation is beyond SCEC's direct influence so this will be reported without specific milestones to achieve. 2013: 3.8 million			
	2.b.005: # of ShakeOut drill franchises (cumulative)	SCEC will report the number of franchises but while we support many we do not actively promote new ShakeOuts as a goal (more is not necessarily better), so specific milestones are not appropriate. For example, at some point multiple ShakeOuts might be combined, reducing the overall total distinct drills. 2013: 23			
	Metrics to be tracked internally (not reported)				
	2.b.006: # of ShakeOut drill franchises at each level (1-5)	This new ratings system is in development and will be used to specify what each franchise needs to do to be self-managing Still in development			

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.

Area	Performance Metric	2013	2014	2015	2016
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.)		✔		if available
	2.c.003: # of area-specific supplements in English (ShakeOut regions and Designated Media Areas	1 1	12	15	15
	2.c.004: # of CA versions in different languages or for other audiences (statewide, cumulative)	1 4	6	10	15
	Metrics to be reported annually (without specific targets)				
	2.c.005: # of 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 2013: >30,000			
	2.c.006: Evaluation activities (status will be reported, results may be in following year)	Reviewed with statewide prep. Survey	Assess business version	Assess multi-language versions	Reviewed with statewide prep. Survey
	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	>$300K (CalOES and CEA)	TBD	TBD	TBD

d. Earthquake Education and Public Information centers (EPIcenters)

This network of "free-choice" learning institutions within the ECA has grown rapidly, with over 60 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 14 EPIcenters (as of June, 2013).

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. A proposal to NSF submitted in early 2013 will help support this evaluation.

Area	Performance Metric	2013	2014	2015	2016
2.d: Public Education and Preparedness – EPIcenter Network	*Metrics and Milestones to be reported annually*				
	2.d.001: # of participating museums, parks, and other free-choice learning venues in California and in other states (cumulative)	65 65 (60 CA)	75	85	90
	2.d.002: # of partner national organizations (e.g. research organizations, museum associations, etc.) (cumulative)	5 5	7	8	10
	2.d.003: # of SCEC-developed exhibits, interpretive trails, or programs in use (cumulative)	4 5	6	8	8
	2.d.004: # of EPIcenters with active QCN sensors	19 19+15 at schools	30	40	50
	2.d.005: # of EPIcenter field trips or other professional development field experiences (each year)	1 2	2	4	5
	2.d.006: # of EPIcenters using network materials (including materials from national organizations and the ShakeOut) (each year)	50 >30 (being checked)	65	70	85
	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, such as the 2010 Haiti and Chile earthquakes. As a result the demand on SCEC scientists after a large California earthquake will be even greater than in previous earthquakes. In addition, the breadth of SCEC's research, including its information technology programs and the development of time- dependent earthquake forecasting, will also increase the need for expanded media relations. New strategies and technologies will be developed to meet these demands.

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

Social media capabilities are being expanded in SCEC4, and 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 will be offered to assist CEO staff in developing these technologies and resources.

An important component to our media relations strategy will be media and risk communication training for the SCEC Community. Training will likely be held each year at the SCEC Annual Meeting (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.

Area	Performance Metric (NOTE: Each milestone is split between SCEC Research and CEO-ECA topics, each year)	2013	2014	2015	2016
2.e: Public Education and Preparedness – Media Relations	*Metrics and Milestones to be reported annually*				
	2.e.001: # of traditional news advisories and releases	4 / 8 0 / 5	5/10	7 / 10	8 / 10
	2.e.002: # of podcasts (audio and/or video)	1 / 2 0 / 1	2 / 4	4/ 6	4 / 6
	2.e.003: # of virtual news conferences / webinars	1 / 1 0 / 0	2 / 2	3 /3	3 /3
	2.e.004: # of people in SCEC Experts directory (with summar-	5 0	10	20	30
	2.e.005: # of experts identified, trained (if necessary) and available for interviews in non-English lan-	2 / 5 2 / 3	4 / 10	5 / 15	6 / 20
	Metrics to be reported annually (without specific targets)				
	2.e.006: # of traditional news stories (online, print, radio, tv) (SCEC, ECA, ShakeOut)	SCEC: >50 but all not in database. ECA/ShakeOut: >1200 online and many more live TV and radio news stories			

