SCEC-VDO Visualization of M3+ Earthquakes (1991-2015) with UCERF3 Fault Model

PROCEEDINGS VOLUME XXV
September 12-16, 2015
The Board of Directors (BoD) is the primary decision-making body of SCEC; it meets three times annually to approve the annual science plan, management plan, and budget, and deal with major business items. The Center Director acts as Chair of the Board. The liaison members from the U.S. Geological Survey are non-voting members.

The leaders of the Disciplinary Committees and Interdisciplinary Focus Groups serve on the Planning Committee (PC) for three-year terms. The PC develops the annual Science Collaboration Plan, coordinates activities relevant to SCEC science priorities, and is responsible for generating annual reports for the Center. Leaders of SCEC Special Projects (i.e., projects with funding outside the core science program) also serve on the Planning Committee. They ensure the activities of the Special Projects are built into the annual science plans.

The Communication, Education, and Outreach Planning Committee (CEO PC) comprises of stakeholders representing SCEC and external organizations. The CEO PC provides guidance for CEO programs, reviews reports and evaluations, and identifies synergies with other parts of SCEC and external organizations.

The external Advisory Council (AC) provides guidance in all aspects of Center activities, including basic and applied earthquake research and related technical disciplines, formal and informal education, and public outreach. Members of the AC are elected by the Board for three-year terms and may be re-elected. The Council meets annually to review Center programs and plans, and prepares a report for the Center.
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Welcome to the 2015 Annual Meeting!

I welcome you to the 25th Annual Meeting of the Southern California Earthquake Center. Each year of the past quarter century, the SCEC community has gathered from across the country and around the world to share research accomplishments and make ambitious science plans. This year, 568 people have pre-registered for the meeting (Figure 1), and 295 poster abstracts have been submitted. The pre-registrants include more than 140 first-time attendees and almost two hundred undergraduate and graduate students.

We are entering the last year of the SCEC4 program, and this meeting will give us a chance to assess our accomplishments and review our research plans. We will also be gearing up for the next phase of the Center, SCEC5. The proposal to continue our core program for another five years has been written and will be submitted to the National Science Foundation (NSF) and U.S. Geological Survey (USGS) at the end of this month. But, as usual, the main focus of this meeting will be on science: to learn all we can about earthquakes from the formal presentations and posters and from the informal discussions with our scientific colleagues.

For the next few days here in Palm Springs, the weather and the science will be hot! As always, the Planning Committee has put together a blazing program. Saturday and Sunday feature workshops and discussions on seven important topics:

- SCEC Community Rheology Model Workshop
- CSEP/USGS/GEM Workshop: Epistemic Uncertainties in Earthquake and Ground Motion Forecasts
- SCEC Collaboratory for Interseismic Simulation and Modeling (CISM)
- SCEC Community Software for Extreme-Scale Computing in Earthquake System Science Meeting
- SCEC Community Stress Model (CSM) Workshop
- Open Discussion: Estimating Fault Zone Properties using Space-Based Measurements
- California Earthquake Clearinghouse: Training and Fieldwork Limited Liability Certification

At 6 pm Sunday evening, this year’s Distinguished Speaker, Professor James Rice of Harvard University, will kick off the main meeting with a plenary lecture on “Heating and weakening of faults during earthquake slip.” Over the next three days, the agenda will feature keynote speakers addressing fundamental problems, discussions of major science themes, poster sessions on research results, earthquake response exercises, technical demonstrations, education and outreach activities, and some lively social gatherings. The topical titles of the sessions indicate the range of the science we will discuss: Special Fault Study Areas, and SCEC Community Models on Monday; Earthquakes—From the Lab to the Field, and Physics-Based Forecasting and Ground Motions on Tuesday; and Connecting Hazard to Risk on Wednesday.
Assessing SCEC Accomplishments

The SCEC4 science plan is posed in terms of the “six fundamental problems of earthquake science” (Table 1). These system-level problems are interrelated and require the type of interdisciplinary, multi-institutional research at which the SCEC community excels. Each year, SCEC Co-Director Greg Beroza and the Planning Committee (PC) assemble an annual report on research accomplishments, which is submitted in November as part of a full report on SCEC activities to our primary sponsoring agencies, the National Science Foundation and U.S. Geological Survey. The PC’s 2015 report is included in these Proceedings. Greg will summarize the research results, with an emphasis on our more recent accomplishments, in his plenary address on Monday morning. This meeting volume also contains a report by Mark Benthien, the SCEC Associate Director for Communication, Education, and Outreach (CEO), on the remarkable accomplishments of the CEO program.

<table>
<thead>
<tr>
<th>Table 1. Fundamental Problems of Earthquake Science for SCEC4</th>
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<tbody>
<tr>
<td>1. Stress transfer from plate motion to crustal faults: long-term fault slip rates</td>
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<td>2. Stress-mediated fault interactions and earthquake clustering: evaluation of mechanisms</td>
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<td>3. Evolution of fault resistance during seismic slip: scale-appropriate laws for rupture modeling</td>
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<td>4. Structure and evolution of fault zones and systems: relation to earthquake physics</td>
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<td>5. Causes and effects of transient deformations: slow slip events and tectonic tremor</td>
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<tr>
<td>6. Seismic wave generation and scattering: prediction of strong ground motions</td>
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The five poster sessions scheduled between Sunday evening and Tuesday evening will display the entire spectrum of SCEC accomplishments. Posters will stay up for the entire meeting to allow more face-to-face interactions on the nitty-gritty aspects of SCEC scientific research.

The SCEC5 Proposal

We are preparing to submit the SCEC5 proposal to the NSF and USGS on October 1, 2015. The proposal site review is scheduled for January, 2016, and we can anticipate a funding decision by the agencies before the next annual meeting. The SCEC5 Science Plan has been developed by the non-USGS members of the SCEC Planning Committee and Board of Directors with extensive input from issue-oriented “tiger teams” and the community at large. The tiger teams organized research ideas and plans from the SCEC community into white papers on most compelling topics. An ad hoc committee, appointed by the Board and chaired by Paul Segall, abstracted from this and other input a strategic framework for prioritizing SCEC5 research objectives, which they cast in terms of five basic questions of earthquake science:

<table>
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<th>Table 2. Basic Questions of Earthquake Science for SCEC5</th>
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<tr>
<td>1. How are faults loaded across temporal and spatial scales?</td>
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<td>2. What is the role of off-fault inelastic deformation on strain accumulation, dynamic rupture, and radiated seismic energy?</td>
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<tr>
<td>3. How do the evolving structure, composition and physical properties of fault zones and surrounding rock affect shear resistance to seismic and aseismic slip?</td>
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<tr>
<td>4. How do strong ground motions depend on the complexities and nonlinearities of dynamic earthquake systems?</td>
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<tr>
<td>5. In what ways can system-specific studies enhance our general understanding of earthquake predictability?</td>
</tr>
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</table>

The SCEC5 science plan addresses these questions through an interdisciplinary program comprising 14 topics in four main thematic areas:

**Theme A. Modeling the Fault System**
1. Stress and Deformation Over Time
2. Special Fault Study Areas: Focus on Earthquake Gates
3. Community Models
4. Big Data

**Theme B. Understanding Earthquake Processes**
5. Beyond Elasticity
6. Modeling Earthquake Source Processes
7. Ground Motion Simulation
8. Induced Seismicity

**Theme C. Characterizing Seismic Hazards**
9. Probabilistic Seismic Hazard Analysis
10. Operational Earthquake Forecasting
11. Earthquake Early Warning
12. Post-Earthquake Rapid Response

**Theme D. Reducing Seismic Risk**
13. Risk to Distributed Infrastructure
14. Physics of the Geotechnical Layer
While these are by no means the only research topics to be undertaken in SCEC5, they constitute a plausible framework for making progress on the basic questions of Table 2. The proposal team (Beroza, Benthien, Chester, Huynh, Jordan, Maechling, McRaney, and Young) has generated a mature draft, based on excellent input from the SCEC tiger teams and the Segall Committee, and this draft is under review by the non-USGS members of the Board, PC, and AC.

**Organization and Leadership**

SCEC is an institution-based center, governed by a Board of Directors, who represent its members. The Center is an open consortium, available to all qualified individuals and institutions seeking to collaborate on earthquake science in Southern California, and its membership continues to evolve. The institutional membership currently stands at 69, comprising 17 core institutions and 52 participating institutions, which are listed on the inside back cover of the meeting program. As you can see from the list, SCEC institutions are not limited to universities, nor to U.S. organizations. The three USGS offices in Menlo Park, Pasadena, and Golden and the California Geological Survey are core institutions, and AECOM-URS Corporation is a participating institution. Twelve foreign institutions are recognized as partners with SCEC through a set of international cooperative agreements.

*SCEC is an Open Collaboration. For attendees who don’t see your institution on this list, please note that it's really easy to apply; all we need is a letter from a cognizant official (e.g., your department chair or dean) that requests participating-institution status and appoints an institutional representative who will act as the point-of-contact with the Center.*

SCEC currently involves more than 1000 scientists and other experts in active SCEC projects. A key measure of the size of the SCEC community—registrants at our Annual Meetings—is shown for the entire history of the Center in Figure 1. For the last six years, more than 500 people have attended each of the Annual Meetings.

**Leadership Changes.** Last year, I recommended, and the Board approved, several changes in the SCEC leadership structure intended to redistribute some of the Director’s responsibilities and workload. Greg Beroza was promoted to a newly formed Center Co-Directorship; he will serve as the Co-PI on the SCEC5 core proposal and will retain his position as PC Chair. The modified by-laws enable mechanisms for the Co-Director to act as the PI of SCEC special projects. For example, in July, 2015, a SCEC proposal with Beroza as PI was submitted through Stanford to the NSF/EAR Geoinformatics Program; USC was included as one of several collaborating institutions. Two new science leadership positions have been created: a PC Vice-Chair (PC-VC), filled by Judi Chester; and an Executive Director of Special Projects (ED-SP), filled by Christine Goulet. Another new leadership position was also created within SCEC’s Communication, Education and Outreach Program, the CEO Assistant Director for Strategic Partnership, which has been filled by Sharon Sandow. Please join me at this meeting in welcoming these outstanding new leaders!

**Board of Directors.** Under the SCEC4 by-laws, each core institution appoints one member to the Board of Directors, and two at-large members are elected by the Board from the participating institutions. The Board of Directors is the primary decision-making body of SCEC; it meets three times annually to approve the annual science plan, management plan, and budget, and deal with major business items. The liaison members from the U.S. Geological Survey are non-voting members. As Center Director, I chair the Board and also serve as the USC representative. Nadia Lapusta of Caltech serves as its Vice-Chair. We also elect two people from our participating institutions as at-large members of the Board. These positions are currently filled by Michele Cooke of the University of Massachusetts and Roland Bürgmann of UC-Berkeley. The complete Board of Directors is listed on the inside front cover of the meeting program.

**External Advisory Council.** The external Advisory Council (AC) 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 SCEC and helping its leadership chart new directions. The Center has always provided its sponsoring agencies and participants, with verbatim copies of the yearly AC reports. The full 2013 AC report is included in this volume. The current AC membership can be found in the meeting program.

**Planning Committee.** The chair of the Planning Committee (PC) is the SCEC Co-Director, Greg Beroza of Stanford, and its new Vice-Chair is Judi Chester of Texas A&M. The PC comprises the leaders of the SCEC science working groups—disciplinary committees, focus groups, and special project groups—who, together with the working group co-leaders, guide SCEC’s research program. The PC is responsible for formulating the Center’s science plan, conducting proposal reviews, and recommending projects to the Board for SCEC support. Its members will play key roles in formulating the SCEC5 proposal. I urge you to use the opportunity of the Annual Meeting to communicate your thoughts about future research plans to them.

**Working Groups.** The SCEC organization comprises a number of disciplinary committees, focus groups, special project teams, and technical activity groups (TAGs). These working groups have been our engines of success, and many of the discussions at this meeting will feed into their plans. The current working group structure of SCEC4 is shown in Figure 2, and a complete listing of the working group leaders is on the inside cover of the meeting program.
The Center supports disciplinary science through standing committees in Seismology, Tectonic Geodesy, and Earthquake Geology. A new disciplinary committee in Computational Science was added for SCEC4. These groups (green boxes of Figure 2) are responsible for disciplinary activities relevant to the SCEC Science Plan, and they make recommendations to the Planning Committee regarding the support of disciplinary research and infrastructure.

SCEC coordinates earthquake system science through six interdisciplinary focus groups (yellow boxes): Unified Structural Representation (USR), Fault & Rupture Mechanics (FARM), Earthquake Forecasting & Predictability (EFP), Southern San Andreas Fault Evaluation (SoSAFE), Stress and Deformation Through Time (SDOT), and Ground Motion (GMP). A seventh interdisciplinary group, the Earthquake Engineering Implementation Interface (EEII, an orange box), is coordinating research partnerships with earthquake engineering organizations.

Technical Activity Groups are self-organized 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.

**Special Projects**

The Special Project teams (pink boxes in Figure 2) are organized around large-scale projects funded through special grants outside the NSF-USGS cooperative agreements that support the SCEC4 base program. The three major SCEC initiatives that I outlined at last year’s Annual Meeting have since been funded at relatively high levels: Advancing Extreme-Scale Computing in Earthquake System Science (AXCESS), through a $2.2M SI2 grant from NSF/ACI; the Collaboratory for Interseismic Simulation and Modeling (CISM), through a $2M grant from the W. M. Keck Foundation; and the Central California Seismic Project (CCSP), an evolving partnership with PG&E.

Community Modeling Environment (CME), Advancing Extreme-Scale Computing in Earthquake System Science (AXCESS) is managed through its Community Modeling Environment (CME) collaboration, which has been very active in developing new capabilities for earthquake simulation, including validated software for engineering-oriented simulations (the Broadband Platform), the use of large ensembles of simulations for complete probabilistic seismic hazard analysis (the CyberShake project), the extensions of simulations to high frequencies (the High-F project), and the assimilation of earthquake and ambient-field data into 3D velocity structures using full-3D tomography (the F3DT project). CME has become one of the most well-recognized collaborations in high-performance computing, bringing together world-leading geoscientists, computational scientists, earthquake engineers, and software engineers to develop new large-scale computational capabilities for earthquake system science.

Major grants to support CME software engineering have come from the NSF/CISE Directorate and the NSF/EAR Geoinformatics program, as well as from the utility industry. SCEC competes for supercomputer allocations through the NSF XSEDE and PRAC
programs and the DOE INCITE program. In 2015, SCEC was awarded allocations totaling 362 million service units, primarily on the NCSA’s Blue Waters, ANL’s Mira, and ORNL’s Titan supercomputers (Figure 3). These resources have enabled SCEC to sustain its HPC usage at an average rate of ~1 million CPU-hours per day.

**Collaboratory for Interseismic Simulation and Modeling.** In July, 2015, SCEC received a three-year, $2M grant from the W. M. Keck Foundation to construct a Collaboratory for Interseismic Simulation and Modeling. CISM will provide a unique environment for developing large-scale numerical models that can simulate sequences of fault ruptures and the seismic shaking they produce. The goal of CISM is to equip earthquake scientists with HPC-enabled infrastructure for creating a new generation of comprehensive, physics-based earthquake forecasts using California as the primary test bed. CISM will provide a computational framework for combining earthquake simulations that account for the physics of earthquake nucleation and stress transfer with ground-motion simulations. It will be engineered as a workflow-oriented cyberinfrastructure with common tools for integrating various types of scientific software modules provided by different research teams into well-structured forecasting models that can be calibrated against existing data and tested against observations within CSEP. As part of this project, W. M. Keck Foundation Fellowships in Earthquake Forecasting Research will support participation in CISM by graduate students, post-docs, and early-career researchers.

Central California Seismic Project. The Central California Seismic Project was initiated this year as a partnership between SCEC and Pacific Gas & Electric Co. to use the central coast region of California as a testbed for developing and validating new tools for probabilistic seismic hazard analysis. The main goal of the CCSP is to assess the effectiveness of seismic wavefield modeling in reducing the epistemic uncertainties in path effects that control hazard estimates at low exceedance probabilities. The specific objectives of this long-term (~8-yr) effort include (i) assimilation of existing data into improved 3D models of Central California crustal structure; (ii) collection of new data on local earthquake activity and regional path effects, (iii) validation of improvements to synthetic seismograms derived from 3D models, and (iv) demonstration that physics-based modeling can reduce path-effect uncertainties. Work on objective (i) has begun, and a 2016 start on the instrument deployments required to achieve (ii) looks feasible.

**Center Budget and Project Funding**

The SCEC base program has been more-or-less flat funded since the beginning of SCEC2, when I took over as Director (Figure 1). In 2013 NSF/EAR cut our base budget by 10%, from the $3.0M received in 2012 to $2.7M. The USGS cuts were proportionately smaller (3%), from $1.34M to $1.30M. A similar cut of 10% was expected in 2014, a result of the federal sequester law and congressional funding levels, but NSF announced at last year’s annual meeting that SCEC would get its full $3.0M in 2014. The USGS did continue its small 3% cut. To date in 2015, we have received $2.9M from NSF and $1.3M from the USGS, both cuts of ~3%. Supplementing the $4.2M in base funding was $560K from Pacific Gas & Electric, the Keck Foundation, the NSF SAVI supplement, and the geodesy royalty fund. In total, SCEC core funding for 2015 is $4,760K, up slightly from $4,628K in 2014.

Our 2015 funding was not finalized until June, which again caused delays in the 2015 funding for some investigators. The continuing budget uncertainties are disruptive to SCEC investigators but we were able to preserve most of the research projects approved by the PC and Board in February. We have shovel ready projects should the final $100K still come from NSF.

The base budget approved by the Board of Directors for this year allocated $3.384M for science activities managed by the SCEC Planning Committee; $440K for communication, education, and outreach activities, managed by the CEO Associate Director, Mark Benthien; $175K for information technology, managed by Associate Director for Information Technology, Phil Maechling; $400K for administration and $320K for meetings, managed by the Associate Director for Administration, John McRaney; and $130K for the Director’s reserve account.

Structuring of the SCEC program for 2015 began with the working-group discussions at our last Annual Meeting in September, 2014. An RFP was issued in October, 2014, and 168 proposals requesting a total of $5.15M were submitted in November, 2014. Both the number of proposals and the total funds requested were slightly lower than those submitted in 2013 for the SCEC science program. Including collaborative proposals, there were more than 250 individual budget requests. All proposals were independently reviewed by the Director and by either the PC Chair (G. Beroza) or Vice-Chair (J. Chester). Each proposal was also independently reviewed by the leaders and/or co-leaders of three relevant focus groups or disciplinary committees. (Reviewers were required to recuse themselves when they had a conflict of interest.) The PC met in January 2015, and spent two days discussing every proposal. The objective was to formulate a coherent, budget-balanced science program consistent with SCEC’s basic mission, short-term objectives, long-term goals, and institutional composition. Proposals were evaluated according to the following criteria:

1. Scientific merit of the proposed research
2. Competence and performance of the investigators, especially in regard to past SCEC-sponsored research
3. Priority of the proposed project for short-term SCEC objectives as stated in the RFP
4. Promise of the proposed project for contributing to long-term SCEC goals as reflected in the SCEC3 science plan
5. Commitment of the P.I. and institution to the SCEC mission
6. Value of the proposed research relative to its cost
7. Ability to leverage the cost of the proposed research through other funding sources
8. Involvement of students and junior investigators
9. Involvement of women and underrepresented groups
10. Innovative or "risky" ideas that have a reasonable chance of leading to new insights or advances in earthquake physics and/or seismic hazard analysis.
11. The need to achieve a balanced budget while maintaining a reasonable level of scientific continuity

The recommendations of the PC were reviewed by the SCEC Board of Directors. The Board voted unanimously to accept the PC’s recommendations. After minor adjustments and a review of the proposed program by the NSF and USGS, I approved the final program in late February 2015. The science plan was then sent to our NSF and USGS program officers for agency review. Once that approval was received, notifications to investigators were sent starting in March 2015.

**Communication, Education, and Outreach**

The success of SCEC’s CEO program matches that of its science program. CEO offers a wide range of student research experiences, web-based education tools, classroom curricula, museum displays, public information brochures, online newsletters, workshops, and technical publications. Highlights of CEO activities for the past year are reported in these Proceedings by the Associate Director for CEO, Mark Benthien, who will present an oral summary on Monday morning.

In the past year, we establish a new CEO Planning Committee with members selected to represent the four CEO focus areas. The CEO-PC was chartered to provide guidance and support for the portfolio of SCEC CEO activities and partnerships, review reports and evaluations, and identify synergies with other parts of SCEC and external organizations. The CEO-PC was convened in Spring 2015 with members drawn from the AC and SCEC stakeholders. The Chair of the CEO-PC is Tim Sellnow (U. Central Florida), and the Vice-Chair is Kate Long (CalOES). Both represent the Public Education and Preparedness CEO focus area and are also on the AC. Danielle Sumy (IRIS) represents K-14 Earthquake Education Initiative. Sally McGill (CSU San Bernardino) represents the Experiential Learning and Career Advancement focus area. Jacobo Bielak (Carnegie Mellon University) and Chris Wills (California Geological Survey) both represent the Implementation Interface CEO focus area. Chris is also the representative of the SCEC Board on the CEO-PC.

**A Special Word of Thanks**

SCEC has been successful because of the collaborative efforts of many people over many years. As SCEC Director, I want to express my deep appreciation to all of you for your attendance at the Annual Meeting and your sustained commitment to the collaboration. Greg Beroza and the PC have developed another outstanding program, so the entire meeting should be a very pleasant experience.

Special recognition is in order for SCEC staff, which comprises individuals of remarkable skills and dedication (Figure 5). We all benefit immensely from the financial wizardry and personal empathy of John “The Chaplain” McRaney, the organizational skills of Mark “Mr. ShakeOut” Benthien, and the innovative expertise of Phil “Big-Iron” Maechling.

And we all owe a very special thank you! to Tran Huynh and Deborah Gormley, the SCEC Meetings Team, and their diligent associates, Karen Young, John Marquis, David Gill, and Jason Ballmann, for their exceptional efforts in organizing this meeting and arranging its many moving parts. Please do not hesitate to contact me, Greg, Tran, or other members of the SCEC team if you have questions or comments about our meeting activities and future plans. Now please enjoy the sessions, the meals, and the pool in the spectacular and toasty setting of Palm Springs!
2014 Report of the Advisory Council
Gail Atkinson, SCEC Advisory Council Chair

October 25, 2014

Introduction

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

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

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

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

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

Changes in Leadership Structure

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

The AC view is that the proposed leadership plan effectively addresses the immediate challenges and sets the stage for a successful leadership succession. The AC welcomes the well-deserved appointment of the SCEC co-Director and co-PI, the
Planning Committee Vice-Chair, and the addition of the USC-funded Executive Science Director – these are tangible and important changes that will enable SCEC5 and subsequently facilitate a successful search. In particular, it will become a much more tractable proposition for an internationally-based leadership candidate to step in near the beginning of SCEC5, with the SCEC5 structure and plan in place, and a lead time of several years to work with the rest of the SCEC team before the need to consider SCEC6 is upon him or her. We feel that this plan, as well as the new pool of candidates that may well be available in a year or two, will be of great benefit in the search. We recommend that although the search is now officially paused, that SCEC use this pause to good advantage in discussing and broadcasting this upcoming opportunity with potential leaders, so that the search may be “primed” with top-level candidates when it resumes.