	2.e.007: # of 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 @SCEC: 269 tweets, 153 followers facebook.com/scec: XXX posts,1295 likes
	2.e.008: # of 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) None in 2013
	2.e.009: # of 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. 1: 250 (at SCEC Annual Meeting)
	2.e.010: # of 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. None in 2013

3. K-14 Earthquake Education Initiative

The primary goal of this new Initiative is to educate and prepare California students for living in earthquake country. This includes improved 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, educational materials must also be improved or supplemented to provide better information about local earthquake hazards and increase relevance for learning about earthquakes (place-based education). SCEC's role as a content provider is its ability to convey current understanding of earthquake science, explain how this understanding is developed, and provide local examples. The SCEC4 focus on time-dependent earthquake forecasting may take many years to appear in textbooks, yet SCEC can develop useful resources for teachers now.

SCEC's approach will be as follows. First, we will facilitate learning experiences and materials for use with real earthquakes and the ShakeOut drill. This will include online resources and activities, appropriate for various subjects (science, math, geography, etc.) for teachers to download immediately after large earthquakes and prior to the ShakeOut, 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.

Area	**Performance Metric** (all categories include materials developed in collaboration with SCEC partners)	**2013**	**2014**	**2015**	**2016**
3. K-14 Earthquake Education Initiative	*Metrics and Milestones to be reported annually*				
	3.001: # of event-based or "place-based" local/regional education opportunities (each year)	1 1	2	3	3
	3.002: # of educational materials improved or created to provide information about local earthquake hazards and relevance for learning about earthquakes (per year)	1 2	2	4	4
	3.003: # of educator workshops offered to introduce these resources to educators (each year)	1 1	2	3	3
	3.004: # of educators participating in all programs	30 125	60	90	90
	3.005: # of participating educational and research organizations in the initiative (cumulative)	3 3	5	8	10
	Metrics to be reported annually (without specific targets)				
	3.006: # of 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 Not yet developed			

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).

(* Note: SCEC has involved more than 50 interns each year during SCEC3, through extensive leveraging of stipend support from mentors and institutions. However funding for travel and other program expenses has not increased. We are developing ways to provide experiences to as many students as possible which likely means a more selective program that may grow more slowly.)

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.

Area	Performance Metric	2013	2014	2015	2016
4. Experiential Learning and Career Advancement	*Metrics and Milestones to be reported annually*				
	4.001: # of participants (each summer) in SCEC undergraduate internship programs, based on current funding levels and potential leveraging (see note in text above)	30 24 UseIT 10 SURE	30	30	30
	4.002: # of students involved in academic-year research or outreach projects (SCEC/ShakeOut/etc.) (each year)	10 18	12	15	15
	4.003: % of undergraduate interns who are women / % under-represented minorities (each year)	40 / 20 38 / 38	50 / 25	50 / 25	50 / 25
	4.004: # of high school students provided research, education or outreach experiences, (each year)	4 4	6	6	8
	4.005: # of master's level opportunities (see text above) (each year)	2 5	4	5	6
	4.006: # of early career researcher presentations supported (each year)	2 2	3	4	4
	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 Data being reanalyzed			
	4.008: # of intern alumni in STEM professions or internships (cumula-				
	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 Will be tracked within new SCEC website			
	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 Total active in SCEC (attended 2013 Annual Meeting or submitted proposal in 2013): 584 Early career: 314			
	4.012: % of women/ underrepresented minorities in SCEC leadership positions	4.012 (women): 8 of 32 Planning Committee members, 5 of 19 Board Members, 5 of 11 Advisory Council members 4.012 (minorities): 4 of 32 Planning Committee members, 2 of 19 Board Members, 0 of 11 Advisory Council members			

C. 2013 Report of the SCEC Advisory Council

The SCEC Advisory Council (AC) met several times at the SCEC Annual Meeting in Palm Springs, September 8-11, 2013. The AC met with SCEC leadership, including representatives of the SCEC Board of Directors, with representatives of the funding agencies, and in informal settings with individual SCEC scientists and students. Prior to meeting, following the usual custom, we received a confidential letter from SCEC Director Tom Jordan that summarized SCEC's response to last year's Advisory Council recommendations and highlighted some new and continuing issues to solicit the Council's opinion this year. The AC also received copies of the draft SCEC science plan for 2014, copies of major proposals and reports submitted, and other relevant material. The AC set its agenda for discussion based on a combination of issues raised in the SCEC4 proposal reviews, those raised by the Director, and unresolved issues from previous AC reports.

The discussion in the AC meetings mostly fell into the following categories:

- How is SCEC4 doing? We chose to take a look at progress to date on the 6 fundamental questions that SCEC posed for itself in SCEC4.
- CEO-AC, the SCEC CEO advisory committee
- The SCEC Director Succession
- Budget Challenges

As in past years, the AC is deeply impressed by the SCEC organization and community. SCEC is viewed positively by the broader earthquake science community and by its funding agencies, and this impression has been well earned. The SCEC collaboration remains vibrant, with enthusiastic participation across many disciplines. As the section of this report on SCEC4 progress indicates, SCEC has made progress on all of the main goals that it set for SCEC 4, although considerable work remains to be done. In our opinion, SCEC is on the right track and should continue in its present directions.

1. Membership

Nine members of the Advisory Council attended the SCEC Annual Meeting and participated in all discussions of the AC at that venue. This report is a collaborative product of these AC members. The members who attended are:

- Jeff Freymueller, *Chair* (University of Alaska Fairbanks)
- Gail Atkinson (University of Western Ontario)
- Roger Bilham (University of Colorado)
- Donna Eberhart-Phillips (UC Davis)
- Bob Lillie (Oregon State University, Emeritus)
- Kate Long (California Office of Emergency Services)
- M. Meghan Miller (UNAVCO)
- John Vidale (University of Washington)
- Andrew Whittaker (University of Buffalo; Director, MCEER)

Two additional members of the Advisory Council were not able to attend the meeting, but they participated in a session by phone:

- Farzad Naeim (John A. Martin and Associates)
- Susan Cutter (University of South Carolina)

2. The future SCEC Director transition

Tom Jordan, the current Director, intends to step down before the start of SCEC5, should it be funded, and he has made it clear that he will do so. This imposes a tight timeline for the search for the next SCEC Director, as the new Director will need to be in place at USC in time to prepare the SCEC5 proposal. The SCEC Board has developed a good plan for a search and orderly succession to the next Director, with a realistic timeline and process; that process is now well under way. We were pleased to see that the Chair of the search committee was at the SCEC meeting to learn more about SCEC and the SCEC community. This is a positive step, and we hope that there will be a strong candidate identified soon for this critical position.

3. Facing Budgetary Challenges

Like most scientific and engineering enterprises today, SCEC is facing serious budgetary challenges. The cuts to the SCEC core funding are significant, but not unprecedented and not a worst-case scenario; it is not hard to find organizations or projects that are faring much worse. If the cuts continue, there will be no choice but to scale back some SCEC activities, which will compromise progress toward important SCEC goals.

The actions taken by SCEC to date to deal with the budgetary shortfalls represent the most sensible options available. We agree that the budget cuts taken this year are not sustainable long-term, and some of the cuts taken this year will need to be restored (at the cost of some other SCEC activities) if the current budget levels continue. The key budgetary decisions in Congress have been out of the scientific community's control, and all SCEC can do is roll with the punches until our country has a stable and functioning budgetary process again. SCEC needs to be prepared for further budgetary turmoil in the future, in case the present situation continues indefinitely.

4. Communication, Education and Outreach (CEO) Advisory Structure and Goals

The 2010–2012 Advisory Council Reports recommended that advisory oversight for the SCEC CEO program be provided through a CEO-focused advisory subcommittee of the Advisory Council that reports to SCEC through the AC. This would allow a small, focused group to give full attention to the needs and opportunities for SCEC CEO, and also ensure that the full Advisory Council is informed about and supportive of the advice for SCEC.

An ad-hoc SCEC AC-CEO subcommittee had an initial meeting on April 9, 2013 at the SCEC offices at USC. Advisory Council members attending the meeting included Susan Cutter, Jim Goltz, Kate Long, Bob Lillie, and Farzad Naeim. Mark Benthien, the SCEC Associate Director for CEO, facilitated the meeting. The meeting also included phone conversations with Greg Anderson (NSF Program Manager for EarthScope and SCEC) and Jeff Freymueller (Advisory Council Chair). Participants reviewed SCEC-CEO Strategic Plan metrics and milestones and recommended:

- Removing, adding or simplifying metrics to focus on activities and achievable results,
- Extending some milestones, and
- Developing a statement of how metrics and milestones will be used as a management tool to improve programs, not just a reporting process.