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

Highlights of SCEC4

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

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

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

We noted the following advances:

**Plastic deformation in fault zones**

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

**Role of San Gorgonio Pass**

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

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

Seismology-Engineering interface

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

Time scales in UCERF3

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

ShakeOut and CEO

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

CEO’s exceptional coordination of the EPIcenters Network has expanded well beyond California in 2014 via EarthScope partnership and other activities. SCEC’s Media Relations activities have also expanded in 2014, with SCEC’s social media presence being greatly improved and regularly managed. CEO’s K-14 Education Initiatives in 2014 included many useful components: InSight Vital Signs of the Earth summer institute, providing professional development to educators and students; new lessons based on field research that will be incorporated within other SCEC activities (such as the “Heroes of Earthquake Country” educator kit); teacher workshops in Oregon, Washington, and Alaska (with EarthScope); and a network of QCN sensors at schools of participating teachers. CEO’s intern programs are as vibrant as ever, with 38 UseIT and SURE students in 2014 (and several more students working on ShakeOut recruitment- this may be considered a third intern program in 2015). A notable statistic this year is that 49% of the interns are underrepresented minority students, and 56% are women. CEO self-assessment notes that the long-term tracking of our alumni continues to be a challenging effort (true for most similar programs); plans for Masters level and early career opportunities also need to be better developed. More than half of the active participants of SCEC are considered early career, and CEO needs an effective strategy for supporting their career advancement.
CEO continues to expand SCEC’s national and international visibility, and to bridge understanding of the physical science of earthquakes and social science of behavior change, spurring preparedness action. With its vigorous cross-sector partnerships, CEO is increasingly sought out as the source for expertise in development of earthquake education. An essential component of CEO’s value continues to be its assemblage of broad partnerships, ensuring consistency of messaging among an expanded breadth of organizations which see themselves as earthquake education stakeholders: SCEC is at the table not only as a science education organization, but as a leader in public safety. In California specifically, the CEO Director’s is also the Director of the statewide Earthquake Country Alliance, maintaining a central role in California’s ongoing national leadership in earthquake education and outreach.

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

**CEO Advisory Structure and Goals**

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

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

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

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

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

**Major SCEC Initiatives**

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

**High Performance Computing**

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

**Central California experiment**

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

**CISM**

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

**Annual Meeting Format**

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

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

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

**Plan for SCEC5**

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

**A - Understanding and Reducing Uncertainty**

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

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

Any significant reduction of epistemic uncertainty in ground motions may require a substantial (orders of magnitude) increase in the availability of high quality data. SCEC should find a way to facilitate meaningful expansion of instrumental network capacities, despite the fact that data collection and management is not considered a primary SCEC mission.
Reducing other sources of uncertainty may increase understanding of earthquake likelihood. One among many examples is the role of long-term time dependency of the seismicity rate. A long-term clustering has been found in some of the first versions of earthquake simulators; this clustering may offer an explanation of the so-called ‘open interval’ conundrum – looking at the paleoseismic data of all sites considered in UCERF3 project, it is surprising that none of them has produced another large earthquake in the last century. This could reflect time-dependency in earthquake rates that may have an impact on the assessment of hazard and risk; alternatively it may result from the relatively short period of observations relative to the earthquake cycle.

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

B - Earth/fault properties - what properties of earth/faults are important to understand system behavior?

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

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

C - Simulated EQ motions to assess hazard

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

D - To what extent is EQ behavior predictable?

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

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

E - Preparing for and responding to future earthquakes

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

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

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

F - Communicating what we know and don’t know–placeholder, more input needed.

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

Closing Remarks on SCEC5 Rationale

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

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

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

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

SCEC CEO is organized into four interconnected thrust areas:

• **Implementation Interface** connects SCEC scientists with partners in earthquake engineering research, and communicates with and trains practicing engineers and other professionals;

• **Public Education and Preparedness** thrust area educates people of all ages about earthquakes, and motivates them to become prepared;

• **K-14 Earthquake Education Initiative** seeks to improve earth science education and school earthquake safety;

• **Experiential Learning and Career Advancement** provides research opportunities, networking, and more to encourage and sustain careers in science and engineering.

SCEC CEO is led by SCEC’s associate director for CEO Mark Benthien. Bob deGroot is assistant director for CEO’s Education, Experiential Learning and Career Advancement activities. In June SCEC welcomed Sharon Sandow to the CEO team as assistant director for Strategic Partnerships. John Marquis is digital products manager and webmaster. Jason Ballman is Communications Specialist. David Gill provides support to CEO as web developer. Several contractors for ECA and ShakeOut activities complement the SCEC CEO staff, along with a legion of USC student assistants and interns each year. The Earthquake Engineering Implementation Interface between SCEC and its research engineering partners is led by Jack Baker (Stanford) (who serves on the Planning Committee) and Jacobo Bielak (Carnegie Mellon). Several other SCEC scientists also are regularly involved in program development, intern mentorship, and other roles.

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

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

SCEC CEO has been very successful in leveraging its base funding with additional support. For example, since 2010 FEMA has provided SCEC and its Earthquake Country Alliance partners nearly $1.5 million for ECA activities and national ShakeOut coordination. ShakeOut regions in the U.S. and internationally have also provided funding, and the CEA has spent several million dollars on radio, TV, print, and online advertising which features ShakeOut promotion each year. SCEC’s intern programs have also been supported with more than $1.3 million in additional support from several NSF programs and a private donor, and NASA supports SCEC’s “Vital Signs of the Planet” teacher development program via a subcontract through JPL Most recently NOAA has provided funding to SCEC for developing the TsunamiZone.org website.

SCEC 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.

Research Engineering Partnerships

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

Activities with Technical Audiences

The Implementation Interface also develops mechanisms for interacting with technical audiences that make decisions based on understanding of earthquake hazards and risk, including practicing engineers, geotechnical consultants, building officials, emergency managers, financial institutions, and insurers. This will soon include expansion of the Earthquake Country Alliance to include members focused on mitigation, policy, and other technical issues. SCEC is also planning training sessions and seminars for practicing engineers and building officials to introduce new technologies (including time-dependent earthquake forecasts), discuss interpretation and application of simulation records, and provide a forum for SCEC scientists to learn what professionals need to improve their practice. An example is the annual SEAOSC Buildings at Risk Summits which SCEC has co-organized since 2011 in both Los Angeles and San Francisco (with SEAONC). The 2015 conference is titled “Strengthening our Cities: From Policy to Reality” and will be held November 4-5 in Los Angeles. Also in November SCEC/EGA is supporting two “Quakesmart Business Preparedness Summits” in the San Francisco Bay Area, which will educate business owners and managers on non-structural and structural mitigation practices. We are also collaborating with EERI, NEES, PEER, and others. These activities will increasingly be online, with frequent webinars and presentations and discussions recorded and available for viewing online.
To understand SCEC’s effectiveness in this area, we will track and document use of our technical resources and information, and their impact on practice and codes, guidelines, and standards. Those who utilize SCEC products and information may be asked to notify us, especially partners who understand the value to both SCEC and themselves.

Public Education and Preparedness

This thrust area spans a suite of partnerships, activities, and products for educating the public about SCEC, earthquake science, and how to become prepared for earthquakes and tsunamis. SCEC’s work in this area spans California, the nation, and the world.

Earthquake Country Alliance

The ECA is a public-private partnership of people, organizations, and regional alliances, each of which are committed to improving preparedness, mitigation, and resiliency. People, organizations, and regional alliances of the ECA collaborate in many ways: sharing resources; committing funds; and volunteering significant time towards common activities. ECA’s mission is to support and coordinate efforts that improve earthquake and tsunami resilience. The Earthquake Country Alliance is now the primary SCEC mechanism for maintaining partnerships and developing new products and services for the general public. SCEC Associate Director for CEO Mark Benthien serves as Executive Director of the ECA, under the guidance of a Steering Committee comprised of three representatives of the regional alliances in Southern California, the Bay Area, and the North Coast. To participate, visit www.earthquakecountry.org/alliance.

SCEC created the Earthquake Country Alliance (ECA) in 2003 and continues to play a pivotal role in developing and sustaining this statewide (as of 2009) coalition. Participants develop and disseminate common earthquake-related messages for the public, share or promote existing resources, and develop new activities and products. SCEC develops and maintains all ECA websites (www.earthquakecountry.org, www.shakeout.org, www.dropcoverholdon.org, and www.terremotos.org) and social media accounts (facebook.com/earthquakecountryalliance and twitter.com/eca) and has managed the printing of the “Putting Down Roots” publication series throughout the state. In 2014 a special “Northridge Earthquake Virtual Exhibit” (earthquakecountry.org/northridge) was added to the ECA site with “Northridge Near You” animations created by SCEC UseIT interns, and interviews with people who experienced the Northridge earthquake across southern California. Similar “Near You” animations were also made for the Loma Prieta 25th anniversary (earthquakecountry.org/lomaprieta).

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

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

ECA Associates benefit from their participation by coordinating their programs with larger activities to multiply their impact; being recognized for their commitment to earthquake and tsunami risk reduction; having access to a variety of resources on earthquake and tsunami preparedness; networking with earthquake professionals, emergency managers, government officials, business and community leaders, public educators, and many others; and connecting with the following ECA sector-based committees to develop customized materials and activities:

- Businesses
- Communications
- EPIcenters (museums, parks, libraries, etc.)
- Evaluation
- Fire Advisory Cmte. (2013 subtheme)
- Public Sector
- Healthcare
- K-12 Schools
- Non-Profits and Faith-Based Organizations
- Seniors and People with Disabilities
- Speakers Bureau (Southern California)
Each ECA organization, including SCEC, independently determines the commitment of the their own resources, including human, technical, and financial resources, as they carry out the fundamental actions of this voluntary, non-binding Agreement. As the home of ECA, SCEC allocates appropriate staff and administrative resources (phones, mailing, etc.) and may seek additional funding for these resources in partnership with the EGA. SCEC provides mechanisms for managing ECA-specific funding and resources that are not co-mingled with other SCEC funding, and works with ECA leadership to ensure that such resources are allocated appropriately.

The Earthquake Country Alliance (ECA) has coordinated outreach and recruitment for the California ShakeOut since 2008. Because of the creation and growth of the ShakeOut, and other activities and products, ECA has received national recognition. In 2011 ECA was recognized by FEMA with the “Awareness to Action” award, which resulted in SCEC’s Mark Benthien being named a “Champion of Change” by the White House. In April 2012 ECA also received the “Overall National Award in Excellence” at the quadrennial National Earthquake Conference held in Memphis. In 2014 ECA was given an award from the American Red Cross for “Excellence in Disaster Preparedness”.

**Great ShakeOut Earthquake Drills**

**Great ShakeOut Earthquake Drills** began in southern California in 2008, to involve the general public in a large-scale emergency management exercise based on an earthquake on the San Andreas fault (the USGS “ShakeOut Scenario” developed by a team of more than 300 experts led by Dr. Lucy Jones). ShakeOut communicates scientific and preparedness information based on 30 years of research about why people choose to get prepared. Its purpose is to motivate everyone, everywhere to practice earthquake safety (“Drop, Cover, and Hold On”), and to get prepared at work, school, and home.

For the ShakeOut Scenario SCEC developed advanced simulations of this earthquake used for loss estimation and to visualize shaking throughout the region. In addition, SCEC also hosted the ShakeOut website (www.ShakeOut.org) and created a registration system where participants could be counted in the overall total. In 2008 more than 5.4 million Californians participated. While intended to be held only once, requests from ShakeOut participants prompted partners and state agencies to expand the event statewide as an annual ShakeOut drill on the third Thursday of October. This date is ideal for schools and follows National Preparedness Month in September, allowing for significant media exposure prior to the drill. While K-12 and college students and staff comprise the largest number of participants, the ShakeOut has also been successful at recruiting participation of businesses, non-profit organizations, government offices, neighborhoods, and individuals. Each year participants are encouraged to incorporate additional elements of their emergency plans into their ShakeOut drill.

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

As of September, 2015, 28 Official ShakeOut Regions (each with their own website managed by SCEC) now span 45 states and territories, three Canadian provinces, New Zealand, Southern Italy (U.S. Naval bases), and a rapidly growing number of Japanese cities and prefectures. All of these areas are holding ShakeOut drills annually (see the global homepage at www.ShakeOut.org), except New Zealand (every few years). In addition, people and organizations in any other state or country can now register to be counted in the overall global total each year. ShakeOut websites are now online in English, Spanish, French, Italian, and Japanese. We are developing outreach materials to encourage other countries to participate, including Iran (which has annual earthquake drills in its schools involving several million people).

**Growth of ShakeOut Drills**

<table>
<thead>
<tr>
<th>Year</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>5.4 million</td>
</tr>
<tr>
<td>2009</td>
<td>6.9 million</td>
</tr>
<tr>
<td>2010</td>
<td>7.9 million</td>
</tr>
<tr>
<td>2011</td>
<td>12.5+ million</td>
</tr>
<tr>
<td>2012</td>
<td>19.4 million</td>
</tr>
<tr>
<td>2013</td>
<td>24.9 million</td>
</tr>
<tr>
<td>2014</td>
<td>26.5+ million</td>
</tr>
<tr>
<td>2015</td>
<td>30+ million</td>
</tr>
</tbody>
</table>
Recruitment is well underway for the 2015 ShakeOut on October 16 at 10:16 a.m., with over 9.1 million participants registered in California and more than 16.4 million worldwide as of September 9. Including drills held on other dates in 2015, more than 21.5 million people worldwide have registered in 2015. Our goal is to exceed 30 million participants.

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

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

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

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

Other Preparedness Campaigns

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

To expand our educational and preparedness efforts for tsunamis, SCEC created www.tsunamizone.org in 2014 for California’s participation in National Tsunami Preparedness Week (last week of March), with support from NOAA via CalOES. The site is essentially a clone of the ShakeOut model, allowing registration of tsunami preparedness activities, educational content including inundation maps, and much more. In 2015 the site was expanded to provide similar services for other parts of the US and internationally. Like ShakeOut, TsunamiZone registrations are included in America’s PrepareAthon.

Putting Down Roots in Earthquake Country, and other publications

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

The booklet has spawned the development of region specific versions for the San Francisco Bay Area, California’s North Coast, Nevada, Utah, Idaho, and the Central U.S. (totaling an additional 4 million copies). In Fall 2008, SCEC and its partners developed a new supplement to *Putting Down Roots* titled The Seven Steps to an Earthquake Resilient Business, a 16-page guide for businesses to develop comprehensive earthquake plans. It and other Roots handbooks can be downloaded and ordered from the main ECA website (www.earthquakecountry.org).

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

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

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

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

Earthquake and Tsunami Education and Public Information Centers (EPIcenters)

SCEC CEO has developed exhibits and partnered with information education venues for many years, including an interpretive trail on the San Andreas fault at Wallace Creek, a permanent earthquake exhibit at a youth museum in Hemet, CA, a temporary earthquake exhibit at the UCSD Birch Aquarium, and most recently with the San Bernardino County Museum (SBCM) we are developing an interpretive site at Pallet Creek. The expansion of these partnerships, especially with the SBCM in 2007, led SCEC to create the Earthquake and Tsunami Education and Public Information Center (EPIcenter) Network in 2008. EPIcenters include museums, science centers, libraries, universities, parks, and other places visited by a
variety of audiences including families, seniors, and school groups. Each implements a variety of activities including displays and talks related to the ShakeOut and other activities year round. The California network of more than 60 institutions is coordinated by SCEC’s Robert de Groot.

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

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

SCEC CEO has also established relationships with institutional partners in other states (2 in Oregon, 2 in Alaska, 1 in Arizona, and 3 in New England) Growth has been enhanced through the collaboration with the Cascadia EarthScope Earthquake Education and Tsunami Education Program (CEETEP) and the EarthScope Interpreters workshops in Oregon, Washington, and Alaska (see K-12 Education Initiative below for more details). Recently the Network has been collaborating with the Central United States Earthquake Consortium to create an EPIcenter network for the Central U.S. Quake Catcher-EPIcenter Network. In 2015 a new partnership was established between SCEC, IRIS, Caltech, and USGS to continue the expansion and development of QCN worldwide, beginning with installations in summer 2015 by SCEC in several Central U.S. schools. For several years, SCEC has expanded the Quake Catcher Network of low-cost seismic sensors with installations at over 26 EPIcenter locations in California and Oregon, and more than 100 at schools in each west coast state including Alaska. Sensors have been installed at all high schools in the Lake Elsinore Unified School District. Installation of sensors in the Chaffey Joint Union High School District started in October 2013. The goal is to establish several K-12 sensor stations around a given EPIcenter as a means to build long-term educational partnerships around the ShakeOut, citizen science, and an opportunity to enrich standards-based K-12 curriculum. We have found that free-choice learning institutions are hungry for new programming that will engage science educators and their students in “citizen science” projects. SCEC is collaborating with various members of the EPIcenter network to establish a QCN professional development program for science educators to be administered by free-choice learning institutions across the Network. Once the teachers are trained to use QCN as research and classroom learning tool, we will build a “citizen science” community among those teachers (and their students) using the local EPIcenter as a hub. The first hub has been established at the San Bernardino County Museum in Redlands.

Other Activities. Recent EPIcenter activities include completion of the Science Spectacular Earthquake Program (co-developed with the California Science Center) and San Andreas fault content for the IRIS “Active Earth” display, and an earthquake and tsunami workshop for Southern California educators was hosted by the Cabrillo Marine Aquarium in Spring, 2014. New EPIcenter exhibits have also recently been completed at the California Academy of Sciences, San Francisco, and the earthquake themed highway reststop in Marston, MO. Ongoing projects include the Hatfield Marine Science Center in Newport, OR and San Diego Mesa College.

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

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

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

Social media capabilities have also been expanded in SCEC4 (twitter.com/scec now has 891 followers, and facebook.com/scec has 2,531 “likes”) under the management of SCEC’s new Communication Specialist Jason Ballmann (whose hiring is the result of increased support from FEMA). The SCEC Youtube Channel (youtube.com/scec) is now regularly supplemented with new content. Will soon include the use of podcasts, webinars and other virtual news conferences, and other technologies. SCEC and the ECA are increasing the availability of multi-lingual resources (materials, news releases, experts, etc.) to more effectively engage all media, including foreign media. Summer and school-year internships for journalism or communications students assist CEO staff in developing these technologies and resources.

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

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

K-14 Earthquake Education Initiative

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

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

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

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

**Partnerships with Science Education Advocacy Groups and Organizations with Similar Missions**

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

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

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

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

**InSight Vital Signs of the Planet (VSP) Program**

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

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

VSP is now a three-week summer institute that provides 10-15 educator fellows with authentic experiences in scientific inquiry, encourages instructional improvement in schools, and fosters deep engagement with local underserved communities. The Summer Institute is 3 weeks long which includes seminars, field research, field trips, and curriculum development. The program is centered around a 5-day field research component in partnership with California State University, San Bernardino using survey mode GPS to monitor tectonic deformation in Southern California, and are installing QCN sensors in their classrooms. In 2015, twelve science educators and one student participated and their posters are displayed at the 2015 SCEC Annual Meeting. Teacher participants also help plan and implement the workshop for science educators held in conjunction with the SCEC Annual Meeting, where they share the research lessons they developed. During the fall these lessons are test taught at the schools and revised. Each lesson will also be developed into a lending kit that can be shared among all current participants and alumni of the program.

Other Activities

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

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

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.).

Undergraduate Internships

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

- The **Summer Undergraduate Research Experience (SURE)** internship places undergraduate students in research projects with SCEC scientists. Internships are supported from base SCEC funding and funding from internship mentors. More than 270 interns have been supported since 1994. SCEC/SURE has supported students working on numerous projects in earthquake science, including the history of earthquakes on faults, risk mitigation, seismic velocity modeling, science education, and earthquake engineering.

- The **Undergraduate Studies in Earthquake Information Technology (USEIT)** internship brings together undergraduates from many majors and from across the country in an NSF Research Experience for Undergraduates Site at USC. The eight-week program develops and enhances computer science skills while teaching the critical importance of collaboration for successful learning, scientific research and product development. Since 2002, 264 students have participated. UseIT interns tackle a scientific “Grand Challenge” that varies each year but always entails developing software and resources for use by earthquake scientists or outreach professionals, including SCEC-VDO (visualization software developed and refined each summer by UseIT interns). The Grand Challenge for the 2014 UseIT program was to **develop SCEC-VDO and GIS tools for exploring and evaluating the aftershock hazards implied by the new Uniform California Earthquake Rupture Forecast (UCERF3)**. These evaluations were guided by using M7 rupture scenarios developed for the 25th Anniversary of the 1989 Loma Prieta earthquake. Due to the Special Olympics World Games being hosted at USC, the UseIT program was not held in 2015.

These internship opportunities are connected into an intellectual pipeline that encourages students to choose STEM (Science, Technology, Engineering, and Math) careers and is improving the diversity of the scientific workforce. These
programs are the principal framework for undergraduate student participation in SCEC, and have common goals of increasing diversity and retention. In addition to their research projects, participants come together several times during their internship for orientations, field trips, and to present posters at the SCEC Annual meeting.

Since 2002, over 1600 eligible applications for SCEC internship programs were submitted (at www.scec.org/internships), with more than 540 internships awarded in current and past programs. Leveraging of additional funding has allowed SCEC to double the number of internships offered each year (38 in 2014). Since 2010, underrepresented minority interns averaged 36.4% of each year’s class, with a high of 43% in 2014. Women represented an average of 48.2% of interns, with a high of 57% in 2014. First generation college attendees have averaged 31.2% of each class. Much of the success in increasing diversity has come from increased efforts to recruit students from other states and also from community colleges, making the internship programs an educational resource that is available to a broader range of students.

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

Additional Programs

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

**High School level.** Experiential learning opportunities for high school students are closely linked with SCEC’s K-14 Earthquake Initiative and its programs such as InSight Vital Signs of the Planet. The goal is to provide activities that expose high school students to earthquake research, inquiry-based curricula, and interactions with SCEC scientists. Students who have participated in SCEC research experiences during high school that have now advanced to college are now beginning to participate in USEIT or a SURE. One high school student participated in the 2015 Insight VSP program (some years there have been up to 4; this depends on the teachers involved).

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

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.

Seismology
The Seismology Group gathers data on the range of seismic phenomena observed in southern California and integrates these data into seismotectonic interpretations as well as physics-based models of fault slip. Resources include the Southern California Earthquake Data Center (SCEDC) that provides extensive data on Southern California earthquakes as well as crustal and fault structure, the network of SCEC funded borehole instruments that record high quality reference ground motions, and the pool of portable instruments that is operated in support of targeted deployments or aftershock response.

This past year’s accomplishments include:

- Tremor Detection and Analysis;
- Fault Coupling, Slip Behavior, and Source Properties;
- Estimating Stress from Anisotropy;
- Induced Seismicity

Figure 1. About 3 weeks of tremor activity along the San Andreas Fault as detected by the array analyses. Note the streaking nature of tremor propagation. Azimuth is with respect to the array center.

Tremor Detection and Analysis
Deep fault slip can manifest in the form of tremor and has been observed on several faults in California, yet is far from ubiquitous. Several studies explore tremor along the select set of faults in California where it occurs, notably the San Andreas fault, San Jacinto fault. Tremor along the Parkfield segment of the San Andreas was the first to be identified outside of a subduction zone, but the factors that control tremor activity are still not well understood. Ghosh has been operating a...
temporary seismic array in the region and finds that tremor occurs almost daily. They use backprojection to locate the tremor and determine that it occurs in distinct patches along the fault (Figure 1). Additionally, they find that tremor rates increase dramatically in the hours following the South Napa earthquake. Peng and Yang conducted a systematic search for tremor in California, focusing on a region below the San Gabriel Mountains and along the San Jacinto fault. They find no evidence for tremor beneath the San Gabriel Mountains despite near lithostatic pore pressures (Yang and Peng, 2013). And, in an extensive search for tremor along the San Jacinto fault that utilized matched filter techniques they only find one instance of clear tremor; this tremor was previously reported and occurs during passing surface waves of the 2002 Denali earthquake (Figure 2). These results confirm that a unique set of conditions are needed for tremor to occur.