At the 2013 SCEC Annual Meeting the Advisory Council formally established the CEO Subcommittee membership as follows:

Four (voting) Advisory Council Members

- Farzad Naeim, John A Martin & Associates
- Susan Cutter, University of South Carolina
- Kate Long, California Governor's Office of Emergency Services
- Bob Lillie, Oregon State University

Four (non-voting) Subject Matter Advisors, each representing one of the CEO Strategic Plan "Thrust Areas"

- Implementation Interface
- Public Education and Preparedness
- K-14 Earthquake Education Initiative
- Experimental Learning and Career Advancement

Farzad Naeim was offered and accepted the position of Chair of the CEO Subcommittee.

The AC-CEO Subcommittee members attending the 2013 SCEC Annual Meeting (Kate Long and Bob Lillie) met with Mark Benthien to discuss the structure for CEO Strategic Planning for the next eight years. Susan Cutter and Farzad Naeim also attended via phone. The subcommittee agreed to the following plan over the next few months to initially examine SCEC-CEO needs and consider ways to address them.

CEO subject matter experts will present semi-monthly webinars from the broader community representing various disciplines. Examples include social psychology, public health, risk communication, natural history interpretation, marketing, advertising, and emergency management.

The webinar presentations will address "How can earth science communication be improved?" from the viewpoint of the various disciplines.

The webinars will be open to the entire SCEC Community as well as the broader communications, education and outreach community. This will allow the CEO Subcommittee to hear feedback from a wider stakeholder base, and the webinars themselves will serve an outreach purpose.

The CEO Subcommittee will consider these presentations in making ongoing recommendations to the Advisory Council for improvements in the SCEC-CEO program and the SCEC 5 proposal.

5. An Assessment of SCEC4 Progress

The AC chose to focus its assessment of SCEC4 progress on the 6 fundamental questions that SCEC posed for itself in the SCEC4 proposal. Members of the AC divided up the questions and brought back information to the full AC, which then produced a summary for each question. These follow here, with the key question or challenge given in bold type as a sub-heading.

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

Highlights. Fault slip rates determine the long-term slip budget over multiple earthquake cycles, making them particularly important inputs to earthquake hazard assessments. SCEC has supported an impressive set of estimates of geological slip rates on important faults across Southern California. For many faults there are now enough slip-rate estimates to measure with high resolution variations in slip rates in both time and space with high resolution. This is important because slip rates may vary in space across complex fault systems and could vary in time if the fault systems are changing with time; given too few data, it would be easy to confuse spatial variation with time variation, or vice versa. One key result of all this work is that geological and geodetic estimates of fault slip rates are increasingly in agreement. This suggests that many if not most of the previously noted disagreements were the result of problems with the data or with modeling slip rates. The most recent work now suggests that changes in fault slip rates over time are not large for the major faults. That suggests that the present fault system geometry and stressing pattern has remained largely stable for hundreds of thousands of years. Agreement between geologic and geodetic slip rates is not limited to the major faults; even for many smaller faults with slower slip rates the two datasets are now in agreement within uncertainties.

Geodetic estimates of fault slip rates are not measured directly, but rather are inferred from models of fault slip rates and deformation due to the earthquake cycle. We know that postseismic deformation in the years after an earthquake can be very large, but how profound are the changes in deformation rates over longer times? Evidence from deformation before some earthquakes has suggested that deformation over much of the earthquake cycle may be relatively stable and similar to that predicted by simple elastic models, but other observations have suggested otherwise. This problem has not yet been fully resolved, but SCEC has supported significant new work that is shedding light on these questions. The answer may be different for larger and smaller earthquakes, depending on whether they cause significant stress changes in viscoelastic materials with a long relaxation time. Recent work has focused on the impact of very large events such as the 1857 Fort Tejon earthquake on geodetic estimates of present-day fault slip rates, and suggests that the discrepancy between geologic and geodetic slip rate estimates there may be explained by lingering postseismic deformation. Reducing such discrepancies will decrease the uncertainties in future hazard estimations, in addition to providing a more coherent model for tectonic stressing of Southern California faults. If so, then this earthquake has also affected the state of stress on numerous faults for more than a century.