Figure 2. An example of tremor waveform detection along the San Jacinto Fault using a LFE template (red). In the left panel, continuous data is shown in black. Time is set in reference to the origin time of the 2002 Denali Fault earthquake. On the right panel, a zoom-in plot of the template (red) and detected event (blue).

Figure 3. From Jolivet et al. (2015). Seismic and aseismic asperities along the central San Andreas Fault. Color represents the mode of the a posteriori PDF of slip in the along-strike direction. Semi-transparent areas marked with red dashed lines correspond to asperities where significant earthquakes are known to have occurred, including the 1857 M7.9 Fort Tejon, 1906 M7.9 San Francisco and 1966 and 2004 M6.0 Parkfield earthquakes. White transparent areas with question marks are zones that are inferred to be coupled and the potential source for future earthquakes.
Fault Coupling, Slip Behavior, and Source Properties

Both seismic and aseismic slip distribution and source properties can vary significantly along strike and with depth with changes in fault coupling, frictional properties, pore-fluid pressures, and/or fault structure. Ampuero conducted the first probabilistic estimate of fault coupling along the Parkfield-Cholame section of the San Andreas fault. Fault coupling is estimated from high-resolution SAR- and GPS-derived observations of surface displacements. The results show that locked asperities are consistent with the inferred locations of M > 6 earthquakes, including patches possibly associated with two foreshocks of the 1857 M7.9 Fort Tejon earthquake (Figure 3). A study by Peng examined the variation in aftershock distributions for a set of 10 M>4 mainshocks along the San Jacinto fault (SJF) near Anza. They find that all aftershock distributions are extended in the along-strike direction. Additionally, deeper mainshocks have abnormally long aftershock zones suggesting that they are modulated by changes in fault frictional properties as depth increases (Figure 4). Further, Peng postulates that the deep aftershocks zones may be driven by deep creep along the SJF (Meng and Peng, 2015). McGuire and Ben-Zion explore rupture velocity and directivity for M>3 earthquakes along the SJF to determine how fault structure and damage zones can affect these source properties and use second moment estimates and measurements of peak ground motions to estimate the directivity. They observe a clear correlation between Peak Spectral Accelerations (PSAs) near the corner frequency and the expected directivity from second moment estimates for the 2013 M5.1 earthquake on the SJF (Figure 5).

Estimating Stress from Anisotropy

Anisotropy can be used to estimate crustal stress and mantle flow and provide a better understanding of tectonic forcing that drives deformation. Miller and Becker are collecting disparate anisotropy datasets to develop a 3D model of anisotropy for southern California. They conduct a number of comparisons between different inferences of crustal stress and strain-rates. For example, they compare coseismic stress estimates using a focal mechanism inversion and compare to Kostrov summed strain-rates. They find that throughout much of southern California these two estimates are closely aligned (Figure 6); however, they do find some deviation in the estimates near the Transverse Ranges and near the southern segment of the San Andreas. The origin of the differences is being investigated but may be caused by heterogeneous rock rheology or time-dependent alignment of stress and strain through the seismic cycle.

Induced Seismicity

The identification of induced seismicity and its impact on seismic hazard are of growing interest to scientists and the public alike. Chen and McGuire examine how earthquake source properties vary near geothermal operations in the Salton Sea region. They find that stress drops correlate with distance from geothermal wells, such that stress drops are lowest within 300 m of injection wells. Additionally, they also find low stress drops on a nearby fault that hosted a series of earthquake swarms in 2005, 2009, and 2010. Their results show that geothermal operations can locally change the source properties of earthquakes and provide new insights.
into the interaction between faults and fluids in a geothermal field. In 2014, a flurry of moderate earthquakes in the Los Angeles region raised concern as to whether some of the seismicity was of anthropogenic origin rather than tectonic origin. Hauksson et al. (2015) searched for evidence of induced earthquakes associated with oilfield operations in the seismically active Los Angeles basin (LA basin) (Figure 7). Such anthropogenic earthquakes can be caused by changes in loading on the adjacent crust as well as inflation or collapse of an oilfield reservoir when large volumes of fluids are injected or extracted. Overall, they found no obvious previously unidentified induced earthquakes, and that the management of balanced production and injection of fluids appears to reduce the risk of induced earthquake activity in the oilfields. To quantify the relationship between oil field activities and potential induced seismicity, Goebel et al. (2015) developed a novel method to identify likely induced seismicity in tectonically active regions based on short-range spatio-temporal correlations between changes in fluid injection and seismicity rates. They applied this method to Kern County, central California, and found that most earthquakes within the region are tectonic in origin, except for four different possible cases of induced seismicity.

Figure 7. (Left) Comparison of coseismic “stress” from Michael (1984) type inversion (green, from Yang and Hauksson, 2013) and Kostrov summed strain-rates (yellow) based on the same focal mechanisms (Yang et al., 2012) (compressive axes show). (Right) Angular difference between the two axes, with sign determined as indicated in the legend, along with histogram (y axis showing frequency percent) over all sampled regions (sub plot), with legend stating the mean ± standard deviation of angular difference.

Figure 6. Relocated seismicity 1981-2014/06 recorded by SCSN and oilfields shown as irregular light blue areas (DOGGR web site). Symbol sizes are scaled with the earthquake magnitude with Mw ≥ 5 shown as octagons (see scale in upper right corner), and color-coded by date. LB – Long Beach oilfield; MB – Montebello oilfield; MDR – Marina Del Rey; N-I-Fault: Newport-Inglewood Fault; WC – West-Coyote;

Select Publications
RESEARCH ACCOMPLISHMENTS


Tectonic Geodesy

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

This past year’s accomplishments include:

- Continued development of the CGM
- Geodetically constrained deformation modeling
- Observation of strain transients
- R&D for joint use of GPS and seismic data in Earthquake Early Warning
- 3D offset measurement from repeat-pass LiDAR

Community Geodetic Model

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

McGill, Bennett, and Spinler continued campaign GPS data collection and modeling for the San Bernardino Mountains (SBM) and San Gorgonio Pass (SGP) area (Figure 8). This has resulted in the publication of velocities for 41 sites in the SBM and the establishment of 23 sites in the SGP. Additional data collection for the latter during 2015 will improve existing preliminary velocities. This project continues to involve SCEC interns, undergraduates, and teachers in field work and data analysis.

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

In support of the CGM and to ensure the maximum usage of SCEC-funded data in years to come, Floyd has taken the lead on transfer of legacy GPS data from the SCEC archive to the UNAVCO archive. This effort has involved identification of relevant datasets and verification of metadata. In addition, Floyd has interacted with PIs to facilitate the gathering of GPS data from recent SCEC-funded efforts and the provision of these data for inclusion in the CGM.
Drawing upon these and other data, Shen has produced an updated set of campaign GPS time series that incorporates data collected since the CMM4 (2004) and utilizes current, self-consistent processing strategies. This compilation features 130 new campaign sites, and 50 continuous sites have been included for the purpose of reference frame alignment. Metadata were thoroughly reviewed and corrected as needed to ensure the accuracy of processed results.

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

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

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

Integration and interpretation of GPS and InSAR observations requires accurate characterization of vertical deformation. Hammond et al. carried out a detailed analysis of vertical rates in the Ventura Basin by combined use of InSAR, GPS, leveling, and tide gauge data. The long-term vertical GPS velocities were obtained through application of a non-parametric median-based approach that is robust in the presence of steps and outliers. LOS velocities derived from the GPS rates, along with a regional deformation model, are used to constrain the InSAR LOS velocities and isolate the vertical motion. The resulting rates document basin subsidence due to groundwater level fluctuations and uplift consistent with contraction due to the Western Transverse Ranges and San Andreas Fault (SAF) systems. The four data sets span different time periods from the 1930s to the present but suggest steady vertical rates except in areas of anthropogenic signals.

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

**Figure 9 (a - c).** (a) Average LOS velocity from Envisat data 2003 – 2010; LOD ramp error is visible across scene. (b) LOS velocity with application of empirical LOD correction. (c) LOS velocity with application of GPS-based correction. The two correction approaches show comparable results. (Figure courtesy Z. Liu)
In a second important development, Liu found that by correcting empirically for a temporally correlated local oscillator drift (LOD) error in Envisat data, it is possible to generate a deformation map based on InSAR data alone that is comparable to one obtained with a GPS-based correction (Figure 9). Agreement between InSAR-only motion estimates and GPS observations demonstrates the possibility of obtaining accurate velocity maps and time series from InSAR data even in regions with sparse GPS coverage. Application of the empirical correction to data from the Eastern California Shear Zone shows that transient deformation inferred from the InSAR data cannot be explained by the LOD error and is more likely due to long-term postseismic deformation.

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

**Additional Tectonic Geodesy activities**

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

**Strain transient observation and technique development.** Wyatt and Agnew continue to operate the Piñon Flat Observatory (PFO), despite budget constraints. The long history of laser strainmeter (LSM) observations have recorded repeated transient events in the days to weeks after moderate local and larger distant earthquakes as well as events not correlated with earthquakes. Motivated by their observations of swarm-like clustering of small earthquakes and swarm migration, Shearer et al. are using PFO LSM and PBO borehole strainmeter data to investigate possible causative processes including fluid flow and aseismic slip (Figure 10). This work has identified at least ten instances of strain anomalies correlated with peaks in the local seismicity rate. Some, but not all, of the anomalies correlate with M>3 earthquakes, however not all moderate earthquakes have associated strain transients and some transients occur without a M>3 earthquake. These observations may indicate that the strain anomalies associated with increased seismicity rate arise from slow slip at depth on the San Jacinto Fault just north of the 2006 M5.2 Anza earthquake. Agnew and colleagues are meanwhile testing the newly developed Trench Optical Fiber Strainmeter (TOFS) which may present an alternative to LSMs that is easier to install and operate. Two TOFSs have been installed at PFO, and a third is planned for 2015, to enable testing and calibration of the systems. While TOFS data are noisy at periods exceeding several hours, ongoing work is focused on noise reduction techniques.

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

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

**Select Publications**

**Research Accomplishments**


**Earthquake Geology**

Earthquake Geology promotes studies of the geologic record of the Southern California natural laboratory that advance SCEC science. Its primary focus is on the Late Quaternary record of faulting and ground motion, including data gathering in response to major earthquakes.

**Ventura Special Fault Study Area**

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

Geochronology and Fault Slip Rates

Geochronology advances supported under SCEC 4 continue to yield new and more precise slip-rate data for the southern California fault system. A workshop convened in last October brought together geologists and geochronologists in a productive discussion of emerging techniques in exposure and luminescence dating. One of the highlights of SCEC geochronology has been the development of the pIR-IRSL technique on K-feldspar (Roder et al., 2012). Application of this technique to alluvial fan offsets along the Garlock fault yields a new, short term rate of 12.8 +/- 2.4 mm/yr that encompasses a cluster of four earthquakes between 500 and 1900 years ago (Dolan et al., in review). This is double the Holocene average rate of 6 mm/yr, and well in excess of the current loading rate of the Garlock fault inferred from geodesy. Overall, it appears that loading and strain release on the Garlock fault are temporally clustered, probably in alternation with right-lateral slip through the Eastern California Shear Zone. Newly collected lidar data from the Agua Blanca fault, northern Baja California, reveals several slip-rate sites in new detail (Behr et al., 2014 SCEC report). Pending geochronometry of these sites will reveal important information on how much plate-boundary strain is transferred to the California borderland, as well better understanding of seismic hazard for northern Baja California. Slip rate of the Sierra Madre fault, located on the margin of the Los Angeles basin, and the Wheeler Ridge blind thrust, southern San Joaquin Valley, are also being revisited with lidar data and modern geochronology approaches (Hanson et al., this meeting; Kleber et al., this meeting).

Fault Slip vs. Distributed Deformation

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

Select Publications

RESEARCH ACCOMPLISHMENTS


Computational Science

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

This past year’s accomplishments include:

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

Dynamic Rupture Simulations

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

OpenSHA/UCERF3 Development

Kevin Milner and Thomas Jordan continue to develop OpenSHA, an open-source, Java-based platform for conducting SHA. This development transform the results of SCEC science into practical products like UCERF3. Recently, supercycles and synchronization signatures are analyzed in synthetic seismic sequences. Synchronization is a key concept in nonlinear dynamics. UCERF3 does not explicitly model supercycles, but they emerge from long runs of physics-based rupture simulators, such as the RSQSim model and the ALLCAL model. In these models, the synchronization of large events on different fault sections leads to variations in seismic energy release of ± 50% on time scales of about 200 years. Spectral analysis of a million-year RSQSim catalog shows synchronization harmonics with a fundamental period of 200 years and a
Accelerating dynamic rupture and wave propagation simulations

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

Computational Developments of Earthquake Simulators

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

Simulation Tools for Earthquake Sequences in Heterogeneous and Inelastic Media

Earthquake simulators typically employ boundary elements that compute elastic interactions assuming a homogeneous, linear elastic half-space. Work by Brittany Erickson and Eric Dunham has introduced a novel finite-difference method for earthquake sequence simulations with rate-and-state fault friction. The finite difference method permits a wide range of material response, including elastic heterogeneity, viscoelasticity, and even plasticity. Erickson and Dunham (2014) introduced this method to study how earthquake sequences on faults cutting through sedimentary basins are affected by the compliant basin. The basin can both impede and facilitate rupture, and in many cases it leads to alternative sequences of sub-basin and surface-rupturing events. There are tantalizing similarities to the 1940 and 1979 Imperial Valley events; the former featured over 5 m of surface slip, while the latter was primarily confined to beneath the basin. Further work by Erickson and Day (2015) extended the method to faults along bimaterial interfaces. Erickson and Dunham are now exploring the development of plastic strain over multiple earthquakes; preliminary calculations suggest that under certain conditions residual stresses associated with plastic strain during early events can suppress plasticity in subsequent events. Allison and Dunham are concurrently looking at earthquake cycles accounting for viscoelastic response of the lower crust and upper mantle. The methodology naturally predicts the depth at which overall tectonic deformation transitions from being accommodated by fault slip to more distributed viscous creep, with implications for the structure of faults below the seismogenic zone.

FD Discontinuous Mesh Implementation

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

SEIMS-IO is designed with highly condensed, easy-to-understand APIs for users to choose. This library simplifies the programming of parallel I/O, with an interface hiding complex low-level operations. To accommodate the generalized interface, the earlier SEISM-IO library is modified to integrate different initialization/open/write processes in MPI-IO, HDF5, PnetCDF and ADIOS. The generalized interface has been tested using the wave propagation AWP-ODC solver on the NSF TACC Stampede system, the library has been used in the latest ShakeOut simulations by Daniel Roten. Scott Callaghan et al. have optimized CyberShake workflow, which automates and manages I/O and enable remote job execution on HPC systems. The enhanced workflow execution is efficiently split across multiple HPC systems, and previous heavy I/O workload from/to HPC parallel file systems is significantly reduced to achieve optimal performance. Charles Williams and Laura Wallace have developed a workflow for using PyLith-Generated Green’s Functions with the Defnode Geodetic Inversion Code. The workflow allows to perform the necessary tasks for both SSE inversions and interseismic coupling inversions in a semi-automated way.

Efficient Similarity Search for Continuous Waveform Data

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

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Figures

Figure 14. Summary results and analysis of simulations for the Mw 5.4 2008 Chino Hills earthquake using different velocity models (CVM-S and CVM-H) and showcasing the connection from geoscience modeling to engineering applications. The top row shows results corresponding to the simulation done using CVM-S, while the bottom row shows those corresponding to CVM-H. Each column from left to right shows: (1) The surface shear wave velocity for each model. 3D meshes built for these simulations consist of up to 15 billion finite elements. (2) The simulation results for the surface horizontal peak ground velocity. The star indicates the epicenter location. (3) Validation results using goodness-of-fit metrics to compare synthetics to data. In this study we used over 300 recording stations. GOF scores closer to 10 (lighter colors) indicate a better fit with the data. (4) Comparison with attenuation relationships used in engineering to estimate peak ground velocity. The red line corresponds to the actual trend from earthquake data, the two black lines indicate an upper and lower bound based on empirical relationships, and the green line shows the trend of the surface results from the simulation, which are shown as a gray cloud of points on the background. Simulations were done using Hercules by Taborda and Bielak (2013, 2014).

Figure 15. Fourier amplitude as a function of distance centered at 2.25 Hz using 100+ strong motion stations for the 2008 Mw5.4 Chino Hills, CA, earthquake. Dots depict values for individual stations and lines depict a 5-point moving average. Rrup indicates the closest distance to the ruptured surface of the fault plane. From Withers et al., 2015
Unified Structural Representation (USR)

The Unified Structural Representation (USR) Focus Area develops models of crust and upper mantle structure in California for use in a wide range of SCEC science, including strong ground motion prediction, earthquake hazards assessment, and fault systems analysis. These efforts include the development of Community Velocity Models (CVM’s) and Community Fault Models (CFM’s), which together comprise a USR. In partnership with other working groups in SCEC, the USR Focus Area also helps support the evaluation and improvement of these models through ground motions simulations, 3D waveform tomography, earthquake relocations, and fault systems modeling.

This past year’s accomplishments include:

- Refinement of the SCEC Community Fault Model (CFM) for southern California based on relocated seismicity catalogs and detailed fault traces in the USGS Quaternary Fault and Fold database. The latest updates include significant refinement to fault representations in the Peninsular Ranges, Mohave region, Santa Barbara Channel, and Western Transverse Ranges. These refinements include the faults systems that are the focus of the SCEC Special Fault Study Areas, and will be released in a forthcoming new model version.
• Completion of the first fully-evaluated Statewide Community Fault Model (SCFM v. 3.0), which involved peer review of the northern California fault representations. These faults were combined with the latest iteration of the southern California Fault model (CFM 5.0) to comprise the new statewide model.

• Development of new sets of regularly gridded representations for the fault included in the southern California CFM, to facilitate their use in earthquake simulators and other modeling applications.

• Release of a new version of the SCEC southern California USR, which includes the aforementioned CFM’s and an updated version of the SCEC Community Velocity Model (CVM-H 15.1.0).

• Development of a first iteration Central California USR, including new representations of the Central Valley and Santa Maria basin structures that are compatible with fault representations in the SCEC SCFM. This new model is intended to support SCEC’s Central California Seismic Project (CCSP), which will use these new structural representations to facilitate 3D waveform inversion studies.

Community Fault Models (CFM’s)

SCEC has engaged in a major effort to refine systematically the Community Fault Model (CFM) using detailed fault traces from the USGS Quaternary Fault & Fold Database, precisely relocated earthquake hypocenters, and new focal mechanism catalogs. This results in fault representations that are more precise, and often more highly segmented than in previous model versions (Figure 18). The first new model version incorporating these updates (CFM 5.0) was released at the 2014 Annual meeting, and this past year further refinements have been made with an emphasis on the Peninsular Ranges, Santa Barbara Channel, Transverse Ranges, and Mojave Desert regions. As part of this process, we have also developed detailed sets of fault representations in the Ventura Basin and San Gorgonio Pass regions, which are the focus of the SCEC Special fault Study Areas (SFSA’s). These new updates will be made available in a forthcoming model release.

In addition, we facilitated a formal evaluation of the northern California fault model, which together with CFM 5.0 comprises the SCEC Statewide Community Fault Model (SCFM). The northern California models consists of more than 150 fault representations, many of which include sets of alternative representations (Figure 19). To facilitate the review, we provided the fault representations along with a spreadsheet with fault metadata to the evaluation group, which is comprised of scientists from SCEC, the USGS, and CGS. Evaluators were instructed to use SCEC VDO software to view and assess the fault representations. To coordinate this activity, we held a kick-off evaluation meeting at the USGS in Menlo Park (May 2015). Participants provided rankings for alternative fault representations, which are used to define the set of faults that define the preferred model version (SCFM v. 3.0).

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

Building Unified Structural Representations (USR’s)

The concept of a Unified Structural Representation (USR) has been pioneered by the SCEC Community to support a wide range of earthquake science and hazard assessment efforts. The SCEC USR for southern California is a three-dimensional
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description of crust and upper mantle structure consisting of interrelated Community Fault (CFM) and Velocity (CVM) models (Figure 20). The development of these models has been inspired by recent advances in numerical methods and parallel computing technology that have enabled large-scale 3D simulations of seismic wavefields in realistic earth models. SCEC released its first formal USR version this year (Shaw et al., 2015), consisting of CFM 5.0 and CVM-H 15.1.0. The CVM component of this model includes a series of updates to the basin representations in the model, which are compatible with the locations and displacements of major faults in the CFM. The USR also includes a Geotechnical layer (GTL) that describes near surface velocities, and has been iterated using 3D adjoint waveform tomography. This model, as well as alternative velocity representations supported by SCEC, are actively being tested by comparison of observed and synthetic waveforms for earthquakes in southern California. Another related, current effort is focused on the implementation of statistical representations of small-scale velocity heterogeneity in these models, which offers the prospect of accurately simulating seismic waveforms to higher frequencies.

Figure 20. Perspective view of components of the Unified Structural Representation (USR). A) Topography and bathymetry; B) top basement surface; C) Community Fault Model (CFM) (Plesch et al., 2007); and D) USR showing Vp. SAF is the San Andreas Fault. Topographic and bathymetric surfaces are derived from USGS 3° digital elevation model data and a National Oceanic and Atmospheric Administration 30° grid (TerrainBase).

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

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**Fault and Rupture Mechanics (FARM)**

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

**Heterogeneous Fault Stress and Structure**

Considerable effort has remained focused on how heterogeneous fault stress and fault structure (e.g., roughness, larger scale fault segmentation and geology) influence seismicity and rupture propagation. Several studies have explored the role of fault roughness on earthquake processes. For example, new suites of calculations provide further insight into how fault roughness on non-planar faults actually promotes supershear rupture (Figure 21; Bruhat et al., 2015), an effect opposite of conventional wisdom. The role of local variations in fault orientation (i.e. fault roughness) has also been exploited to constrain the width of surface creep zones of the Southern San Andreas fault (Fialko et al.); application of coulomb plasticity (accounting for variations in normal stress arising from fault strike) provides a good explanation for the variations in the creeping width determined from geodetic studies. Further, Fialko et al. note that distributed interseismic creep needs to be accounted for to prevent systematic bias in paleoseismic slip rate estimates, especially where coseismic slip is distributed near the surface (owing to low normal stress and/or stable frictional properties). These studies highlight the need for improved geologic constraints on processes that promote strain localization within evolving faults - a focus of structural studies of exhumed faults (Figure 22; Shervais and Kirkpatrick).

The level of background stress, stress heterogeneity, and heterogeneity of fault zone properties influence both rupture propagation and the distribution of aftershocks. Shi and Day investigate the role of fault geometry and initial stress on the likelihood of through-going ruptures across the San Gorgonio Pass Section of the San Andreas fault (Figure 23). They developed dynamic rupture simulations integrating information from SCEC CFM and CSM and found that the three different stress models available in the SCEC CSM lead to different answers regarding ruptures across the SGP, highlighting the need for reliable and self-consistent stress inputs in fault systems with complex geometry. The role of fault heterogeneity has also been explored in earthquake cycle models that include realistic frictional properties (Jiang and Lapusta). Models with different large-scale fault properties and
the same heterogeneity produce microseismicity with different b-values in the G-R relation, reflecting variations in stress gradient and fault coupling. Such studies illustrate how observations of microseismicity can be used to constrain the frictional properties of faults, which can in turn be included into integrative earthquake cycle and rupture models and relationships between seismicity and geodetic data.

**Dynamic weakening and fault slip at the base of the seismogenic zone**

Understanding rupture processes at the base of the seismogenic zone remains critical for evaluating the potential for large events in Southern California. New modeling studies on this topic focus on how realistic depth-dependent fault properties affect the spatio-temporal complexity of earthquake slip and the variability of arresting depth (Figure 24; Jiang and Lapusta). With reasonable depth-dependent parameters, thermal pressurization (TP) allows large earthquakes to penetrate deeper into creeping fault extensions, even when the shear zone width increases with depth below the seismogenic layer. An issue that remains potentially problematic is that incorporation of TP and flash heating (FH) into such models generally leads to rapid and near-total (and perhaps unrealistic) coseismic stress drops. Future work will be directed towards identifying fault properties that allow for reasonable stress drops for large events. Ma and colleagues hypothesize that dynamic compaction of fault gouge may provide a solution to this issue. They show that large dynamic stresses during rupture propagation cause the gouge layer to compact ahead of the rupture front, leading to rapidly elevated pore pressure in the effectively undrained fault zone - and significant dynamic weakening of the principal fault surface. Compared to other dynamic weakening mechanisms such as flash heating and thermal pressurization, this mechanism does not require slip to initiate. After the passing of the rupture front, dilatancy of undrained fault gouge reduces the pore pressure and restrengthens the fault, promoting a more pulse-like rupture. Thus dynamic gouge compaction and dilatancy provides a simple mechanical explanation for weak mature faults and pulse-like earthquake ruptures on these faults.

Figure 22. Kirkpatrick and Shervais mapped the internal structure of the Boyd fault, Southern California, using the structure-from-motion methodology, to establish the dimension of contact asperities and how the fault roughness evolves with displacement. Example of the field workflow: a.) Photograph of an exposure of the Boyd fault. Around 150 photos similar to this were used to construct the outcrop model. b.) Model generated with Agisoft’s PhotoscanPro shown from the same perspective as a. Boxes in a and b show the extent of c. c.) Rectified image exported from PhotoscanPro after the model was rotated to view the exposure down the slip vector. Lines show traces mapped in the field that were used to calculate roughness. White lines are the edges of the principal slip zone and green lines define the extent of the fault core.

Figure 23. Shi and Day developed dynamic rupture simulations to investigate the role of initial stresses and fault geometry on the likelihood of a San Andreas rupture through the San Gorgonio Pass. The study integrates fault geometry from SCEC CFM-v4 (top) and initial stress constraints from the SCEC CSM (bottom). The results highlight the critical sensitivity of dynamic rupture to initial stress assumptions in geometrically complex faults.
Analysis of dynamic weakening mechanisms also remains a focus of experimental and geological studies. New laboratory experiments have been performed to characterize the processes responsible for flash weakening in gouge (Griffiths and Prakash; studying dynamic weakening in samples from the SAFOD drill hole) and thermal pressurization (Tullis; who developed protocols to constrain competing effects of thermal and hydraulic diffusivity by controlling the permeability of the experimental samples). Theoretical studies provide new insights into the physical processes responsible for dynamic weakening, and rationale for their inclusion into earthquake cycle and rupture models. The role of thermally-activated contact processes have now been included into STZ models of gouge deformation (Carlson and colleagues); these PIs have also combined the STZ theory with fracture mechanics to model grain fragmentation. These analyses show that grain splitting dominates at small shear strains and grain abrasion dominates at larger displacements. A feedback between strain localization and grain fragmentation provides an explanation for the formation of a thin gouge layer with a characteristic particle size several orders of magnitude smaller than those outside the shear band. Further observations on the role of dynamic weakening on natural faults are being compiled using novel new techniques to date and constrain peak temperatures during past earthquakes on exposed faults in Mecca Hills (Evans).

Figure 24. Jiang and Lapusta studied the effect of the depth limit of dynamic weakening on microseismicity patterns over several cycles. They compared fault models with down-dip limit of dynamic weakening being shallower (top row, Model A) and deeper (bottom row, Model B) than the transition between velocity-weakening (VW) and velocity-strengthening (VS). (Left) Schematic illustrations of the two models. Regions with the VW and VS low-rate properties are shown in white and yellow, respectively. Regions with enhanced dynamic weakening are shown as red hashed rectangles. Nucleation-promoting spots with altered friction properties are shown as open grey circles. (Right) The resulting microseismicity is illustrated as circles using the circular crack model with 3 MPa stress drop. Colors indicate typical final slip in a large event. The intensity and locations of microseismicity differ in the two models due to different stress distribution with depth and its evolution with time.

Tectonic tremor and fault rheology

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

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- Shervais, K., and J. D. Kirkpatrick (2014), Fault core and slip zone geometry, wear and evolution, Southern California Earthquake Center Annual Meeting, Palm Springs, CA.

Southern San Andreas Fault Evaluation (SoSAFE)

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

San Gorgonio Pass Special Fault Study Area

Recent work by several independent geologic slip rate investigators have called into question slip models developed in UCERF2 which held that slip along the Coachella strand of the San Andreas fault was largely transferred westward onto the San Gorgonio Pass thrust and northward into the Eastern California Shear Zone, with no slip continuing northwest through other SAF strands in the San Gorgonio Mountains. At the eastern end of the Indio Hills, on-going work by Bilinski et al. (2014) is consistent with a previous study by Behr et al. (2010) that indicates ~20 mm/yr is carried by the Mission Creek strand and that this rate has been constant since ~90ka. New studies were initiated along the northern strands of the San Andreas fault through the San Bernardino Mountains, where offset of Quaternary gravels on the Mission Creek and Garnet Peak strands indicate some slip continues to these latitudes, ultimately transferring slip onto the Mill Creek and San Bernardino strands of the San Andreas (Kendrick et al., 2015; Oskin et al. 2015). These results are compatible with strain observed in new geodetic results across the San Bernardino Mountains (McGill et al., 2015). To the south, Holocene rates along both ends of the Banning strand indicate slip remains low (2-6 mm/yr) along its entire length (Gold et al., 2015; Scharer et al., 2014). Within the Pass itself, studies by Yule and Heermance report Holocene dip slip rates on the San Gorgonio Pass thrust fault zone of 4-6 mm/yr, consistent with a paleoearthquake record that indicates ruptures are less frequent in the Pass than on the main San Andreas fault strands to the northwest and southeast (Yule et al., 2014). The emerging pattern suggests slip is accommodated along all of the mapped strands of the SAF.

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

**Paleoseismic studies on the San Andreas and San Jacinto Faults**

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

Figure 26. New models of slip transfer from the southernmost San Andreas Fault onto the Mission Creek (MCF), Banning (BF) and Garnet Hill (GHF) strands based on slip rate studies stemming from the San Gorgonio Pass SFSA, from Gold et al. (2015).

Figure 27. Summary of geochronological investigations and methods used in SCEC4 (Scharer et al., 2014).

Figure 28. Paleochannels excavated for slip rate study at the Quincy site by Onderdonk et al. (2015) reveal variable strain release rates on the San Jacinto Fault over the last 2000 years.
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occurred during a lake highstand, indicating the most recent event on the southernmost San Andreas fault occurred several decades later than previously estimated.

SoSAFE/EQ Geology Geochronology Workshop

Members of the Earthquake Geology and SoSAFE groups convened a workshop to discuss new advances and approaches in geochronology used by SCEC scientists. The geochemical background, sampling techniques, data reduction and modeling for terrestrial cosmogenic nuclide dating, U-series dating, and luminescence dating were the primary focus of the workshop. Issues that received strong focus during discussion were (1) the value and improved results stemming from collaboration and close communication between field studies and laboratory experts, (2) the need to utilize multiple dating methods to explore epistemic uncertainties on the timing of deposition or abandonment of geologic units used to determine slip rates on faults, and (3) the value of developing and testing of new methods for fault studies in southern California, such as in-situ 14C dating and burial dating of older units, and continued development of luminescence dating using feldspars. A report (http://sceccore2.usc.edu/proposalfiles/2014reports/Scharer_14169_report.pdf) provides a full summary and conclusions from the workshop.

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3.8 Stress and Deformation Over Time (SDOT)

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

This past year’s accomplishments include:

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

Community Stress Model

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

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

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

Deformation Models

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

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

Shear Wave Splitting

Miller and Becker are working to collect disparate anisotropy data to jointly integrate them into a 3D model of anisotropy for the southern California lithosphere. SKS splitting measurements across the San Andreas fault do not show a strong signature associated with a deep extension of San Andreas fault shear into the mantle. The “fast azimuth” of SKS splits across the San Andreas fault does not show a clear deviation in orientation from the broad-wavelength mantle flow alignment. This is in contrast to the Alpine fault in New Zealand, for example, which shows a clear rotation of the SKS fast direction into alignment with the orientation of the Alpine fault. The tentative conclusion is that mantle flow does not localize in the mantle under the San Andreas fault.

Ventura Special Fault Study Area

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

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

**Figure 30.** Mechanical model-predicted three dimensional slip distributions on the Ventura fault by Marshall et al. A) Not shown. B) The CFM v5.0 no ramp model. C) The CFM v5.0 ramp model.

**Figure 31.** Results of inverting geodetic velocity field for fault slip rates in the Western Transverse Ranges by Johnson, Hammond and Burgette. a. Modeled and observed shortening rates across the region. b. Inferred reverse-slip rates on faults. Model mean and 99% confidence limit of reverse sense of slip rate is shown.

**Earthquake Forecasting and Predictability (EFP)**

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

This past year’s accomplishments include:

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

**Earthquake forecast development and testing**

Traditionally, this is the principal activity of the SCEC EFP community.

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

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

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

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

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

![Figure 32. Map of major structural elements of the plate boundary fault system in and around the US/Mexico border region.](image)
UCERF3

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

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

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

Earthquake clustering

SCEC EFP community continued studies of earthquake clustering.

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

Figure 33. Postcard for final UCERF3 Long Term Time Dependent model showing M=6.7 participation probabilities throughout California.

Figure 34. Event locations from the HYS catalog (1981 – 2014). Similar event clusters that have been relocated by using waveform cross-correlation are shown in black. Events in the SCSN catalog (and uncorrelated events in the other catalogs) are shown in brown. Events with M > 5.5 are shown as stars. Faults are from Jennings (2010) with late Quaternary faults in shades of red.
Zaliapin and Ben-Zion investigated seismic cluster anomalies in relation to different loadings and large earthquakes. The results of this project suggest that (i) the cluster properties systematically evolve in time, according to several robust cluster measures, in the spatio-temporal vicinity of the largest earthquakes in southern California, and (ii) seismic clustering differs, and probably can be used to discriminate between the regions dominated by tectonic vs. human-induced seismicity.

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

**High-quality data**

A project by Shearer and Hauksson focused on automatic processing of the SCSN waveform archive. This continued work has resulted in improving earthquake locations and focal mechanisms using waveform cross-correlation and S/P amplitude ratios, and on computing spectra for use in studies of earthquake source properties and attenuation. The latest version of the relocated catalog (so-called HYS catalog) contains high-precision locations of over 560,000 events from 1981 through 2014. The project also resulted in a newly created stress drop catalog for earthquakes between M1 and ~M3.5 with occasional events up to M5. The new catalog includes stress drops for more than 24,000 earthquakes between 2000 and 2014.

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

**Induced Seismicity**

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

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

**Modeling Stress and Earthquake Stress Triggering**

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

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

![Figure 35. Mean misfit between in situ stress orientation (from focal mechanisms) and scaled in situ stress with modeled topography stress. Misfit function is one minus the mean of the tensor dot product between the two stress fields, such that a value of 0 indicates a perfect fit and a value of 1 indicates complete non-correlation. For 95% misfit reduction, regional differential stress must be > 60 MPa. (From Karen Luttrell)](image)
RESEARCH ACCOMPLISHMENTS

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

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

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

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

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

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

Paleoseismic Data and Earthquake Forecasting

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

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

CSEP/USGS/GEM Workshop: Next Steps for Testing Operational Earthquake Forecasts and Seismic Hazard Models

Organizers: Maximilian Werner (Bristol University), Danijel Schorlemmer (GFZ Potsdam), Thomas Jordan (USC), Andy Michael (USGS) and Morgan Page (USGS)

Date: September 6, 2014

Location: Hilton Palm Springs Resort, Palm Springs, California, USA Website: http://www.scec.org/workshops/2014/csep/index.html

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

Virtual Institute for the Study of Earthquake Systems (VISES)


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

SCEC Utilization of Ground Motion Simulations (UGMS) Committee

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

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

Select Publications

• Field, Edward H., et al. (2014) "Long -Term Time -Dependent Probabilities for the Third Uniform California Earthquake Rupture Forecast (UCERF3)." Bulletin of the Seismological Society of America.
• Luttrell, K., B. Smith-Konter, and D. Sandwell (2015), A regional-scale model of crustal stress in southern California, with constraints from seismology, geodesy, topography, and gravity, manuscript in preparation.
• Persaud P., J. Stock, and D. Smith (2015), Sub Kilometer-scale Variability in In-situ Stress Directions near the Newport-Inglewood Fault, Southern California, SCEC Annual Meeting poster.

Ground-Motion Prediction (GMP)

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

This past year’s accomplishments include:

• Withers et al. incorporated frequency-dependent Q into AWP-ODC as a power-law, and demonstrated the effects using realistic parameters for the Chino Hills earthquake.
Lozos et al. simulated rupture on the northern San Jacinto fault using complex fault geometry with step overs, and a 3D velocity model. The results were combined with high-frequency scattering functions to generate broadband synthetics. The broadband synthetics were found to be in good agreement with the presence of precariously balanced rocks and leading GMPEs.

Graves and Pitarka characterized kinematic ruptures for ground motion simulation of shallow crustal earthquakes, including shallow and deep ‘weak’ zones and mapping the effects of perturbations to the fault surface.

Baker derived a predictive model for fling period and amplitude and compared to existing models. They found that ground motion simulations provided a rich and reliable data source for fling step, indicating an additional engineering use case for simulations. The work also validated the ability of simulations to predict fling in conditions not well captured by empirical data sources.

Bradley et al. developed a new 3D seismic velocity model of Canterbury, New Zealand. The model explicitly represents the Canterbury sedimentary basin, and other significant geologic horizons, which are expected to have important implications on observed ground motions.

Archuleta illustrated the undesired effects of rapid amplitude decay with distance of high-frequency (HF) synthetic ground based on 1D crustal velocity structures. He showed a simple solution to this problem by separating the wave propagation problem into a simplified single layer on top of a half-space for the HF portion of ground motion and a more realistic 1D multilayer model for the low-frequency portion of ground motion.

Holden and Gerstenberger conducted broadband ground motion simulations using a suite of moderately sized aftershocks (M5.3+) from the Canterbury sequence. They used these simulations to investigate the sensitivity of near field ground motions to key engineering parameters including stress drop and rupture details such as velocity, directivity and slip distribution. Results show that adoption of parameters derived from spectral inversions of the strong motion dataset and method provides an improved and robust fit to the observed data, emphasizing the need for region-specific considerations and the implications this has for GMPEs.

Beroza and co-workers worked on using ambient seismic field data to explore amplification in urban Tokyo. They used a combination of 375 Hi-Net deep borehole seismometers across central Honshu as virtual sources and 296 seismic stations of the MeSO-Net work shallow-borehole seismometers within the basin as receivers to map the basin impulse response. They found a linear relationship between vertical ground motion and basin depth at periods of 2 – 10 seconds that could be used to represent 3D basin effects in ground motion prediction equations. They also found that the strength of basin amplification depends strongly on the direction of illumination by seismic waves.

Shaw and Jordan presented a statistical description of fine-scale velocity structure in the sedimentary basins of southern California that is intended to support high frequency ground motion simulations for earthquake hazards assessment. They defined the variability in both Vp and Vs, and established vertical and horizontal correlation lengths for fine-scale velocity structures using wells across the basin as well as in tightly clustered oil fields.

Roten et al. continued to examine the effects of elasto-plastic rheology on ground motions. Previous nonlinear simulations of the ShakeOut scenario based on a kinematic source have suggested that plastic yielding in the fault damage zone may reduce ground motion levels in the Los Angeles basin (LAB) by 30 - 70 % with respect to linear solutions. New simulations of spontaneous rupture were carried out on a planar, vertical fault roughly following the surface trace of the southern San Andreas fault (SAF) along ~250 km between Indio and Lake Hughes. Because the source in these simulations is fully dynamic, these simulations are comparable to benchmarks.

**Figure 37.** Fourier amplitude as a function of distance centered at 0.25 Hz for a simulation of the 2008 M5.4 Chino Hills, Ca, earthquake, with constant Q and frequency-dependent Q. Dots depict values for individual stations and lines depict a 5-point moving average. From Withers et al., 2015.

**Figure 38.** Elasto-plastic reduction of peak ground velocity with respect to a visco-elastic conditions from dynamic simulation (fmax = 2 Hz) of a M 7.8 earthquake rupturing the southern segment of the San Andreas fault.
TPV26 and TPV27 of the SCEC/USGS dynamic rupture code verification exercise, which have been used to verify the AWP-ODC FD code with plasticity against several other FD and FE methods. These new simulations confirm that long-period (< 1 Hz) peak ground velocities in the LAB would be reduced by up to 50% if sedimentary and crustal rocks are assumed to be nearly cohesionless. However, the dynamic simulations also show that PGVs in the LAB may still exceed 2 m/s if the strength of crustal rocks and sediments is very high (> 10 MPa). This result indicates that ground motions are more sensitive to the strength of crustal rocks than indicated by previous dynamic simulations, and highlight the need to better constrain the friction angles and cohesions used in such nonlinear simulations of dynamic rupture and wave propagation.

• Nakata and Beroza developed random-field model representations of a 3D P-wave velocity model under Long Beach, CA, estimated from dense-array recordings of the ambient seismic wavefield. They find that a von Karman model fits the imaged velocity model best, with horizontal and vertical correlation lengths of 0.51 km and 0.1 km, respectively, and a Hurst number of 0.040. They validate their results by showing that their model accurately predicts the observed decay of scattered waves in the coda of a nearby earthquake.

• Using noise correlation measurements from the Long Beach Array, processed to maintain relative amplitude information, Tsai et al. produced maps of surface-wave ground motion amplification over a range of frequencies from 0.67 Hz to 2.0 Hz. These maps show that ground motion site amplification can vary by a factor of 4 over distances as short as a few hundred meters, throughout the city of Long Beach, CA. The spatial amplification patterns are generally consistent with those that would be predicted from shallow velocity anomalies, but provide direct measures of amplification and are therefore more robust than amplification computed indirectly from velocity structure.

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

SCEC Broadband Platform Validation Exercise and SRL Focus Section

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

SCEC High-Frequency Ground Motion Validation Exercise

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

Select Publications

**RESEARCH ACCOMPLISHMENTS**


**Earthquake Engineering Implementation Interface (EEII)**

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

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

This past year’s accomplishments include:

- Implementation of Ground Motion Simulation Validation Gauntlets.
- Utilization of Ground Motion Simulations to Produce Urban Seismic Hazard Maps.

**Implementation of Ground Motion Simulation Validation (GMSV) Gauntlets on the Broadband Platform**

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

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

Utilization of Ground Motion Simulations to Produce Urban Seismic Hazard Maps

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

Select Publications


Working Group on California Earthquake Probabilities (WGCEP)

The Working Group on California Earthquake Probabilities (WGCEP) is charged with developing official, consensus, and time-dependent earthquake forecast models for California. The effort builds on a long tradition of previous WGCEPs (e.g., models published in 1988, 1990, 1995, 2003, and 2008), and involves explicit collaboration between SCEC, the USGS, and CGS, with considerable funding from the California Earthquake Authority (http://www.earthquakeauthority.com). The previous WGCEP model was the Uniform California Earthquake Rupture Forecast version 2 (UCERF2, http://www.scec.org/ucerf2/), which was published in 2008. Since that time we have been working on the next model, UCERF3, for which the main goals have been to: 1) relax segmentation and include multi-fault ruptures; 2) develop an algorithm for computing more self-
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consistent long-term elastic-rebound-based probabilities; and 3) include spatiotemporal clustering effects in acknowledgment that aftershocks and triggered events can be large and damaging. The latter (spatiotemporal clustering) will bring us into the realm of Operational Earthquake Forecasting (OEF). The need for these enhancements has been exemplified by several recent earthquakes, including the 2011 M9 Tohoku earthquake with respect to segmentation, both the 2010 M7.2 El Mayor-Cucapah and 2012 M8.6 Sumatra earthquakes in regard to multi-fault ruptures, and the 2011 M6.3 Christchurch earthquake in terms of spatiotemporal clustering. Progress on each of these goals is given below.

UCERF3-TI, The Time-Independent Model

The backbone of UCERF3 is the long-term, time-independent model (UCERF3-TI), which was published as a USGS Open-File Report on Nov. 5, 2013, and includes a main report, 20 appendices, and various supplements (http://pubs.usgs.gov/of/2013/1165/). The main report and one of the appendices have also been published in a peer-reviewed journal (as Field et al. (2014) and Page et al. (2014), respectively). The primary achievement for this model component was relaxing fault segmentation and including multi-fault ruptures, both limitations of UCERF2. The rates of all earthquakes were solved for simultaneously, and from a broader range of data, using a system-level “grand inversion” that is both conceptually simple and extensible. The inverse problem is large and underdetermined, so a range of models was sampled using an efficient simulated annealing algorithm. The approach is more derivative than prescriptive (e.g., magnitude-frequency distributions are no longer assumed), so new analysis tools were developed for exploring solutions. Epistemic uncertainties were also accounted for using 1440 alternative logic tree branches, necessitating access to supercomputers. The most influential uncertainties include alternative deformation models (fault slip rates), a new smoothed seismicity algorithm, alternative values for the total rate of M≥5 events, and different scaling relationships, virtually all of which are new. As a notable first, three deformation models are based on kinematically consistent inversions of geodetic and geologic data, also providing slip-rate constraints on faults constitutes a system-level framework for testing hypotheses and balancing the influence of different experts. For example, we have demonstrated serious challenges with the Gutenberg-Richter hypothesis for individual faults. UCERF3-TI is still an approximation of the system, however, and the range of models is limited (e.g., constrained to stay close to UCERF2). Nevertheless, UCERF3-TI removes the apparent UCERF2 over-prediction of M6.5-7 earthquake rates and also includes types of multi-fault ruptures seen in nature. Although UCERF3-TI fits the data better than UCERF2 overall, there may be areas that warrant further site-specific investigation. Finally, the supporting products may be of general interest, and we listed key assumptions and avenues for future model improvements in the report.