Remaining challenges. The Garlock fault remains an exception to the general trend of increasing agreement between geologic and geodetic slip rates. The cause of this remains unclear. It may reflect a real time-dependence in fault motions, or problems with current data or models. After the Garlock fault, the Mojave segment of the San Andreas may be the next most significant discrepancy, and it might be no coincidence that these are adjacent and in a conjugate geometry. Disagreements for the Mojave segment may be due to postseismic deformation from the 1857 Fort Tejon earthquake, depending on the rheological model assumed (Hearn et al., 2013). However, significant uncertainty remains about the rheological models.

Fully accounting for all slip on the San Andreas Fault system through the complex geometric bend at San Gorgonio Pass remains difficult, although progress has been made recently. This region has been designated a Special Fault Study Area, and this seems like a ripe area for further study.

Finally, improving time resolution of fault slip rate estimates opens up the opportunity to study the effects of earthquake clustering in the past through its impact on geologic slip rate estimates. If slip rates are really constant in time but earthquake recurrence is not, then the amount of variability in slip as a function of time reflects the real variability in earthquake occurrence. The opportunity to study this may just be opening up in Southern California as the amount of data increases.

b. Stress-modulated fault interactions and earthquake clustering

Highlights. SCEC continues to perform the ultimate test of earthquake interaction models, namely, whether real earthquakes obey the models. Catalogs continue to accumulate with the critical precondition that the models have already been formulated. The model testing underway is unparalleled in rigor and transparency.

The development of the Community Stress Model continues; this is an extremely challenging yet critical measure for both scientific ideas and practical assessment of hazard. It would represent the most comprehensive regional compilation of the state of stress. Its long-term scientific value will come in combination with similarly comprehensive data on stressing rates and fault system modeling to relate the two.

Remaining challenges

As is widely recognized, many questions about big earthquakes will not find a definitive answer just relying on the few observations in California, and consideration of global catalogs will be necessary. Collaborative efforts with scientists in Japan, New Zealand should be continued, and other international partnerships begun where there are clear benefits to understanding Southern California.

Fundamental questions remain in estimating the magnitude and direction of stresses in the ground. Assessing the changes in stress over time is more tractable, but not trivial.

Better understanding of the state of stress and earthquake interaction may also assist in earthquake early warning. SCEC can contribute to some of the numerous fundamental science problems in this timely and societally useful effort. Salient issues include whether the full extent of a fault rupture can be predicted from just observing its start, whether the state of stress (relative to strength) can be mapped out precisely enough to make useful predictions of fault systems' response to stress changes, proper messaging for the public and emergency managers, and more reliable assessment of fault rates, segmentation, and regularity of recurrence.

c. Evolution of fault resistance during seismic slip

Highlights. Dynamic rupture simulations are becoming more realistic. Simulations are using scales < 100 m, complex roughness and off-fault plasticity, which produce varied rupture including occasional rupture up through velocity-strengthening materials near surface. Past simulations were limited to long-period ground motions only, which limited their usefulness. New simulations are pushing these limits towards higher frequencies; predicting high frequency ground motions accurately would allow simulations to be compared to strong ground motion records and used in more engineering applications.

Numerical models are incorporating more realistic heterogeneity that varies with depth, allows broad gouge-filled shear zones, and includes inelastic deformation. These factors influence thermal pressurization and dynamic rupture, the simulations show that the deforming zone may migrate across the shear zone during rupture.

Observations are finding a wider range of slip models between end members of "aseismic" and "seismic" slip. They are also imaging deformation filling volumes rather than only on 2D faults. Seismic and field-based observations of afterslip and slip below the brittle/ductile transition may reveal evolving fault properties.

New insights due to lab experiments continue to emerge from investigations of temperature effects, pore pressure, fault gouge and fault roughness. Cross-disciplinary collaboration within the SCEC community has been successful in bringing new discoveries in rock mechanics into dynamic rupture simulations, and this is important to continue.