UCERF3-TD, The Long-Term, Time-Dependent Model

This model, which builds on UCERF-TI, includes long-term, time-dependent probabilities based on Reid’s elastic-rebound hypothesis, which posits that rupture likelihood drops on a fault after experiencing a large rupture and then builds back up as tectonic stresses re-accumulate with time. A new methodology was developed (Field, 2015) that solves applicability issues in the previous approach for un-segmented models. The new methodology also supports magnitude-dependent aperiodicity and accounts for the historic open interval on faults that lack a date-of-last-event constraint (Field and Jordan, 2015). Epistemic uncertainties are represented with a logic tree, producing 5,760 different forecasts. Results for a variety of evaluation metrics have been presented, including logic-tree sensitivity analyses and
comparisons to the previous model (UCERF2). For 30-year M≥6.7 probabilities, the most significant changes from UCERF2 are a threefold increase on the Calaveras fault and a threefold decrease on the San Jacinto fault. Such changes are due mostly to differences in the time-independent models (e.g., fault slip rates), with relaxation of segmentation and inclusion of multi-fault ruptures being particularly influential. In fact, some UCERF2 segments were simply too long to produce M≥6.7-sized events. Probability model differences are also influential, with the implied gains (relative to a Poisson model) being generally higher in UCERF3. Accounting for the historic open interval is one reason. Another is an effective 27% increase in the total elastic-rebound-model weight. The exact factors influencing differences between UCERF2 and UCERF3, as well as the relative importance of logic-tree branches, vary throughout the region, and they depend on the hazard metric of interest (e.g., M≥6.7 probability changes may not translate to hazard). This sensitivity, coupled with the approximate nature of the model, as well as known limitations, means the applicability of UCERF3 should be evaluated on a case-by-case basis. Overall, UCERF3 represents the best model currently available for forecasting California earthquakes. UCERF3-TD was been reviewed by our Scientific Review Panel, including the aforementioned supporting papers, and the main report was published in the Bulletin of the Seismological Society of America (Field et al., 2015). A USGS fact sheet was also published (http://pubs.usgs.gov/fs/2015/3009/), and we had a press release on the day the model went public (http://www.usgs.gov/newsroom/article.asp?ID=4146).

UCERF3-ETAS, Spatiotemporal Clustering for OEF

With the time-independent and time-dependent models published (described above), we have now turned our attention to including spatiotemporal clustering. In recognition that triggered events can be large and damaging, the ultimate goal is to deploy an Operational Earthquake Forecast (OEF) for California, now listed as one of the USGS's strategic-action priorities (http://pubs.usgs.gov/of/2012/1088; page 32). In short, OEF aims to provide real-time forecasts to help communities prepare for earthquakes. To this end, we have added an Epidemic Type Aftershock Sequence (ETAS) component to UCERF3 (UCERF3-ETAS). Most notably, our model represents a merging of ETAS with finite-fault based forecasts, as well as the inclusion of elastic rebound (both firsts, as far as we are aware). In fact, inclusion of elastic-rebound turns out to be critical in terms of getting spatiotemporal clustering statistic correct (otherwise ~85% of large triggered events simply re-rupture the same fault, which we don’t see in nature). UCERF3-ETAS is currently being “test-driven”. Our intent is to continue documenting the model and subjecting it to more rigorous testing (e.g., via CSEP) over the next year. Toward operationalization, the USGS and SCEC are co-funding a series of OEF-related workshops at the USGS Powell Center in Fort Collins, CO (https://powellcenter.usgs.gov). The first workshop, held in March 2015, addressed the “Potential Uses of OEF”, among other topics, including spatiotemporal clustering. In recognition that triggered events can be large and damaging, the ultimate goal is to improve UCERF3-TD, UCERF3-ETAS and any OEF-based workshops to ultimately produce a model, as well as known limitations, means the applicability of UCERF3 should be evaluated on a case-by-case basis.

Select Publications

- UCERF3-TI Open-File Report, including 20 appendices: http://pubs.usgs.gov/of/2013/1165/
Collaboratory for the Study of Earthquake Predictability (CSEP)

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

This past year's accomplishments include:

- Testing the USGS Hazard Model
- Retrospective evaluations of a rate-and-state Coulomb stress model
- Collaboration with CSEP Japan
- Collaboration with the Global Earthquake Model (GEM) Foundation
- Installing and Evaluating Global Earthquake Forecasting Models
- Retrospective Evaluation of Time-Dependent Earthquake Forecasting Models during the 2010-12 Canterbury, New Zealand, Earthquake Sequence
- Ensemble Modeling
- Development of External Forecasts and Predictions (EFP) Experiments

Testing the USGS Hazard Model

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

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

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

This study reveals a conservative (slight but statistically significant) hazard prediction for California, and a slight (but statistically significant) underprediction for CEUS. It also shows the most recent version of the hazard maps is the most consistent with the observed hazard, see Figure 3.

Retrospective evaluations of a rate-and-state Coulomb stress model

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

Collaboration with CSEP Japan

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

Collaboration with the Global Earthquake Model (GEM) Foundation

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

Installing and Evaluating Global Earthquake Forecasting Models

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

Retrospective Evaluation of Time-Dependent Earthquake Forecasting Models during the 2010-12 Canterbury, New Zealand, Earthquake Sequence

The M7.1 Darfield earthquake triggered a complex earthquake cascade that provides a wealth of new scientific data to study earthquake triggering and evaluate the predictive skill of short-term forecasting models. To provide maximally objective results, a global CSEP collaboration of scientists from the US, New Zealand and Europe conducted a retrospective evaluation of short-term forecasting models during this sequence. Their primary objective was to assess the performance of newly developed physics-based Coulomb/rate-state seismicity models and hybrid statistical/Coulomb models against observations and against extant Omori-Utsu clustering models such as the Epidemic-Type Aftershock Sequence (ETAS) model. In stark contrast to previous CSEP results, Werner et al (2015) observed that Coulomb/rate-state models and hybrid Coulomb/statistical models provided more informative forecasts during the sequence than statistical models over all tested forecast horizons (1-year, 1-month and 1-day). They also evaluated the effect of near-real-time data on the quality of the forecasts by using daily real-time catalog snapshots obtained by the CSEP New Zealand testing center during the sequence. Surprisingly, forecasts do not universally degrade in quality when real-time data is used as input; results are model-dependent.
RESEARCH ACCOMPLISHMENTS

Ensemble Modeling

CSEP is implementing strategies for combining multiple models for optimal forecasts. Both linear as well as multiplicative combination strategies are being pursued. Werner et al. (2015b) combined 1-day forecast models in California using Bayesian Model Averaging (BMA). Their preliminary results (Figure 2), which cover a one year period from 2012 to 2013, show that the optimal ensemble model is heavily dominated by just several models, while the weights of other models quickly diminish towards zero. Specifically, the models K3 and ETAS_K3 (which is itself an ensemble model) comprise the lion’s share of the weights for the ensemble model after several months of data.

Development of External Forecasts and Predictions (EFP) Experiments

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

Select Publications


Community Modeling Environment (CME)

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

This past year’s accomplishments include:

- Implemented the UCERF3 time-dependent model in OpenSHA leading to the release of UCERF3 time-dependent model in 2015 (Field et al., 2015). OpenSHA, a USGS and SCEC software development project since 2001, was recently approved by USGS for use producing national seismic hazard maps.
- Used a version of the SORD dynamic rupture software to simulate ruptures on rough faults (Shi, et al., 2013). These simulations produce ruptures with frequencies up to 10Hz. The group then used the output from these simulations as ruptures for high frequency deterministic ground motion simulations.
- Continued to develop deterministic ground motion software that models advanced physics of earthquakes. Both groups have developed versions of their codes that model frequency dependent Q. Roten et al. (2014) developed code that models plastic yielding. Jacobo’s group has performed simulations for Japan with water-based wave propagation, and simulations using topography (Restrepo et al., 2014).
- Developed GPU versions of earthquake wave propagation codes for both AWP-ODC and Hercules. The GPU version of the AWP-ODC code is about 4-6x faster than the CPU version (Poyraz et al., 2014), while the GPU version of the Hercules code is about 2x faster than the CPU version.
- Performed a series of validation studies that evaluate alternative SCEC CVMs at frequencies up to 5Hz. Taborda et al. (2014) evaluated CVM-S4, CVM-H, and CVM-S4.26 using Chino Hills and La Habra events. They also explored the impact of various GTL implementations, working to identify the one that performs best.
• Created 3D velocity models for central California. As part of SCEC’s Geoinformatics project, the group is improving these models using full 3D tomographic methods including both observed earthquakes and ambient noise (Lee et al., 2014). They have shown significant improvement in how well 3D ground motion simulations fit observed waveforms when results using the improved central California model are compared to results using the starting central California model.

• Produced a public release of the Unified Community Velocity Model (UCVM) software in March 2014, and a public release of the CVM-H velocity model in January 2015. The most recent UCVM software provides access to CVM-S4.26, includes functionality to add small-scale heterogeneities into output models, and provides an improved installation approach. The CVM-H release provides access to the CVM-H discussed in the 2015 USR publication (Shaw et al., 2015).

• Produced two public releases of the SCEC Broadband Platform in March 2014 (Maechling et al., 2015) and in March 2015. The released software was used in two scientific and engineering evaluations including the Southwest US Ground Motion Characterization SSHAC Level 3 Study and the PEER NGA-E project (Dreger et al., 2015).

• Produced two public releases of the SCEC Broadband Platform in March 2014 (Maechling et al., 2015) and in March 2015. The released software was used in two scientific and engineering evaluations including the Southwest US Ground Motion Characterization SSHAC Level 3 Study and the PEER NGA-E project (Dreger et al., 2015).

• Received 167M SUs and nearly 800TB of temporary storage on DOE INCITE computers in 2015, and received 12.2M node hours (~390M CPU hours) and nearly 2PB temporary data storage on NSF Blue Waters computer in 2015-2016. SCEC also received allocations on USC HPC and XSEDE computers in 2015.

• Jordan presented plenary research talks at both the 2014 Blue Waters Meeting and the 2014 Oak Ridge National Lab User Meeting, and Maechling presented at the 2015 Blue Waters Meeting.

• In 2014, used NSF Blue Waters to calculate four alternative southern California Physics-based PSHA CyberShake hazard models based on CVM-S4, CVM-H, BBP 1D model, and CVM-S4.26. These simulations integrated results from UCERF-2, BBP project, USR, full 3D tomography, and SCEC’s HPC GPU code development efforts.

• In 2015, used NSF Blue Waters and DOE Oak Ridge Leadership Computing (OLCF) Titan computers to calculate a 1Hz Los Angeles Region CyberShake hazard model. These calculations are being used to extend the CyberShake urban seismic hazard model for the Los Angeles region up to seismic frequencies as high as 0.5 Hz.

• Held two meetings to discuss CyberShake calculations in collaboration with ASCE and USGS engineering groups.

• Initiated a ground motion modeling validation activity that will simulate historic earthquakes at 4Hz and higher frequencies. Two groups have produced ground motion simulation results at 4Hz using alternative methods. Initial results are for simple velocity models, and will build complexity towards validation against observations.

• Continued to extend, enhance, and operate the CSEP testing center. Liukis has worked with CSEP scientists in order to create a series of new CSEP releases including January, April, and October 2014, and January and April 2015.

**SCEC Velocity Models**

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

**Hercules Code Development**

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

AWP Code Development

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

CyberShake Hazard Model

During year 3 of the SEISM project, we have continued development of the CyberShake Platform. CyberShake is capable of generating the very large suites of simulations (>108 synthetic seismograms) needed for physics-based probabilistic seismic hazard analysis (PSHA). A CyberShake PSHA Study 14.2, begun in February, 2014 during SEISM project year 2, used the UCERF2 earthquake rupture forecast and calculated hazard curves for 286 sites in southern California at frequencies up to 0.5 Hz for multiple 3D velocity models. Starting in April 2015, in SEISM Project year 3, SCEC’s research team used NCSA Blue Waters and OLCF Titan supercomputers to perform CyberShake Study 15.4 which was completed within 38 days, before end of May, 2015. This computation produced a Los Angeles region seismic hazard model, shown in Figure 8a-8b, that doubled the maximum seismic frequency represented in the Los Angeles urban seismic hazard model, from 0.5 Hz to 1 Hz. Seismic hazard curves were derived from large ensembles of seismograms at frequencies below this maximum for 336 surface sites distributed across the Los Angeles region. This new probabilistic model uses refined earthquake rupture descriptions through revisions to the conditional hypocenter distributions and the conditional slip distributions. This seismic hazard calculation used the CVM-S4.26 3D velocity model, which was validated and improved using ALCF Mira, as the best available southern California 3D velocity model. In order to complete our first 1Hz CyberShake simulations within weeks, rather than months, we divided the computational work between OLCF Titan and NCSA Blue Waters. We defined the distributed calculation using scientific workflows that automatically executed our parallel GPU intensive calculations on OLCF Titan, executed GPU parallel jobs and CPU-based post-processing on Blue Waters, and transferred scientific data products back to SCEC systems for visualization and archiving. Combined uses of both systems enable us to complete a CyberShake hazard model within the practical operational limits of our research group. Our previous CyberShake Study 14.3 used only Blue Waters. Adding OLCF Titan resources enabled us to complete a 1Hz CyberShake hazard model for the first time by proving timely access to large number of GPUs, and support for automated, distributed end-to-end scientific production simulation projects. The CyberShake 15.4 model provides new seismic hazard information of interest to broad impact customers of CyberShake, including seismologists, utility companies, and civil engineers responsible for California building codes.
Figure 47. (left): CyberShake Study 15.4 hazard map for 336 sites in the Los Angeles region. Map displays response spectral acceleration at 2 seconds period in units of surface gravitational acceleration (g) for a 2% probability of exceedance in 50 years. Warm colors represent areas of high hazard. (right): Ratio of CyberShake Study 15.4 spectral acceleration at 3 seconds period to values from our previous CyberShake Study 14.2. Red colors represent areas where Study 15.4 has higher hazard, green colors where it has lower values.

Select Publications

### 1. Improved Observations

**YEAR 1 (2012-2013)**

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]

**YEAR 2 (2013-2014)**

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]

**YEAR 3 (2014-2015)**

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]
YEAR 4 (2015-2016)
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]

YEAR 5 (2016-2017)
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

YEAR 1 (2012-2013)
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]

YEAR 2 (2013-2014)
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]

YEAR 3 (2014-2015)
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]

YEAR 4 (2015-2016)
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]

YEAR 5 (2016-2017)
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

YEAR 1 (2012-2013)
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]

YEAR 2 (2013-2014)
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]
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YEAR 3 (2014-2015)
Incorporate stochastic descriptions of small-scale heterogeneities into the upper layers of the CVMs and evaluate the importance of these heterogeneities in ground motion models. Develop and evaluate regional velocity models suitable for 3D ground motion modeling. Incorporate new information on fault complexity from SFSA projects into the CFM. [II, III, IV, VI]

YEAR 4 (2015-2016)
Develop a prototype CyberShake hazard model for the Los Angeles region based on extensions of UCERF2 and large suites of ground motion simulations up to 1 Hz calculated from improved CVMs. Provide interactive access to CyberShake simulation results. [II, III, IV, VI]

YEAR 5 (2016-2017)
Perform ground motion simulations of well recorded southern California earthquakes and apply goodness-of-fit measures to evaluate existing southern California CVMs using earthquake waveform data. Calculate southern California CyberShake hazard models based on extensions of UCERF3, southern California CVMs, and large suites of ground motion simulations up to 1 Hz. Provide interactive and programmable access to CyberShake results. [II, III, IV, VI]

4. Community Geodetic Model

4.1 YEAR 1 (2012-2013)
Obtain input from the SCEC community via a workshop in order to define the conceptual and geographic scope of the CGM, including the time-independent and time-dependent model components, the data to be assimilated into the model, and the type and spatial distribution of model output. [I, II, V]

YEAR 2 (2013-2014)
Start generating a unified GPS time series dataset for secular and transient deformation and compiling LOS velocity maps from available SAR catalogs. Establish strategy for estimating secular rate as well as temporally variable signals (e.g., seasonal, postseismic). Assess the feasibility and the potential benefits of incorporating additional datasets (e.g., strainmeter, LiDAR) into CGM. Specify the CGM output needed for input to the CSM and transient detection and begin providing preliminary datasets as available. [I, II, V]

YEAR 3 (2014-2015)
Assemble existing InSAR LOS velocity models and compile GPS solutions from multiple sources. Conduct comparisons among InSAR velocity models, among GPS solutions, and between InSAR and GPS LOS velocities to highlight areas of disagreement and determine likely sources of disagreement. Continue test exercise to identify best practices for InSAR time series analysis. [I, II, V]

YEAR 4 (2015-2016)
Develop consensus approach for InSAR LOS time series analysis constrained by GPS data. Identify appropriate methods for characterizing noise in GPS time series, estimating derived quantities from GPS time series, and interpolating GPS-derived quantities for use in InSAR analysis. Begin applying these approaches to GPS time series product to provide necessary GPS constraints for InSAR component of CGM. [I, II, V]

YEAR 5 (2016-2017)
Generate GPS-constrained InSAR LOS velocity product for all areas of southern California that are not decorrelated, GPS time series product comprised of southern California continuous and campaign data, GPS-derived secular rates, and GPS and InSAR LOS velocities interpolated to common geographic grid. Demonstrate time series analysis best practices by producing combined InSAR-GPS LOS time series for geographic region used in test exercise. Document best practices and a framework for incorporating future observations. [I, II, V]

5. Community Stress Model

YEAR 1 (2012-2013)
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]
YEAR 2 (2013-2014)
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]

YEAR 3 (2014-2015)
Quantitatively assess discrepancies between various stress models. Begin the process of identifying classes of alternative stress models or branches for the CSM. [I, II, IV]

YEAR 4 (2015-2016)
Populate branches of the CSM that represent alternative approaches, assumptions, and data. Develop new models of stress and stressing rate in the southern California lithosphere to address identified gaps in the CSM. Validate CSM models using relevant data and physical constraints. Begin applying results to the problem of discriminating between competing models of fault system loading. [I, II]

YEAR 5 (2016-2017)
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

YEAR 1 (2012-2013)
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]

YEAR 2 (2013-2014)
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]

YEAR 3 (2014-2015)
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]

YEAR 4 (2015-2016)
Through workshops and other collaborative mechanisms, begin to synthesize SFSA results for integration into SCEC products and activities and address SCEC science questions. [I-VI]

6.5 YEAR 5 (2016-2017)
Submit for publication synthesis studies of the SCEC4 SFSAs. Assess the utility of these syntheses in improving seismic hazard models for California. [I-VI]

7. Ground Motion Simulation Validation

7.1 YEAR 1 (2012-2013)
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]

7.2 YEAR 2 (2013-2014)
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
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Broadband Simulation Platform as a high-performance cyberfacility for ground motion simulation by outside research communities, including earthquake engineers. [III, VI]

YEAR 3 (2014-2015)

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]

YEAR 4 (2015-2016)

Extend validation studies to high-frequency ground motion simulations that incorporate improved representations of source physics, source complexity, attenuation, non-linear effects, and high-frequency scattering by small-scale heterogeneities. [VI]

YEAR 5 (2016-2017)

Through workshops and at the annual meeting, evaluate the work completed under the SFSA and develop synthesis reports on the utility of the work in improving seismic hazard models for California. [VI]

8. Source Modeling

YEAR 1 (2012-2013)

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]

YEAR 2 (2013-2014)

Develop numerical methods that simultaneously resolve fault zone processes and large-scale rupture, including fault interaction, complex geometries, heterogeneities 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]

YEAR 3 (2014-2015)

Verify numerical methods and assess physical formulations of fault geometries. Develop and calibrate parameterization of resistance mechanisms that are suitable for large scale models of dynamic ruptures, including interaction with fault roughness and damage-zone properties. Develop improved source inversion approaches with enhanced information extraction from high frequencies, including by integration with back-projection imaging. [III, VI]

YEAR 4 (2015-2016)

Validate implementation for more realistic models of fault resistance evolution through dynamic rupture code comparisons and work towards incorporating them into CFM-based simulations of earthquakes. Compare fault interaction patterns from dynamic rupture models to earthquake simulators. Generate a uniform database of kinematic source models of past earthquakes and extract constraints on mechanical fault properties. Develop fundamental insight into source inversion uncertainties. [III, VI]

YEAR 5 (2016-2017)

Develop realistic broadband kinematic source models of well-recorded earthquakes 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

YEAR 1 (2012-2013)
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)
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]

YEAR 3 (2014-2015)
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]

YEAR 4 (2015-2016)
Develop earthquake forecasting algorithms and evaluate their utility in deploying new versions of a Uniform California Earthquake Rupture Forecast. [II]

YEAR 5 (2016-2017)
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]


YEAR 1 (2012-2013)
n/a

10.2 YEAR 2 (2013-2014)
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)
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)
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)
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]
I. What's New This Year

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

1. 2016 is the final year of the SCEC4 research program. Proposals should not include plans that will involve multi-year efforts beyond January 2017, except for proposed CCSP-related research projects.

2. Develop methods for combining GPS and InSAR data in the CGM by characterizing seasonal/hydrologic/anthropogenic signals, accounting for earthquake effects as needed, and quantifying covariances in order to produce a reliable consensus model.

3. An explicit call for a synthesis of results at the Ventura and San Gorgonio Pass special fault study areas.

4. A call to develop improved representations of, and user interfaces to, the USR.

5. The need for develop and implement simulation methods for the modeling of bending faults and multi-segment ruptures.

6. A further request to compare and assess engineering metrics in ground motion validation.

7. A call to catalog the quality and supporting evidence for unique offsets, and to develop techniques to estimate slip distributions from field, LiDAR, and SfM datasets.

8. A call to test potential rupture histories using geometrically realistic fault configurations in dynamic rupture models.

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

II. Preamble

The Southern California Earthquake Center (SCEC) coordinates basic research in earthquake science using Southern California as its natural laboratory. SCEC emphasizes the connections between information gathering by networks of instruments, 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 resilience. The Center is a consortium of institutions that coordinates earthquake system science within Southern California. SCEC’s long-term goal is to understand how seismic hazards change across all time scales of scientific and societal interest, from millennia to seconds. The fourth phase of SCEC (SCEC4) moves earthquake science forward through highly integrated collaborations that are coordinated across scientific disciplines and research institutions and enabled by high-performance computing and advanced information technology. It focuses on six fundamental problems of earthquake physics:

1. Stress transfer from plate motion to crustal faults: long-term fault slip rates.
2. Stress-mediated fault interactions and earthquake clustering: evaluation of mechanisms.
6. Seismic wave generation and scattering: prediction of strong ground motions.

The six fundamental problems constitute the basic-research focus of SCEC. They are interrelated and require an interdisciplinary, multi-institutional approach. Interdisciplinary research initiatives focus on special fault study areas, the development of a community geodetic model for Southern California, and a community stress model. The latter is a new platform where the various constraints on earthquake-producing stresses are integrated. Improvements are also being made to SCEC’s unified structural representation and its statewide extensions.

Collaboration Plan. On February 1, 2012, the Southern California Earthquake Center (SCEC) transitioned from SCEC3 to SCEC4 under joint funding from NSF/EAR and the U.S. Geological Survey. SCEC4 is funded for the period February 2012 through January 2017. This document, referred to as the Collaboration Plan, solicits proposals from individuals and groups to participate in the SCEC4 research program.
III. Guidelines for Proposal Submission

A. Eligibility. Investigators or co-investigators with an overdue project report from prior SCEC-funded awards are not eligible to submit a new SCEC proposal.

Proposals can be submitted by eligible Principal Investigators from U.S. academic institutions and U.S. private corporations. For international institutions, funding will mainly be available for travel only to SCEC-sponsored meetings in the U.S. Due to limited funding, requests for travel to the SCEC Annual Meeting must be cost shared by the investigator’s institutions. Cost sharing must be described in the proposal.

B. Due Date. Friday, November 6, 2015, 5:00 pm PST. Late proposals will not be accepted.

C. Delivery Instructions. Proposals do not need to be formally signed by institutional representatives and should be for one year in duration, with a start date of February 1, 2016 and end date of January 31, 2017.

Proposals must be submitted online through the SCEC Proposal System (http://www.scec.org/scienceplan). A proposal submission will be considered complete only if all the following are received through the online system by the due date:

a. Investigator Profiles. Every investigator listed on the proposal must be registered in the SCEC Community Information System and his/her user profile updated with the current contact information. To update your profile log in at www.scec.org and click “My Account”. New investigators can register for a SCEC profile at www.scec.org/user/register.

b. Proposal Information. The Proposal Information information required for the Cover Page must be entered through the online submission system (see 5a below).

c. Budget Information. The Budget Information for each organization requesting funding must be entered through the online submission system and the budget tables with justifications must be included in the full proposal PDF (see below).

d. Current and Pending Support. The Current and Pending Support for each investigator requesting funding must be entered through the online submission system and be included in the full proposal PDF (see below).

e. Full Proposal PDF. The proposal file should include (a) Cover Page, (b) Project Plan, (c) Budget Information, and (d) Current and Pending Support. Proposal PDF file names should follow the SCEC proposal naming convention: PI last name followed by 2016 (e.g. Sleep2016.pdf). If more than one proposal is submitted per PI, then label as follows: Sleep2016_1.pdf, Sleep2016_2.pdf, etc.

i. Cover Page. On the cover page include the words “2016 SCEC Proposal”, Project Title, Principal Investigator(s), Institutional Affiliation(s), Amount of Request per Investigator, Total Amount of Request, and Proposal Category (see Section 5). Also list, in order of priority, three SCEC science objectives that your proposal addresses (e.g. 1a, 3c and 4b; see Section 8). If the proposal includes undergraduate student intern funding, please note this on the cover page.

ii. Project Plan. In 5 pages maximum (including figures), describe the technical details of the proposed project and how it relates to the short-term objectives outlined in the SCEC Research Priorities and Requirements (Section 8). If the proposed project is related to a previously funded SCEC project, the technical description must also include a 1-page summary of previous research results. The research summary is part of the 5-page limit. References are excluded from the 5-page limit. See note below on submission of collaborative proposals.

iii. Budget Information. Every proposal must include a budget table and budget justification for each institution requesting funding. The budgets should be constructed using NSF categories (http://www.nsf.gov/pubs/policydocs/pappguide/nsf15001/gpg_2.jsp#IIC2h). Under guidelines of the SCEC Cooperative Agreements and A-81 regulations, secretarial support and office supplies are not allowable as direct expenses.

iv. Current and Pending Support. Statements of current and pending support should be included for each Principal Investigator requesting funding on the proposal, following NSF guidelines (http://www.nsf.gov/pubs/policydocs/pappguide/nsf11001/gpg_2.jsp). Proposals without a current and pending support statement will not be reviewed.
D. **Principal Investigator Responsibilities.** By submitting a proposal, investigators agree to the following conditions:
   a. **Community Participation.** Principal investigators will interact with other SCEC scientists on a regular basis (e.g., by attending the annual meeting and presenting results of SCEC-funded research in the poster sessions, workshops and working group meetings) and to contribute data, analysis results, and/or models to the appropriate SCEC resource (e.g., Southern California Earthquake Data Center, database, community model).
   b. **Publications.** Principal investigators will register publications resulting entirely or partially from SCEC funding in the SCEC Publications System (www.scec.org/publications) to receive a SCEC contribution number. Publications resulting from SCEC funding should acknowledge SCEC and include the SCEC contribution number.
   c. **Project Report.** Principal investigators will submit a project report by the due date listed below.
      i. **Workshop Awards.** A report on results and recommendations of the workshop funded by SCEC is due no later than 30 days following the completion of the workshop. The report will be posted on the SCEC website as soon as possible after review by SCEC leadership.
      ii. **Annual Meeting Participation Awards.** A report on results and recommendations from travel funded by SCEC is due no later than 30 days following the completion of the travel.
      iii. **Research Awards.** Investigators funded by SCEC must submit a project report no later than March 15 (5:00 pm PST) in the year after the funding was received. Reports should be a maximum of 5 pages (including text and figures). Reports must include references to all SCEC publication during the past year (including papers submitted and in review) with their SCEC contribution number (see 2 above).

E. **Collaborative Proposals.** Collaborative proposals with investigators from the USGS are encouraged. USGS employees should submit their requests for support through USGS channels. Collaborative proposals involving multiple investigators and/or institutions are strongly encouraged. The lead investigator should submit only one proposal for the collaborative project. Information on all investigators requesting SCEC funding (including budgets and current support statements) must be included in the proposal submission. The project plan may include one extra page per investigator to report results of previously-funded, related research. Funding for Collaborative Proposals may be delayed or denied if any of the investigators has overdue project report(s) for prior SCEC funding.

F. **Budget Guidance.** Typical SCEC grants funded under this Science Collaboration Plan fall in the range of $10,000 to $35,000. This is not intended to limit SCEC to a fixed award amount, nor to a specified number of awards, rather it is intended to calibrate expectations for proposals written by SCEC investigators. **Field research investigations outside southern California will not be supported.**

G. **Award Procedures.** The Southern California Earthquake Center is funded by the National Science Foundation and the U.S. Geological Survey through a cooperative agreement with the University of Southern California. Additional funding for the SCEC core research program is provided by the Pacific Gas and Electric Company, geodesy royalty funds, the NSF SAVI supplement, and potentially other sources. All research awards will be funded as subawards or fixed priced contract from the University of Southern California. Workshop and travel award expenditures will be managed through the master SCEC account at USC. **SCEC4 will end on January 31, 2017. All funds awarded as a result of favorable review on a 2016 SCEC proposal must be spent by January 31, 2017. Extensions will not be possible on new or existing SCEC awards.**

### IV. SCEC Organization

A. **Mission and Science Goal.** SCEC is an interdisciplinary, regionally focused organization with a mission to:
   - Gather data on earthquakes in Southern California and other places where such data has direct relevance to southern California
   - 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

SCEC’s primary science goal is to develop a comprehensive, physics-based understanding of earthquake phenomena in Southern California through integrative, multidisciplinary studies of plate-boundary tectonics, active fault systems, fault-zone processes, dynamics of fault ruptures, ground motions, and seismic hazard analysis.

B. **Disciplinary Activities.** The Center sustains disciplinary science through standing committees in Seismology, Geodesy, Geology, and Computational Science. These committees are 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 support of disciplinary research and infrastructure. High-priority disciplinary activities are summarized in Section VIII.

C. **Interdisciplinary Focus Areas.** Interdisciplinary research is organized into 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). High-priority activities are listed for each of these interdisciplinary focus areas in Section IX.

D. **Technical Activity Groups.** Various groups of experts have formed Technical Activity Groups (TAGs) to verify the complex computer calculations needed for wave propagation and dynamic earthquake rupture simulations, to assess the accuracy and resolving power of source inversions, and to develop geodetic transient detectors and earthquake simulators. TAGs can be thought of as "mini-collaboratories" that pose well-defined "standard problems", encourage solution of these problems by different researchers using different algorithms or codes, develop a common cyberspace for comparing solutions, and facilitate meetings to discuss discrepancies and potential improvements.

E. **Communication, Education, and Outreach.** The theme of the CEO program during SCEC4 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:

- a. The **Implementation Interface** connects SCEC scientists with partners in earthquake engineering research, and communicates with and trains practicing engineers and other professionals.

- b. The **Public Education and Preparedness** thrust area educates people of all ages about earthquakes, and motivates them to become prepared.

- c. The **K-14 Earthquake Education Initiative** seeks to improve earth science education and school earthquake safety.

- d. Finally, the **Experiential Learning and Career Advancement** program provides research opportunities, networking, and more to encourage and sustain careers in science and engineering.

Opportunities for participating in the CEO program are described in Section XII.

V. **Proposal Categories**

A. **Data Gathering and Products.** SCEC coordinates an interdisciplinary and multi-institutional study of earthquakes in Southern California, which requires data and derived products pertinent to the region. Proposals in this category should address the collection, archiving and distribution of data, including the production of SCEC community models that are online, maintained, and documented resources for making data and data products available to the scientific community.

B. **Integration and Theory.** SCEC supports and coordinates interpretive and theoretical investigations on earthquake problems related to the Center’s mission. Proposals in this category should be for the integration of data or data products from Category A, or for general or theoretical studies. Proposals in Categories A and B should address one or more of the goals in Section 8, and may include a brief description (<200 words) as to how the proposed research and/or its results might be used in a special initiative (see Section 11) or in education and/or outreach (see Section XII).

C. **Special Fault Study Areas.** Special Fault Study Areas (SFSA) are integrated, multidisciplinary projects focused on areas of complex fault behavior within Southern California that would contribute to an improved understanding of earthquake processes through focused observation and modeling. There are two primary goals of SFSA, as articulated in the SCEC4 proposal: (1) To understand how fault complexities affect the propagation of earthquake ruptures and the heterogeneity of stress in the crust, and (2) To investigate how stress and microseismicity (including induced seismicity) affect the nucleation of large earthquakes. Tackling these problems will require the assembly of teams of researchers with diverse expertise. For example, research areas of fault complexity may seek to merge geological, seismological, and potential-field data to elucidate fault structure and paleoseismic history, integrate this information with geodetic data to derive fault loading and stressing rates, and apply dynamic rupture simulations to explore how earth structure and rupture history affect the potential sizes of future earthquakes. One of the anticipated advantages of SFSA is to leverage the impact of new and/or densified instrumentation. It is expected that collaborations built around SFSA will be open to the community, and generate open community data sets.

Two SFSA were established in SCEC4: the **San Gorgonio Pass** and **Ventura Area** SFSA. The SFSA website (http://www.scec.org/research/sfsa.html) contains a Science Plan and contact information for each area. The Science Plans identify key problems in earthquake science, and research targets, timelines for achieving goals,
and a discussion of integrative activities and broader impacts specific to each area. An updated science plan for the San Gorgonio Pass project, following from the 2014 Workshop, is available on the SFSA website. The SFSA Science Plans should be considered for proposal development.

**SCEC Proposals associated with a SFSA.** Each principal investigator should submit a separate, standard 5-page SCEC proposal that clearly ties the investigator’s work to the Science Collaboration Plan, provides additional background and details on the data collection and/or analyses to be completed by that investigator, and a budget for that investigator. Each investigator’s proposal will be evaluated separately through the standard SCEC proposal process (see Evaluation Process and Criteria). Workshop proposals for activities around the SFSA should be developed according to the standard workshop proposal process as outlined in the Science Collaboration Plan.

**D. Workshops.** SCEC participants who wish to convene a workshop between February 1, 2016 and January 31, 2017 should submit a proposal for the workshop in response to this Collaboration Plan. The proposed lead convener of the workshop must contact Tran Huynh (scecmeet@usc.edu) for guidance in planning the scope, budget and scheduling of the proposed workshop before completing the proposal submission. Note that workshops scheduled in conjunction with the SCEC Leadership Retreat (June) or SCEC Annual Meeting (September) are limited in number and may have further constraints due to space and time availability.

Workshops in the following topics are particularly relevant:

- Summarize collaborative research findings wrapping up research efforts for the current five-year SCEC program (2012-2017). In particular, interactive workshops that engage more than one focus and/or disciplinary group are strongly encouraged.
- Engaging earthquake engineers and other partner and user groups in SCEC-sponsored research.
- Participating in national initiatives such as EarthScope and the Advanced National Seismic System (ANSS).

**E. Communication, Education, and Outreach.** SCEC has developed a long-range CEO plan and opportunities for participation are listed in Section 12. Investigators who are interested in participating in this program should contact Mark Benthien (213-740-0323; benthien@usc.edu) before submitting a proposal.

**F. SCEC/SURE Intern Project.** Each year SCEC coordinates the Summer Undergraduate Research Experience (SCEC/SURE) Program, which supports undergraduate students working one-on-one with SCEC scientists on diverse research projects. Recruitment for SURE intern mentors begins in the fall. Potential research projects are published on the SCEC Internships website (http://www.scec.org/internships), where undergraduate students may apply and identify their preferred projects. Interested SCEC scientists are encouraged to include support for an undergraduate SURE intern in their SCEC proposals. SURE mentors are required to provide at least $2500 of the $5000 intern stipend. Mentor contributions can come from any source, including SCEC-funded research projects. Questions about the SCEC/SURE Program should be referred to Robert de Groot (degroot@usc.edu).

**G. SCEC Annual Meeting participation.** This category includes proposals by investigators requesting travel funding to participate in the SCEC Annual Meeting only. Investigators who are (a) new to SCEC who would benefit from exposure to the SCEC Annual Meeting in order to fine-tune future proposals and/or (b) already funded on study projects outside of SCEC that would be of interest to the SCEC community are encouraged to apply. Due to limited funding, requests for travel to the SCEC Annual Meeting must be cost shared by the investigator’s institutions. **Proposals will not be accepted under the "new to SCEC" element for 2016 (the last year of SCEC4).**

**VI. Evaluation Process and Criteria**

**A.** Proposals should be responsive to the Collaboration Plan. A primary consideration in evaluating proposals will be how directly the proposal addresses the main objectives of SCEC. Important criteria include (not necessarily in order of priority):

1. Scientific merit of the proposed research,
2. Competence and performance of the investigators, especially in regard to past SCEC-sponsored research,
3. Priority of the proposed project for short-term SCEC objectives as stated in the Collaboration Plan,
4. Promise of the proposed project for contributing to long-term SCEC goals,
5. Commitment of the principal investigator and institution to the SCEC mission,
6. Value of the proposed research relative to its cost,
7. Ability to leverage the cost of the proposed research through other funding sources,
8. Involvement of students and junior investigators,
9. Involvement of women and underrepresented groups, and
10. Innovative or "risky" ideas that have a reasonable chance of leading to new insights or advances in earthquake physics and/or seismic hazard analysis.

Proposals may be strengthened by describing:

1. Collaboration within or between disciplinary and/or focus groups; with modeling and/or data gathering activities; and with engineers, government agencies, and other organizations.
2. Leveraging additional resources from other agencies, your institution, and by expanding collaborations.
3. Development and delivery of products, such as community research tools, software, models, databases, and communication and educational materials.
4. Educational opportunities (e.g. graduate student research assistantships, undergraduate summer and year-round internships (funded by the project), K-14 educator and student activities, and participation in data collection).

B. All research proposals will be evaluated by the appropriate disciplinary committees and focus groups, the Science Planning Committee, and the Center Director. CEO proposals will be evaluated by the CEO Associate Director and the Center Director.

C. The Science Planning Committee is chaired by the SCEC Co-Director and Planning Committee Vice-Chair, and includes the chairs of the disciplinary committees, focus groups, and special projects. It is responsible for recommending a balanced science budget to the Center Director.

D. Recommendations of the Science Planning Committee will be combined into an annual spending plan and forwarded to the SCEC Board of Directors for approval.

E. Final selection of research projects will be made by the Center Director, in consultation with the Board of Directors.

F. The annual SCEC Science Collaboration Plan, and associated budget, requires final review and approval by the NSF and USGS.

G. The review process should be completed and applicants notified circa March 2016.

VII. Coordination of Research between SCEC and USGS-EHRP

Earthquake research in Southern California is supported both by SCEC and by the USGS Earthquake Hazards Program (EHP). EHP’s mission is to provide the scientific information and knowledge necessary to reduce deaths, injuries, and economic losses from earthquakes. Products of this program include timely notifications of earthquake locations, size, and potential damage, regional and national assessments of earthquakes hazards, and increased understanding of the cause of earthquakes and their effects. EHP funds research via its External Research Program, as well as work by USGS staff in its Pasadena (California), Menlo Park (California), Vancouver (Washington), Seattle (Washington), and Golden (Colorado) offices. The EHP also directly supports SCEC.

SCEC and EHP coordinate research activities through formal means, including USGS membership on the SCEC Board of Directors and a Joint Planning Committee, and through a variety of less formal means. Interested researchers are invited to contact Dr. Rob Graves, EHP coordinator for Southern California, or other SCEC and EHP staff to discuss opportunities for coordinated research.

The USGS EHP supports a competitive, peer-reviewed, external program of research grants that enlists the talents and expertise of the academic community, state and local governments, and the private sector. The investigations and activities supported through the external program are coordinated with and complement the internal USGS program efforts. This program is divided into six geographical/topical 'regions', including one specifically aimed at Southern California earthquake research and others aimed at earthquake physics and effects and at probabilistic seismic hazard assessment (PSHA). The Program invites proposals that assist in achieving EHP goals.

The EHP web page, http://earthquake.usgs.gov/research/external, describes program priorities, projects currently funded, results from past work, and instructions for submitting proposals. The annual EHP external funding cycle has different timing than SCEC’s, with the USGS RFP due out in February and proposals due in May. Interested PIs are encouraged to contact the USGS regional or topical coordinators for Southern California, Earthquake Physics and Effects, and/or National (PSHA) research, as listed under the "Contact Us" tab.

The USGS internal earthquake research program is summarized at http://earthquake.usgs.gov/research/topics.php.
VIII. SCEC4 Fundamental Problems of Earthquake Physics: Research Priorities and Requirements

The six fundamental problems constitute the basic-research focus of SCEC4. They are listed in the preamble and expanded in detail below. They are interrelated and require an interdisciplinary, multi-institutional approach. Interdisciplinary research initiatives focus on special fault study areas, the development of a community geodetic model for Southern California, and a community stress model. The latter is a new platform where the various constraints on earthquake-producing stresses can begin to be integrated. In addition, improvements are to be made to SCEC’s unified structural representation and its statewide extensions.

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

Priorities and Requirements

1a. Mapping and studying faults in Southern California to determine slip rates for faults at multiple time scales and characterize fault zone properties for which brittle/ductile transitions have been exposed by detachment faulting or erosion.

1b. Focused laboratory, numerical, and geophysical studies of the character of the lower crust, its rheology, stress state, and expression in surface deformation. We will use surface-wave dispersion to improve depth resolution relative to teleseismic studies.

1c. Regional searches for seismic tremor at depth in Southern California to observe if (some) deformation occurs by slip on discrete structures at depth.

1d. Development of a Community Geodetic Model (CGM) for California, in collaboration with the UNAVCO community, to constrain long-term deformation and fault-slip models.

1e. Combined modeling/inversion studies to interpret GPS and InSAR geodetic results on postseismic transient deformation without traditional simplifying assumptions.

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

Priorities and Requirements

2a. Improvement of earthquake catalogs, including non-point-source source descriptions, over a range of scales. Traditional aftershock catalogs can be improved through better detection of early aftershocks. Long-term (2000-yr) earthquake chronologies, including slip-per-event data, for the San Andreas Fault system and other major faults are necessary to constrain long-term recurrence behavior.

2b. Improved descriptions of triggered earthquakes. While temporal earthquake clustering behavior (Omori’s Law) is well known, the spatial and coupled temporal-spatial behavior of triggered earthquakes, potentially key diagnostics, are not well constrained.

2c. Lowered thresholds for detecting aseismic and infraseismic transients, and improved methods for separating triggering by aseismic transients from triggering by other earthquakes.

2d. Development of a Community Stress Model (CSM) for Southern California, based on merging information from borehole measurements, focal mechanisms, paleo-slip indicators, observations of damage, topographic loading, geodynamic and earthquake-cycle modeling, and induced seismicity. Use of seismicity to constrain CSM and investigate how stress may control earthquake clustering and triggering. Collaboration with other organizations in fault-drilling projects for in situ hypothesis testing of stress levels.

2e. Development of physics-based earthquake simulators that can unify short-term clustering statistics with long-term renewal statistics, including the quasi-static simulators that incorporate laboratory-based nucleation models.

2f. Development of a better understanding of induced seismicity, specifically induced by geothermal power production in the Salton Sea area, which warrant study as potential hazards.

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

Priorities and Requirements

3a. Analysis of laboratory experiments on fault materials under appropriate confining stresses, temperatures, and fluid contents/pressures through targeted experiments in collaboration with rock mechanics laboratories.

3b. Observations of geological, geochemical, paleo-temperature, microstructural, and hydrological indicators of specific resistance mechanisms that can be measured in the field. In particular, evidence of thermal decomposition in exhumed fault zones. Collaboration with other organizations involved in fault-drilling projects to measure observables for constraining coseismic resistance mechanisms, such as the temperature on faults before and after earthquakes.
3c. Formulation of theoretical and numerical models of specific fault resistance mechanisms for seismic radiation and rupture propagation, including interaction with fault roughness and damage-zone properties.

3d. Development of parameterized fault rheologies suitable for coarse-grained numerical modeling of rupture dynamics and for simulations of earthquake cycles on interacting fault systems. (Currently, the constitutive laws for co-seismic slip are often represented as complex coupled systems of partial differential equations, contain slip scales of the order of microns to millimeters, and hence allow detailed simulations of only small fault stretches.)

3e. Construction of computational simulations of dynamic earthquake ruptures to help constrain stress levels along major faults, to help explain the heat-flow paradox, and to help us understand extreme slip localization, the dynamics of self-healing ruptures, and the potential for repeated slip on faults during earthquakes.

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

Priorities and Requirements

4a. Detailed geologic, seismic, geodetic, and hydrologic investigations of fault complexities at Special Fault Study Areas and other important regions.

4b. Investigations of along-strike variations in fault roughness and complexity (including slip rate and geometry) as well as the degree of localization and damage perpendicular to the fault.

4c. Improvements to the CFM using better mapping, including LiDAR, and precise earthquake relocations. We will also extend the CFM to include spatial uncertainties and stochastic descriptions of fault heterogeneity.

4d. Use of special fault study areas to model stress heterogeneities both deterministically and stochastically. We will integrate the results of these special studies into the CSM.

4e. Use of earthquake simulators and other modeling tools, together with the CFM and CSM, to quantify how large-scale fault system complexities govern the probabilities of large earthquakes and rupture sequences.

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

Priorities and Requirements

5a. Improvement of detection and mapping of the distribution of tremor across southern California by applying better instrumentation and signal-processing techniques to data collected in the special study areas, such as those outlined in the proposal.

5b. Application of geodetic detectors to the search for aseismic transients across southern California. We will use the CGM as the time-dependent geodetic reference frame for detecting geodetic anomalies.

5c. Collaboration with rock mechanics laboratories on laboratory experiments to understand the mechanisms of slow slip and tremor.

5d. Development of physics-based models of slow slip and tectonic tremor. We will constrain these models using features of tremor occurrence and its relationship to seismicity, geodetic deformation, and tectonic environment, as well as laboratory data.

5e. Use of physics-based models to understand how slow slip events and tremor activity affect earthquake probabilities in Southern California.

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

Priorities and Requirements

6a. Development of a statewide anelastic Community Velocity Model (CVM) that can be iteratively refined through 3D waveform tomography. Integration of new data (especially the Salton Sea Imaging Project) into the existing CVMs with validation of improvements in the CVMs. We will extend current methods of full-3D tomography to include ambient-noise data and to estimate seismic attenuation, and we will develop methods for estimating and representing CVM uncertainties.

6b. Modeling of ruptures that includes realistic dynamic weakening mechanisms, off-fault plastic deformation, and is constrained by source inversions. The priority is to produce physically consistent rupture models for broadband ground motion simulations of hazard-scale ruptures, such as the ruptures defined in UCERF3. An important issue is how to treat multiscale processes; specifically, does off-fault plasticity regularize the Lorentzian scale collapse associated with strong dynamic weakening? If not, how can adaptive meshing strategies be most effectively used to make full-physics simulations feasible?
6c. Development of stochastic representations of small-scale velocity and attenuation structure in the CVM for use in modeling high-frequency (> 1 Hz) ground motions. We will test the stochastic models with seismic and borehole logging data and evaluate their transportability to regions of comparable geology.