Remaining challenges. Future dynamic rupture simulations will need to incorporate the realistic velocity models that are being developed elsewhere in SCEC. Increased comparison of the dynamic rupture simulations to seismic observations is important. A goal of improving agreement with strong ground motion observations will enhance utilization of the rupture model results.

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

Highlights. SCEC scientists have played key roles in several studies, such as JFAST and studies of fault zone chemistry, that are chasing the elusive goal of measuring the heat generated in earthquakes, and thus the stress state during faulting.

Numerical simulations of elastic, plastic, and viscous models of faults in the crust and mantle are advancing. SCEC scientists are increasingly able to distinguish the deformation signature of mantle viscous flow from that of slip concentrated on creeping faults, thus allowing us to better assign the correct amount of motion on the parallel strands of the San Andreas system.

Laboratory experiments are isolating the special frictional properties of fault zone materials, moving toward explaining the low apparent friction, slow earthquakes, and distribution of strength in the crust and mantle.

Paleoseismology is adjudicating the periodicity, clustering, and oscillating patterns of earthquake recurrence. More trenches and more precise dating techniques are contributing both to basic understanding and hazard assessment.

Improved numerical models run on ever-faster computers are allowing ideas about influence of geometry, friction, and scattering to be evaluated, and facilitating ever more realistic models of the crust and crustal faults.

There is continuing progress in constraining fault zone low-velocity zones, their relation to flower structures, and thus the short- and long-term damage and healing due to earthquakes.

Remaining challenges. The subsurface geometry of fault systems is only dimly perceived in many locations, and the effectiveness of segmentation is a critical property and remains hotly debated.

The postulated danger of coastal thrust faults and the brutal tsunamis they could generate is not yet well established and needs investigation.

The development of fault zones deserves more attention, and the details controlling velocity-strengthening versus velocity-weakening behavior are so far not clear. Forecasting of earthquake hazards would benefit from a better understanding of these factors.

e. *Causes and effects of transient deformations; slow slip events and tectonics tremor*

Highlights. Transient deformation offers an exciting opportunity to study the dynamics of fault systems. In addition to postseismic transients, which have been recognized for a long time, transient creep events, slow slip events and tectonic tremor all represent transient slip phenomena or its effects. Understanding the occurrence of these events, their capacity for being triggered or for triggering other events, scaling laws and so on are important for a deep understanding of physics of fault slip.

SCEC has led a multi-year transient detection exercise aimed at detection of transients deformation signals in geodetic data. This exercise, now mature, has been successful in prompting the development of algorithms to detect and model transients. Beyond the exercise, a rich array of geodetic transients has been detected and there has been good progress in characterizing the kinematics of these events.

Tectonic tremor has been detected on an increasing number of faults, including the San Andreas fault system. Tectonic tremor is clearly not restricted only to subduction zones, but can potentially occur on any fault. Both SCEC-funded research and related research by members of the SCEC community have had a leading role in the discovery and description of tectonic tremor on Southern California faults.

More generally, any kind of transient creep acts as an amplifier of stress changes. Creep on a patch of a fault reduces the shear stress on the creeping patch but increases it substantially on its margins. Transient fault creep will temporarily increase the stressing rate on adjacent parts of the fault, potentially increasing the seismicity rate. Some prominent seismic swarms clearly have a causal relation to fault creep, such as the recent Brawley swarm.

Remaining challenges. The causality of these transient events remains puzzling. Seismic swarms or swarm-like sequences have been identified for a long time, and it remains to be seen whether most or all of these can be explained in terms of creep processes, or if other factors that may also vary with time (such as fluid pressure to change the effective normal stress) are also responsible.

In addition to possible failure in earthquake swarms, transient events may affect the occurrence of earthquakes on nearby faults. Stress changes cased by fault creep may bring neighboring faults closer to failure. The magnitude of this stress change depends on the magnitude of the transient, but in general the magnitude of stress changes will fall in between the size of coseismic stress changes and the size of the long-term tectonic stressing rate. In addition to short-term transients, seasonal hydrological loading also cycles the stress state of faults and may play a role in the timing of earthquakes. Seasonal triggering of events is not common (or else there would be more obvious seasonal variations in seismicity), but individual transient events or transient loads may be large enough to have an impact.