6d. Measurement of earthquakes with unprecedented station density using emerging sensor technologies (e.g., MEMS). The SCEC Portable Broadband Instrument Center will work with IRIS to make large portable arrays available for aftershock and flexible array studies.

6e. Measurement of earthquakes with unprecedented station density using emerging sensor technologies (e.g., MEMS). The SCEC Portable Broadband Instrument Center will work with IRIS to make large portable arrays available for aftershock and flexible array studies.

IX. Disciplinary Activities

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

A. Seismology

Objectives

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

Example Research Strategies

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

Priorities for Seismology

5. **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.
6. **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.

7. **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.

8. **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:

9. **Contribute to the development of a Community Geodetic Model (CGM).** The goal of this effort is to develop a crustal motion model consisting of velocities and time series for southern California that leverages the complementary nature of GPS and InSAR observations. This will require development of optimal methods for combining GPS and InSAR data, characterizing seasonal/hydrologic/anthropogenic signals, accounting for earthquake effects as needed, and quantifying covariances in order to produce a reliable consensus model. Proposals should demonstrate coordination with the current activities and established timeline of the CGM project. 2016 work should focus on completion of the CGM merged GPS time series solution, estimation of velocities from these time series, and development of InSAR velocity maps for the southern California region. Technique development to prepare for full utilization of legacy and newly available SAR data for time series analysis and identification of optimal approaches for mitigating temporally and spatially correlated noise in GPS or InSAR time series are also particularly encouraged.

10. **Analysis of geodetic data to address specific SCEC4 research targets.** Studies addressing geodetic/geologic slip rate discrepancies, assessing the role of lower crust/upper mantle processes in driving fault loading, developing more physically realistic deformation models, providing input to the development of Community Stress Models, and constraining physics-based models of slow slip and tremor are encouraged, as are studies that pursue integrated use of geodetic, geologic, seismic, and other observations targeting special fault study areas. Proposals that include collection of new data should explicitly motivate the need for such efforts. In compliance with SCEC’s data policy, data collected with SCEC funding must be made publicly available upon collection by archiving at UNAVCO (contact Jessica Murray (jrmurray@usgs.gov) for further information on archiving). Annual reports should include a description of archive activities.

11. **Improve our understanding of the processes underlying detected transient deformation signals and/or their seismic hazard implications through data collection and development of new analysis tools.** Work that advances methods for near-real-time transient detection and applies these algorithms within the SCEC transient detection testing framework to search for transient deformation in southern California is encouraged. Approaches that can be automated or semi-automated are the highest priority, as is their inclusion in the testing framework now in place at SCEC (contact Rowena Lohman (rbl62@cornell.edu) for details on how to address this in the proposal). Extension of methods to include InSAR and strainmeter data and, when available, the CGM is also a priority. Work that develops means for incorporating the output of transient detection algorithms into time-dependent earthquake forecasting is encouraged.

12. **Develop and apply algorithms that use real-time high-rate GPS data in concert with seismic data for improved earthquake response.** We encourage proposals that explore new approaches for assimilating real-time high-rate GPS, seismic data, and other potential observations into efforts to rapidly characterize earthquake sources. Also of interest is the development and application of rigorous retrospective and prospective tests to evaluate algorithm performance.
C. Earthquake Geology

Objectives

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

Example Research Strategies

- Gathering well-constrained slip-rates on the southern California fault system, with emphasis on major structures (Problem 1).
- Mapping and analysis of fault-zone properties where the seismogenic zone or brittle-ductile transition has been exhumed (Problems 1a, 3b).
- Paleoseismic documentation of earthquake ages and displacements, with emphasis on long paleoseismic histories, slip-per-event, and slip-rate histories, including a coordinated effort to develop slip rates and slip-per-event history of southern San Andreas fault system (Problem 2a, in collaboration with the SoSAFE focus group).
- Improve understanding of the architecture and tectonic activity of the Ventura and San Gorgonio Pass special fault study areas (Problem 4a), such as using B4 and other lidar data sets to better define fault traces, fault activity, and geologic structure.
- Improve the statewide community fault model in areas of inadequate fault representations or where new data is available, such as using high-resolution topographic data sets to better define fault traces, spatial uncertainty, and stochastic heterogeneity of fault geometry (Problem 4c).
- Quantifying along-strike variations in fault roughness, complexity, strain localization, and damage in relation to the rupture propagation processes, including evaluation of the likelihood of multi-fault ruptures (Problem 4b).
- Validation of ground motion prediction through analysis and dating of precariously balanced rocks and other fragile geomorphic features (Problem 6).

Geochronology Infrastructure

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

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

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

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

**Priorities for Earthquake Geology**

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

**D. Computational Science**

**Objectives**

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

**Computational Requirements**

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

1. The scientific goal of your computational research
2. The scientific software you plan to use or develop
3. A list of computations you plan to run
4. The estimated computing time and/or storage space you believe will be required
5. 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/allocation).

**Example Research Strategies**

13. Porting and optimization of HPC codes, including high-order algorithms, required to reach SCEC research goals, and utilize hybrid programming models, combined with shared memory directives (e.g., OpenMP) and/or accelerator-programming APIs (e.g, OpenACC, pthreads) and languages (e.g. OpenCL, CUDA) to take advantage of advanced multi-core, many-core and/or next-generation homogeneous/heterogeneous architectures.
14. 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).
15. 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.
16. Tools and algorithms for uncertainty quantification in large-scale inversion and forward-modeling studies, for managing I/O, data repositories, workflow and data analysis, fault tolerance, and advanced seismic data format.
17. 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**

1. Seismic wave propagation
   a. Validate SCEC community velocity models.
   b. Develop high-frequency simulation methods and investigate the appropriate upper frequency limit of deterministic ground motions.
   c. 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.
   d. Develop wave propagation incorporating more advanced media response, including inelastic material response and scattering by small-scale heterogeneities and topography.

2. Tomography
   a. Assimilate regional waveform data into the SCEC community velocity models.

3. Rupture dynamics
   a. 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.
   b. Evaluate different representations of earthquake source complexity, including stress heterogeneity, variability in frictional properties, fault geometrical complexity, and dynamic rupture propagation in heterogeneous media.

4. Scenario earthquake modeling
   a. Model a suite of scenario ruptures, incorporating material properties and fault geometries from the unified structural representation projects.
   b. Isolate causes of amplified ground motions using adjoint-based sensitivity methods.

5. Data-intensive computing
   a. 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.

6. Engineering applications
   a. Investigate the implications of ground motion simulations results by integrating observed and simulated ground motions with engineering-based building response models. Validate the results by comparison to observed building responses.
   b. Facilitate the “rupture-to-rafters” modeling capability to transform earthquake risk management into a Cyber Science and Engineering discipline.

**X. Interdisciplinary Focus Areas**

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

**A. Unified Structural Representation (USR)**

The Unified Structural Representation group develops three-dimensional models of active faults and earth structure (velocity, density, attenuation, etc.) for use in fault-system analysis, ground-motion prediction, and hazard assessment. This year's efforts will focus on (1) making improvements to existing community models (CVM, CFM) that will facilitate their uses in SCEC science, education, and post-earthquake response planning; (2) developing methods to represent smaller scale features, such as stochastic variations of seismic velocities and attenuation structure; and (3) improving IT tools that are used to deliver the USR components to the user community.
Priorities for FARM will contribute to our understanding of earthquakes in the Southern California fault system. Properties, geometric irregularities and heterogeneities in stress and strength over multiple length and time scales, and that mission through field, laboratory, and modeling efforts directed at characterizing and understanding the influence of material behavior through interdisciplinary investigation of the special fault study areas. We encourage researchers to address this fundamental problems in earthquake physics defined in the SCEC4 proposal and enhance understanding of fault system propagation, and arrest of dynamic earthquake rupture. We specifically solicit proposals that will contribute to the six

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

B. Fault and Rupture Mechanics (FARM)

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

Priorities for FARM

- Investigate the importance of different dynamic weakening and fault healing mechanisms, and the slip and time scales over which these mechanisms operate (3a, 3b, 3c, 3e).

- Determine the properties of fault cores and damage zones (1a, 1b, 3a, 3b, 4a, 4b) and characterize their variability with depth and along strike (1a, 1b, 4a, 4b) to constrain theoretical and laboratory studies, including width and particle composition of actively shearing zones, signatures of temperature variations, extent, origin and significance of on- and off-fault damage, healing, and poromechanical behavior.

- Determine the relative contribution of on- and off-fault damage to the total earthquake energy budget (3c, 4a, 4b), and the absolute levels of local and average stress (3e). Collaboration with the Community Stress Model (CSM) TAG is encouraged.

- Develop, test, and apply innovative source-inversion strategies to image the space-time rupture evolution of earthquakes reliably, propose source-inversion methods with minimal assumptions, and provide robust uncertainty quantification of inferred source parameters; propose and develop new source-inversion benchmarks, and generate synthetic data of various types (seismic, static, far-field, near-field) in cooperation with other SCEC groups; collaboration with the Source Inversion Validation (SIV) TAG is encouraged.

- Develop realistic descriptions of heterogeneity in fault geometry, rock properties, stresses and strains, and tractable ways to incorporate heterogeneity in numerical models of single dynamic rupture events and multiple earthquake cycles (3e, 3f, 4b, 4d, 6b). Test dynamic rupture modeling that incorporates these heterogeneities first by verifying the computational algorithms with benchmark exercises of the Dynamic Rupture Code Verification TAG, then by comparing the results with geological and geophysical observations.

- Understand the significance of fault zone characteristics and processes for fault dynamics (3a, 3b, 3c) and formulate constitutive laws for use in dynamic rupture models (3d).

- **Community Velocity Model (CVM).** Improve the current SCEC CVMs, with emphasis on more accurate representations of Vp, Vs, density, attenuation, and basin structure. Incorporate new data (NOTE: May choose to highlight specific items following discussions at the Annual Meeting.) into the CVMs with validation of improvements for ground-motion prediction. Perform waveform and geophysical inversions for evaluating and improving the CVMs. Develop and apply procedures (i.e., goodness-of-fit measures) for evaluating updated models against observations (e.g., waveforms, gravity, etc) to discriminate among alternatives and quantify model uncertainties.

- **Community Fault Model (CFM).** Improve and evaluate the CFM and statewide CFM (SCFM), placing emphasis on defining the geometry of major faults that are incompletely, or inaccurately, represented in the current model, and on faults of particular concern, such as those that are located close to critical facilities. Refine representations of the linkages among major fault systems. Extend the CFM to include spatial uncertainties and stochastic descriptions of fault geometry. Evaluate the new CFM version (5.0) with data (e.g., seismicity, seismic reflection profiles, geologic slip rates, and geodetic displacement fields) to discriminate among alternative models. Update the CFM-R (rectilinear fault model) to reflect improvements in the CFM. Improve the statewide CFM in regions outside the SCEC CFM in coordination with the appropriate agencies (e.g., USGS for central and northern CA).

- **Unified Structural Representation (USR).** Develop better IT mechanisms for delivering the USR, particularly the CVM parameters and information about the model's structural components, to the user community for use in generating and/or parameterizing numerical models. Develop improved representations of and user interfaces to the CVMs in support of additional features, including characterization of uncertainties and small-scale features, and scalable computing (laptops to large scale clusters). Develop new tools and formats for making the CFM geometries and properties available to the user community. Generate maps of geologic surfaces compatible with the CFM that may serve as strain markers in crustal deformation modeling and/or property boundaries in future iterations of the USR. These efforts should be coordinated with SCEC CME efforts.
• 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 Earthquake Predictability (CSEP), see Section 11 to learn of its capabilities. Successful investigators proposing to utilize CSEP would be funded via core SCEC funds to adapt their prediction methodologies to the CSEP framework, to transfer codes to the externally accessible CSEP computers, and to be sure they function there as intended. Subsequently, the codes would be moved to the identical externally inaccessible CSEP computers by CSEP staff who will conduct tests against a variety of data as outlined in the CSEP description.

Priorities for EFP

- Support the development of statistical or physics-based real-time earthquake forecasts.
- Utilize and/or evaluate the significance of earthquake-cycle simulator results. See sections on WGCEP and CSEP for more details.
- Study how to properly characterize and estimate various earthquake-related statistical relationships (including the magnitude distribution, Omori law, aftershock productivity, etc.).
- Focus on understanding patterns of seismicity in time and space, as long as they are aimed toward
- 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 and higher) approaches. This work could include implementation of simulation methodologies onto the Broadband Simulation Platform, or implementation of more efficient approaches in wave and rupture propagation schemes (in collaboration with CME), allowing accurate simulation of higher frequency ground motion in models with lower seismic wave speeds (e.g. in sedimentary basins). Determine spectral and spatial limits for simulating deterministic high-frequency wave propagation.
- Waveform modeling of past earthquakes to validate and/or refine the structure of the Community Velocity Models (CVMs) (in collaboration with USR). This includes exploration and validation of the effects of statistical models of structural and velocity heterogeneities on the ground motion, the significance of the lowest (S-wave) velocities as frequencies increase, the significance of including geotechnical layers (GTLs) in the CVMs, and development and validation of improved (possibly frequency-dependent) attenuation (intrinsic or scattering) models in physics-based simulations (in collaboration with USR). Quantify uncertainty in the CVM structure and
its impact on simulated ground motions. Note that the Central California Seismic Project (CCSP, see below) targets this goal specifically for Central California.

- Develop and implement simulation methods for the modeling of bending faults and multi-segment ruptures. The highest priority need is for kinematic rupture generators for implementation on the Broadband Platform (BBP). Proposals are requested for 1) including the software modeling capability itself and 2) scientific research to inform input parameters such as the timing of ith segment rupture, moment distribution on segments and so on (see CME section on this RFP for related efforts).

- Develop and implement methods for computing and storing 3D Green's functions (GFs) for use in the Broadband Platform. Proposals for both source- and site-based GFs are solicited (see CME section on this RFP for related efforts).

- Develop and implement new models or implement existing models for frequency-dependent site effects into the SCEC BroadBand Platform (site effects module). Because site-specific profiles are rarely available for large scale simulations, the priority will be given to models that can work with generic site profiles or that use simplified site factors (e.g. empirical Vs30-based factors for example). Models that require a site profile as input will also be considered. The site effects models are to be applied so as to produce time series that include site effects.

- Incorporate off-fault plasticity into physics-based ground motion simulation methodologies, quantify uncertainties, and validate the effects using observations from large earthquakes.

- Development of more realistic implementations of dynamic or kinematic representations of fault rupture, including simulation of higher frequencies (up to 10+ Hz). Possible topics include simulation of dynamic rupture on nonplanar faults and studying the effects of fault roughness on the resulting synthetic ground motion, and development of kinematic representations based on statistical models constrained by observed and/or dynamic ruptures. This research could also include the examination of current source-inversion strategies and development of robust methods that allow imaging of kinematic and/or dynamic rupture parameters reliably and stably, along with a rigorous uncertainty assessment. Close collaboration with the Technical Activity Group (TAG) on Source Inversion Validation (SIV) is encouraged. Construct Equivalent Kinematic Source (EKS) models that approximate the effects of near-fault nonlinearity in a linear scheme and test the EKS model in CyberShake. Projects that involve dynamic earthquake rupture simulations should involve preliminary code testing using benchmarks developed by the Dynamic Rupture Code Verification Technical Activity Group (TAG).

- Investigate the importance of including 3D basin effects on ensemble averaged long-period ground motions on the BroadBand Platform, e.g., by comparing ensemble averages of long-period (<~1Hz) ground motions computed in 1D and 3D crustal models for events included in the GMSV.

- Verification (comparison against theoretical predictions) and validation (comparison against observations) of the simulation methodologies with the objective to develop robust and transparent simulation capabilities that incorporate consistent and accurate representations of the earthquake source and three-dimensional velocity structure. Compare and assess engineering metrics in ground motion validation. Comparison of synthetic ground motions from deterministic and stochastic approaches to data for overlapping bandwidths. Close collaboration with the Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV) is encouraged.

It is expected that the products of the Ground-Motion Prediction group will have direct application to seismic hazard analysis, both in terms of characterizing expected ground-motion levels in future earthquakes, and in terms of directly interfacing with earthquake engineers in the analysis of built structures. Activities within the Ground-Motion Prediction group will be closely tied to several focus areas, including the GMSV TAG, with particular emphasis on addressing ground motion issues related to seismic hazard and risk (see EEII below).

F. Southern San Andreas Fault Evaluation (SoSAFE)

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

Priorities for SoSAFE

- Lengthen existing paleoearthquake chronologies that will improve understanding of the last 2000 years of this fault system. This includes radiocarbon dating and analysis of stratigraphic evidence of paleoearthquakes.

- Determine slip rates at many time scales, so that possible system-level interaction can be documented.
• Obtain the best possible measurements of geomorphic slip distributions from past earthquakes by developing field, LiDAR, or SFM datasets and validate the different measures or test uncertainties determined by each method. Catalogue the quality and supporting evidence for unique offsets, develop techniques to estimate slip distributions from these datasets.

• Explore chronometric, geomorphic, or statistical approaches to linking geomorphic offsets to dated paleoearthquakes.

• Use novel methods for estimating slip rates from geodetic data.

• Methodologies for integrating paleoseismic (including geomorphic measures of slip) and geologic data into rupture histories. For example, studies may improve or inform interactions between SoSAFE results and scenario rupture modeling or rupture forecasts, test rupture histories using geometrically realistic fault configurations in dynamic rupture models.

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

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

G. Earthquake Engineering Implementation Interface (EEII)

The purpose of the Earthquake Engineering Implementation Interface is to create and maintain collaborations with research and practicing engineers, much as the Seismic Hazard and Risk Analysis focus group did during SCEC3. These activities may include ground motion simulation validation, rupture-to-rafters simulations of building response as well as the end-to-end analysis of large-scale, distributed risk (e.g., ShakeOut-type scenarios). Our goal of impacting engineering practice and large-scale risk assessments 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 2016. Interested researchers are invited to visit the GMSV TAG wiki (http://collaborate.scec.org/gmsv/) and contact Dr. Nicolas Luco (nluco@usgs.gov) and Dr. Sanaz Rezaeian (srezaeian@usgs.gov) to discuss opportunities for coordinated research. Note that any PIs funded to work on GMSV-related projects will become members of the TAG and will be required to coordinate with each other, in part via participation in monthly conference calls and annual workshops/meetings.

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

• Develop validated and efficient methods for either i) adjusting ground motion time series simulated by the SCEC Broadband Platform to account for the local site conditions at historical earthquake stations; or ii) deconvolving recorded ground motion time series to a reference site condition corresponding to that for simulated ground motions.

• Develop and demonstrate validation methodologies that use common models of structures of interest (e.g. multi-degree-of-freedom nonlinear models of building or geotechnical systems) for particular engineering applications. Such research must be coordinated with the validation efforts of the Software Environment for Integrated Seismic Modeling (SEISM) project.

• Develop and demonstrate validation methodologies for the use of CyberShake ground motion simulations in developing probabilistic and deterministic hazard maps for building codes and other engineering applications. In particular, investigations of observed versus simulated region-specific path effects for small-magnitude earthquakes in Southern California are encouraged. Such research must be coordinated with the Committee for Utilization of Ground Motion Simulations (UGMS).
• Research important ground motion or structural (e.g., building or geotechnical system) response parameters and statistics that should be used in validation of simulations. Demonstrate similarities and differences between otherwise parallel validation tests/ratings using these ground motion or structural response parameters.

• Demonstrate validation methodologies with ground motions simulated with deterministic and stochastic methods above 1 Hz.

• Improve ground motion simulations by closely collaborating with modelers on iterative applications of validation methodologies.

**Improved Hazard Representation**

• Develop improved hazard models that consider simulation-based earthquake source and wave propagation effects that are not already well reflected in observed data. These could include improved methods for incorporating rupture directivity effects, basin effects, and site effects in the USGS ground motion maps, for example. The improved models should be incorporated into OpenSHA.

• Use broadband strong motion simulations, possibly in conjunction with recorded ground motions, to develop ground motion prediction models (or attenuation relations). Broadband simulation methods must be verified (by comparison with simple test case results) and validated (against recorded strong ground motions) before use in model development. The verification, validation, and application of simulation methods must be done on the SCEC Broadband Simulation Platform. Such developments will contribute to the future NGA-H Project.

• Investigate bounds on the median and variability of ground motions for a given earthquake scenario.

**Ground Motion Time History Simulation**

• Develop acceptance criteria for simulated ground motion time histories to be used in structural response analyses for building code applications or risk analysis. This relates closely to the GMSV section above.

• Assess the advantages and disadvantages of using simulated time histories in place of recorded time histories as they relate to the selection, scaling and/or modification of ground motions for building code applications or risk analysis.

• Develop and validate modules for simulation of short period ground motions (< 1 sec) for incorporation in the SCEC Broadband Platform.

• Develop and validate modules for the broadband simulation of ground motion time histories close to large earthquakes, and for earthquakes in the central and eastern United States, for incorporation in the SCEC Broadband Platform.

• Develop and validate modules for nonlinear site response, including criteria for determining circumstances under which nonlinear modeling is required. Incorporate the modules into the SCEC Broadband Platform.

• Compare simulated versus recorded ground motions for different models of the regional geologic structure.

**Collaboration in Engineering Analysis**

• Infrastructure Systems. Assess the performance of distributed infrastructure systems (e.g., water, electrical and transportation) using simulated ground motions. Evaluate the potential impact of basin effects, rupture directivity, spatial distribution of ground motion, or other phenomena on risk to infrastructure systems.

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

• End-to-End Simulation. Interactively identify the sensitivity of structural response to ground motion parameters and structural parameters through end-to-end simulation. Buildings of particular interest include non-ductile concrete frame buildings.

• Reference Buildings and Bridges. Participate with PEER investigators in the analysis of reference buildings and bridges using simulated broadband ground motion time histories. The ground motions of large, rare earthquakes, which are poorly represented in the NGA strong motion database, are of special interest. Coordination with PEER can be done through Yousef Bozorgnia (yousef@berkeley.edu).

• Earthquake Scenarios. Perform detailed assessments of the results of scenarios such as the ShakeOut exercise, and the scenarios for which ground motions were generated for the Tall Buildings Initiative (including events on the Puente Hills, Southern San Andreas, Northern San Andreas and Hayward faults) as they relate to the relationship between ground motion characteristics and structural response and damage.
**Ground Deformation**

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

**Risk Analysis**

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

**Other Topics**

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

**XI. Special Projects and Initiatives**

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

**A. Working Group on California Earthquake Probabilities (WGCEP)**

The WGCEP is a collaboration between SCEC, the USGS, and CGS aimed at developing official earthquake-rupture-forecast models for California. The project is closely coordinated with the USGS National Seismic Hazard Mapping Program, and has received financial support from the California Earthquake Authority (CEA). The WGCEP has now completed the time-independent UCERF3 model (UCERF3-TI, which relaxes segmentation and includes multi-fault ruptures) and the long-term, time-dependent model (UCERF3-TD, which includes elastic-rebound effects). We are not working on adding spatiotemporal clustering (UCERF3-ETAS) to account for the fact that triggered events can be large and damaging. As the latter will require robust interoperability with real-time seismicity information, UCERF3-ETAS will bring us into the realm of operational earthquake forecasting (OEF). We are also starting to plan for UCERF4, which we anticipate will utilize physics-based simulators to a greater degree (see last bullet below).