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

Highlights. Under this challenge, SCEC aims to understand the generation and propagation of seismic waves, including scattering effects, particularly within the context of prediction of strong ground motion. Highlights in this area that were evident at the 2013 meeting include the following:

- Development of broadband simulation platform. A major collaborative effort has been the development of a common and testable computing platform for simulation of ground motions across a broad band of frequencies. Intense activity in this area over the last year has led to a suite of programs that can generate in a common format many ground motion simulations, from a standard set of general input parameters. The vibrant activity in this area was showcased in a well-attended and lively workshop at the 2013 meeting. There are also other exciting developments in ground-motion simulation that were highlighted during the 2013 meeting, in particular the insights gained from dynamic rupture modeling.
- Development of metrics to evaluate ground motions. A parallel effort to the development of the broadband platform has been progress in developing a common set of objective metrics with which to evaluate the performance of simulated motions. This set of metrics is modest at present, but the framework is in place that will allow the catalogue of metrics to continue to grow and become more useful. This sets the stage for objective validation of ground-motion simulation methods.
- Coordination with earthquake engineering in the use of simulations. There has been substantial progress in bringing the results of SCEC research closer to use in engineering practice, through the work of a technical activity group to address uses of simulations in evaluating structural performance. This holds the promise of transforming the role of SCEC and broadening its reach. The progress in this area is particularly significant. Engineers are increasingly recognizing the potential for simulations to address important problems in earthquake engineering, including filling gaps in available time-history datasets, and facilitating investigations of a range of engineering problems (soil-structure interaction, and structure-soil-structure interaction, for example). Moreover, engineers are becoming more positive about the potential applications of simulations to critical infrastructure and tall buildings.

Remaining challenges.

- Understanding the physics of wave propagation at higher frequencies and its practical implications remains a challenge, despite substantial progress in codes to simulate such motions. This is an ongoing task for SCEC ground-motion modelers and researchers.
- There is a need to make the degree of complexity in building modeling commensurate with the level of complexity in simulations. Overly simplified building models are being used, which makes conclusions drawn from simulations of limited value. This is partly a matter of continuing seismology-engineering interface efforts such that the overall framework of the simulations and their use in engineering is understood on both sides. If engineers and seismologist both understand the basics of what is being generated, and how the products are to be used, there will be continued improvement in both the utility of the simulation tools being developed, and in the appropriateness of their application.
- There is a potential to integrate simulations with engineering effects at local scales, offering both new challenges and new opportunities. Simulations can play a role in understanding complex effects in the upper soil column that can be highly nonlinear, and of importance when inputting motions to a structural system. How to use simulations to explore such issues, and others such as liquefaction and landslide potential, remains a challenging opportunity.
- SCEC scientists need to continue the excellent progress in working with engineers to build acceptance of simulations as a useful tool of practice in the engineering community. We note that there is a tendency in the engineering community to have a misplaced faith in GMPEs (ground-

motion prediction equations) as providing a reliable prediction of ground motions for engineering applications. This is really a matter of educating engineers as to what they are getting - with both the GMPEs and simulations - and illustrating the connection between the two. We think that this topic is mature enough (and important enough) to engage a broader engineering community (i.e., the much larger community that uses codes of practice for analysis and design) through a wide-audience webinar. Such a webinar could be delivered by an engineer and advertised through websites and newsletters that reach much of the earthquake engineering community across North America.

- A logistical challenge will be to deliver the simulation products (as they become ready) in a format that is useful for practicing engineers. For example, many engineers are familiar and comfortable with USGS-type webtools that deliver PSHA-based ground-motion parameters and deaggregations for building code applications. Further links/tools could allow results of selected simulations that meet identified criteria to be downloaded in a standard format for engineering use.
- The treatment of site effects in simulations is a challenging task that requires further work, particularly with regards to the level of detail that should be attempted when providing generic simulations for broad-based applications. This issue has not yet been addressed in the broadband platform.
- There is a need to integrate lessons learned and products obtained across the range of simulation technologies being explored in SCEC. This includes those being developed on the broadband simulation platform, CyberShake, and dynamic simulations. These methodologies differ in their level of detail, maturity of development, and readiness for practical application. It remains a challenge to weave these strands into a coherent simulation cloth.