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 total long-term rates of observed earthquakes for different sized volumes of space.

• Refine our magnitude completeness estimates (as a function of time, space, and magnitude). Develop such models for real-time applications (as will be needed in operational earthquake forecasting).

• Develop methods for quantifying elastic-rebound based probabilities in un-segmented fault models.

• Help quantify the amount of slip in the last event, and/or average slip over multiple events, on any major faults in California (including variations along strike).

• Develop models for fault-to-fault rupture probabilities, especially given uncertainties in fault endpoints.

• Determine the extent to which seismicity rates vary over the course of historical and instrumental observations (the so-called Empirical Model of previous WGCEPs), and the extent to which this is explained by aftershock statistics.

• Determine the applicability of higher-resolution smoothed-seismicity maps for predicting the location of larger, more damaging events.

• Explore the UCERF3 “Grand Inversion” with respect to: possible plausibility filters, relaxing the UCERF2 constraints, not over-fitting data, alternative equation-set weights, applying a characteristic-slip model, and applicability of the Gutenberg Richter hypothesis on faults (see report at www.WGCEP.org).

• Develop applicable methods for adding spatiotemporal clustering to forecast models (e.g., based on empirical models such as ETAS). Are sequence-specific parameters warranted?

• Determine if there is a physical difference between a multi-fault rupture and a separate event that was triggered quickly.

• Develop more objective ways of setting logic-tree branch weights, especially where there are either known or unknown correlations between branches.

• Develop easily computable hazard or loss metrics that can be used to evaluate and perhaps trim logic-tree branches.

• Develop techniques for down-sampling event sets to enable more efficient hazard and loss calculations.

• Develop novel ways of testing UCERF3, especially ones that can be integrated with CSEP.

• Study and test the behavior of computational earthquake-cycle simulators, envisioning that they could become essential ingredients in future UCERF projects and a cornerstone of SCEC5. The goal is to develop the capability of simulators to be able to contribute meaningfully to hazard estimates. Examples of important tasks:
  a. Study and test, using code verification exercises and more than one code, the sensitivity of simulator results to input details including fault-system geometry, stress-drop values, tapering of slip, methods of encouraging rupture jumps from fault to fault, cell size, etc.
  b. Develop physically realistic ways of simulating off-fault seismicity.
  c. Add additional physics into simulators, for example, the inclusion of high-speed frictional weakening and of off-fault viscoelastic and heterogeneous elastic properties.
  d. Develop alternate methods of driving fault slip besides “back-slip”.
  e. 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.
  f. 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.
  g. Develop validation tools for simulators, utilize existing UCERF data comparison tools with them, and develop capabilities for simulators to interact with UCERF infrastructure.
  h. Develop the capability of simulators to deal with UCERF and SCEC CFM fault geometries, both for rectangular and triangular cell representations.
  i. 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-slip faults. Use small time-steps to permit evaluation of short-term clustering.
  j. Use these catalogs as synthetic laboratories for CSEP testing as described under CSEP.
k. 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.

l. Develop and test a variety of statistical methods for determining the predictability of the of earthquakes in these simulated catalogs.

m. Compute other data types such as gravity changes, surface deformation, InSAR images, in order to allow additional comparisons between simulated results and observations.

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

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

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

Priorities for CSEP

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

General contributions 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;

• Expanding the range of physics-based models to test hypotheses that some aspects of earthquake triggering are dominated by dynamic rather than quasi-static stress changes and that slow slip event activity can be used to forecast large earthquakes;

• Working to develop testable fault-based forecasting models;

• Evaluating hypotheses critical to forecasting large earthquakes, including the characteristic earthquake hypothesis, the seismic gap hypothesis, and the maximum-magnitude hypothesis;

• Conducting workshops to facilitate international collaboratories;

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

C. Community Modeling Environment (CME)

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

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

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

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

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

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

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

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

D. Central California Seismic Project (CCSP)

See note below regarding budget restriction on CCSP Proposals

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

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

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

The Planning Committee seeks additional effort in order to:

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

In evaluating CCSP-targeted proposals, the Planning Committee will consider the relevance of the proposed work to the overall project plan and the ability of investigators to deliver timely results during the pilot study. The PC will also consider novel approaches to the uncertainty-reduction problem in addition to those explicitly listed in the project plan.

Terms of the master agreement funding CCSP limits indirect costs to 15%. Please use this rate only for CCSP proposals.
E. National Partnerships through EarthScope

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

XII. Communication, Education, and Outreach

The theme of the CEO program during SCEC4 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:

1. The Implementation Interface connects SCEC scientists with partners in earthquake engineering research, and communicates with and trains practicing engineers and other professionals.

2. The Public Education and Preparedness thrust area educates people of all ages about earthquakes, and motivates them to become prepared.

3. The K-14 Earthquake Education Initiative seeks to improve earth science education and school earthquake safety.

4. Finally, the Experiential Learning and Career Advancement program provides research opportunities, networking, and more to encourage and sustain careers in science and engineering.

These thrust areas present opportunities for members of the SCEC community to partner with CEO staff. Limited funding (typically no more than $2000-$5000) may be available as direct payments from SCEC (not subcontracts) for materials or activities and typically does not require a formal proposal. For larger activities, joint proposals with SCEC CEO to potential sources are the best approach. Those interested in partnering with SCEC CEO on activities, submitting a joint proposal, or in submitting a CEO proposal responding to this Collaboration Plan should first contact the Associate SCEC Director for CEO (Mark Benthien: benthien@usc.edu, 213-740-0323).
Saturday, September 12

08:30 - 09:00  Workshop Check-In at Plaza Ballroom Foyer of Hilton Palm Springs

09:00 - 17:00  A Workshop to Begin Building a Community Rheology Model (CRM) of the Southern California Lithosphere

Conveners: Liz Hearn, Wayne Thatcher, Yuri Fialko, Greg Hirth, Gary Fuis, and Thorsten Becker

Location: Plaza Ballroom A&B

09:00  Overview on CRM goals and ingredients (Liz Hearn)
- CRM goals and plan per SCEC5 proposal
- Outcomes from this workshop
- Structure of today’s workshop

09:20  Discussion

09:30  Active-source results for southern California; comparison with noise-source Vs modeling (Gary Fuis)

10:00  Earthquake-source Vp and Vp/Vs modeling of southern CA; interpretation of top and bottom of seismogenic zone (Egill Hauksson)

10:15  Interpretation of Vp/Vs in the shallow crust from active source studies (Rufus Catchings)

10:30  Directed Discussion (Gary Fuis and All)

11:00  Break

11:15  Rock Mechanics and Exhumed Fault Constraints (Greg Hirth)

11:40  The problem (and potential) of using seismic anisotropy to constrain effective viscosity and strain localization in Southern California (Phil Skemer)

11:55  Constraints from xenoliths on the rheology of southern California lower crust and lithospheric mantle (Whitney Behr)

12:10  Integrating fault zone microstructural observations with rock mechanics data (Fred Chester)

12:25  Directed Discussion (Greg Hirth and All)

13:00  Lunch

14:00  How can the CRM contribute to improved understanding of secular and transient deformation in Southern California and loading of seismogenic faults? (Yuri Fialko)

14:25  Links between short-term and long-term deformation boundary conditions from regional geodynamic models (Thorsten Becker)

14:40  Effects of heterogeneous rheology on deformation, inferred slip rates and inferred stresses (Liz Hearn)

14:55  Linear rheologies versus lab-derived flow laws and heterogeneity of lithosphere deformation (Roland Bürgmann)

15:10  Directed Discussion (Yuri Fialko and All)

15:30  Break

15:45  Wrap-Up Session: How to put all the pieces together (Liz Hearn and Co-PI’s)
- Perspectives on disciplinary sessions: 5-minute summaries and discussions
- Next steps: Priorities for SCEC4 2016 RFP; SCEC5 objectives and staged interim goals; discussion

17:00  Adjourn
Saturday, September 12

09:00 - 17:00  SCSE CSEP/USGS/GEM Workshop: Epistemic Uncertainties in Earthquake and Ground Motion Forecasts

Conveners: Max Werner, Danijel Schorlemmer, Tom Jordan, Andy Michael, Morgan Page, Marco Pagani
Location: Plaza Ballroom C&D

09:00  Welcome, Introductions, Meeting Objectives (M. Werner and D. Schorlemmer)

CSEP & OEF: Overview and Status
Moderator: D. Schorlemmer  Reporter: M. Liukis

09:10  CSEP Overview and Status (M. Werner)

09:35  Current CSEP & OEF Activities in New Zealand (D. Rhoades)

09:50  Five-year Japanese earthquake predictability experiment with multiple runs since 2009 including the 2011 Tohoku-oki earthquake and the 2014 Northern Nagano earthquake (N. Hirata)

10:05  Status and Challenges for Implementing CSEP in China (C. Jiang)

10:20  Operational Earthquake (and Loss) Forecast in Italy: The CSEP Legacy and Future Perspectives (W. Marzocchi)

10:35  Status of OEF Development at the USGS (M. Blanpied)

10:45  Testing UCERF2 [and UCERF3?] (D. Schorlemmer)

10:50  Break

OEF, Aftershocks and Retrospective Experiments
Moderator: P. Maechling  Reporter: A. Llenos

11:05  Testing UCERF3-ETAS (N. Field)

11:15  Retrospective Canterbury Experiment (M. Werner)

11:25  Ensemble Model Earthquake Forecasts during the 2010-2012 Canterbury, New Zealand, Earthquake Sequence (M. Taroni)

11:35  Organization of teh Collaboratory for Interseismic Simulation and Modeling [CISM] (T. Jordan)

11:40  Dynamic Ensemble Model Testing and Global Earthquake Forecast Evaluation (A. Strader)

11:50  Panel Discussion: Epistemic Uncertainties in CSEP (W. Marzocchi and D. Rhoades)
    - How should epistemic uncertainties be handled in testing and evaluation?

13:00  Lunch

Evaluating Hazard Models
Moderator: W. Marzocchi  Reporter: N. van der Elst

14:00  Testing PSHA against accelerometric data and intensities (C. Beauval)

14:15  GEM Hazard Modelling and Testing (M. Pagani)

14:30  Testing IPEs and Seismic Hazard Maps (S. Mak)

14:45  Discussion
    - How should GEM & USGS ground motion forecasts and hazard models be evaluated?
    - How can T&E results feed into hazard model updates?

15:30  Break
Induced Seismicity
Moderator: M. Page  Reporter: M. Taroni
15:45 Earthquake Rate Models for Evolving Induced Seismicity Hazard in the Central and Eastern U.S. (A. Llenos)
15:55 Forecasting Next Year's Earthquakes in Oklahoma: Scientific and Public Policy Challenges (B. Ellsworth)
16:05 Discussion
- CSEP Experiments of Induced Seismicity Forecasts
16:45 Wrap-Up and Next Steps  M. Werner and D. Schorlemmer
17:00 Adjourn

Sunday, September 13

07:00 - 18:00  SCEC Annual Meeting Registration & Check-In at Hilton Lobby
07:00 - 08:00  Breakfast at Hilton Poolside
08:00 - 12:00  SCEC Collaboratory for Interseismic Simulation and Modeling (CISM) Workshop
Conveners: Tom Jordan, Phil Maechling
Location: Palm Canyon Room

08:00 Introduction and Overview of CISM (T. Jordan)
08:10 State of Forecast Development and Considerations for CISM
Moderator: T. Jordan
- USGS (M. Blanpied and N. Field)
- New Zealand (D. Rhoades and A. Christophersen)
- Europe (W. Marzocchi and D. Schorlemmer)
- CSEP (M. Werner)

08:50 Earthquake Simulators
Moderator: T. Tullis
- RSQSim Code Development (K. Richards-Dinger)
- Potential Applications of RSQSim for the CISM Project (J. Dieterich)
- Panel Discussion (Participants in Earthquake Simulators Technical Activity Group)

10:10 Ground Motion Forecasting
Moderator: G. Beroza
- CyberShake and UCERF3 (K. Milner)
- Validation of Ground Motion Models (C. Goulet)

10:40 CISM Infrastructure
Moderator: P. Maechling

11:00 Objectives and Plans for CISM
Moderator: T. Jordan
Sunday, September 13

10:00 - 12:00 Open Discussion: Estimating Fault Zone Properties using Space-Based Measurements

Conveners: Andrea Donnellan (NASA JPL), Ramon Arrowsmith (ASU), Yehuda Ben-Zion (USC)

Location: Oasis 3

Everyone is welcome to join in the discussion.

We are developing a concept for a spaceborne gazing imager that would serve as a community resource for fault zone studies. Gazing imaging, or Structure from Motion (SfM), measurements are increasingly being applied to studying fault zones. The method combines images from several vantage points to provide topography, reflectance, and imagery over fault zones (see http://www.kiss.caltech.edu/study/gazing2014/index.html). Resulting topography can be used to study geomorphology of fault zones, while reflectance and imagery can be used to estimate material properties, texture, and porosity of the zone and surrounding area. Images collected before and after surface rupturing earthquakes would provide 3D change maps. Combining these measurements with other data should improve estimates of strain partitioning across the fault zone, fault rock damage, strength, and healing. Current SfM methods rely on balloons, drones, and aircraft. A spaceborne platform would allow for global, systematic, repeated measurements of fault zones. We are seeking community input on the science that could be achieved with a spaceborne imager, potential targets (globally), and the needed resolution to achieve the science goals.

12:00- 13:00 Lunch at Hilton Restaurant, Tapestry Room, and Poolside

13:00 - 17:00 SCEC Community Software for Extreme-Scale Computing in Earthquake System Science Meeting

Conveners: Tom Jordan, Phil Maechling

Location: Palm Canyon Room

13:00 Introductions, Overview, Milestones, and Logistics (T. Jordan and P. Maechling)
13:30 Physics in High-Frequency Simulations (K. Olsen)
14:15 Validation Procedures for High-F and CyberShake (R. Taborda)
15:00 Break
15:15 Extreme Scale Software (Y. Cui)
16:00 Future CyberShake (P. Maechling)
16:45 Wrap-Up (T. Jordan and P. Maechling)
17:00 Adjourn
Sunday, September 13

13:00 - 17:00  **SCEC Community Stress Model (CSM) Workshop**

Conveners: Bruce Shaw, Joann Stock, Jeanne Hardebeck, and Thorsten Becker

Location: Horizon Ballroom

- 13:00  Overview (B. Shaw)
  Stressing Rate, Seismicity, and Stress
- 13:10  A Comparison of 17 Strain-Rate Models from GPS Geodesy (D. Sandwell)
- 13:25  Alignment of Stressing Rate from GPS with SHmax Orientations from Stress Inversions (E. Hauksson)
- 13:45  Crustal Stress: Constraints from Seismology, Geodesy, Topography, and Gravity (K. Luttrell)
- 14:05  Comparison of Off-Fault and Interseismic Stressing Patterns with Seismicity (M. Cooke)

**CSM Website**
- 14:30  The CSM Web Site and Facilitating User Access (T. Becker)
- 14:45  Break

**Data Constraints on Stress**
- 15:00  Scales of Stress Field Variation Determined from Borehole Observations in Southern California (J. Stock)
- 15:30  Questions and Audience Discussion on Borehole Stress
- 15:40  Stress Orientation from Active Deformation of Borderland Basins (M. Legg)
- 15:55  Heat Flow Constrains on Off-Fault Stresses in Central California (N. Sleep)

**Snap Talks**
- 16:00  Community-Contributed Presentations on Results and Forward Directions (1-2 slides maximum)

**Wrap-Up Panel Discussion on Directions Forward**
- 16:30  Wrap-Up Panel Discussion on Directions Forward
- 17:00  Adjourn

13:00 - 15:00  **California Earthquake Clearinghouse: Training and Fieldwork Limited Liability Certification (Session 1)**

Conveners: Anne Rosinski, Maggie Ortiz, and Mike Oskin

Location: Oasis Room 2

- 13:00  Introduction to Clearinghouse and SCEC Response
- 13:15  Introduction to Disaster Service Workers Program
- 13:30  Overview of National Incident Management System (NIMS)
- 13:45  Safety in the Field
- 14:00  Clearinghouse Operations After an Earthquake (checking in, coordination calls, briefings, overflights, etc.)
- 14:15  Data Collection
- 14:30  Questions/Discussion
- 14:40  Oath
- 14:45  Concluding Remarks
- 15:00  Adjourn
MEETING AGENDA

15:00 - 17:00  California Earthquake Clearinghouse: Training and Fieldwork
Limited Liability Certification (Session 2)
Conveners: Anne Rosinski, Maggie Ortiz, and Mike Oskin
Location: Oasis Room 2

15:00  Introduction to Clearinghouse and SCEC Response
15:15  Introduction to Disaster Service Workers Program
15:30  Overview of National Incident Management System (NIMS)
15:45  Safety in the Field
16:00  Clearinghouse Operations After an Earthquake (checking in, coordination calls, briefings, overflights, etc.)
16:15  Data Collection
16:30  Questions/Discussion
16:40  Oath
14:45  Concluding Remarks
17:00  Adjourn

16:00 - 20:00  Poster Set-Up in Plaza Ballroom

17:00 - 18:00  Welcome Social in Hilton Lobby and Plaza Ballroom

18:00 - 19:00  Distinguished Speaker Presentation in Horizon Ballroom
Heating and weakening of faults during earthquake slip (James R. Rice)

19:00 - 20:30  Welcome Dinner at Hilton Poolside
19:00 - 21:00  SCEC Advisory Council Meeting in Palm Canyon Room
21:00 - 22:30  Poster Session 1 in Plaza Ballroom

Monday, September 14

07:00 - 08:00  SCEC Annual Meeting Registration & Check-In at Hilton Lobby
07:00 - 08:00  Breakfast at Hilton Poolside

08:00 - 10:00  The State of SCEC in Horizon Ballroom
08:00  Welcome and State of the Center (Tom Jordan)
08:30  Agency Reports
 - National Science Foundation (Jim Whitcomb)
 - U.S. Geological Survey (Bill Leith)
 - FEMA/NEHRP (Wendy Phillips)
 - NASA (Ben Phillips)
09:00  Communication, Education, & Outreach (Mark Benthien)
09:20  SCEC Science Accomplishments (Greg Beroza)
10:00 - 10:30  Break

10:30 - 12:30  Session 1: SCEC Special Fault Study Areas
Moderators: Kate Scharer, Scott Marshall
San Gorgonio Pass Special Fault Study Area (Michele Cooke)
The Ventura Special Fault Study Area: Assessing the potential for large, multi-segment thrust fault earthquakes and their hazard implications (John Shaw)
MEETING AGENDA

12:30 - 14:00  Lunch at Hilton Restaurant, Tapestry Room, and Poolside

14:00 - 16:00  **Session 2: SCEC Community Models** in Horizon Ballroom  
**Moderators:** Brad Aagaard, Rowena Lohman  
- Blending data and dynamics into equilibrium for the Community Stress Model (Peter Bird)  
- The Community Geodetic Model (Jessica Murray)

16:00 – 17:30  **Poster Session 2** in Plaza Ballroom

19:00 - 21:00  **SCEC Honors Banquet** at Woodstock Ballroom, Hard Rock Hotel

21:00 - 22:30  **Poster Session 3** in Plaza Ballroom

**Tuesday, September 15**

07:00 - 08:00  Breakfast at Hilton Poolside

08:00 - 10:00  **Session 3: Earthquakes — From the Lab to the Field** in Horizon Ballroom;  
**Moderators:** Judi Chester, Cliff Thurber  
- FARockM Perspectives on Earthquake Processes from the Lab to the Field (Greg Hirth)  
- Shallow structure of the San Jacinto fault zone and detailed catalog of seismic sources based on spatially-dense array data (Yehuda Ben-Zion)

10:00 - 10:30  Break

10:30 - 12:30  **Session 4: Physics-Based Forecasting and Ground Motions** in Horizon Ballroom;  
**Moderators:** Eric Dunham, Edward Field  
- Getting Real: The Promise and Challenges of 3D Ground-Motion Simulations (Arthur Frankel)  
- Physics-based Earthquake Forecasting: Encouraging Results from a Retrospective CSEP Evaluation of Forecasting Models during the 2010 Canterbury, New Zealand, Earthquake Sequence (Max Werner)

12:30 - 14:00  Lunch at Hilton Restaurant, Tapestry Room, and Poolside

14:00 - 16:00  **Session 5: Connecting Hazard to Risk** in Horizon Ballroom;  
**Moderators:** Jacobo Bielak, Sanaz Rezaeian  
- From Seismic Hazard to Risk: Summary of Critical Issues and How SCEC Research Can Foster New Solutions (Christine Goulet)  
- Managing Earthquake Hazards and Risks to Implement an Infrastructure Resilience Program (Craig Davis)

16:00 - 17:30  **Poster Session 4** in Plaza Ballroom

19:00 - 21:00  **SCEC Advisory Council Meeting** in Boardroom

21:00 - 22:30  **Poster Session 5** in Plaza Ballroom

22:30 - 23:00  Poster Removal from Plaza Ballroom
Wednesday, September 16

07:00 - 08:00  Breakfast at Poolside

08:00 - 10:00  Session 6: Post-Earthquake Rapid Scientific Response in Horizon Ballroom; Moderators: Mike Oskin, Ken Hudnut
   The Gorkha Mw=7.8 earthquake: an incomplete Himalayan rupture (Roger Bilham)
   The high frequency ‘anomaly’ that saved lives: Site effects and damage patterns of the 2015 Gorkha Earthquake (Domniki Asimaki)

10:00 - 10:30  Break

10:30 - 12:30  The Future of SCEC in Horizon Ballroom
   10:30  Report from the Advisory Council (Gail Atkinson)
   11:00  This Next Year: 2016 SCEC Science Collaboration (Greg Beroza)
   11:45  Towards SCEC5 Priorities (Tom Jordan)
   12:30  Adjourn

12:30 - 14:30  SCEC Planning Committee Lunch Meeting in Palm Canyon Room A

12:30 - 14:30  SCEC Board of Directors Lunch Meeting in Palm Canyon Room
**Distinguished Speaker Presentation**

**Heating and weakening of faults during earthquake slip.**

*James R. Rice (Harvard University)*

**Sunday, September 13, 2015 (18:00)**

Field and borehole observations of active fault zones show that earthquake shear is often highly localized to principal slipping zones of order 10s of microns to a few mm wide, lying within a broader gouge layer typically of order of a few cm wide, and with all that being a feature located within a much broader zone of cracked/damaged rock bordering the fault over a scale of 1-10s m width. Fault gouges are often rate-strengthening, especially at higher temperatures, and are then resistant to shear localization under typically slow laboratory deformation rates. However, extreme localization due to shear heating and development of highly elevated pore pressure is shown to be a predicted and lab-verified consequence of rapid straining. That pressurization can develop in fluid which pre-exists in the gouge as groundwater, or in the volatile H2O or CO2 phases emerging at high pressure from thermal decomposition reactions in hydrated silicates (clays, serpentines) or carbonates. These processes join the ubiquitous weakening by flash-heating at frictional asperity contacts to make conventional friction properties almost irrelevant at seismic slip rates. Results have implications for the mode of slip-rupture propagation in earthquakes (self-healing vs. crack-like) and shed new light on why statically strong faults like the SAF can produce large ruptures which show negligible localized heat outflow and little evidence of melt formation, at least in the shallow to middle crust. As some have recently advocated, evaluating the susceptibility of major fault zones to extreme thermal weakening, when feasible, should become a component of seismic hazard analysis.

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James R. Rice, born 1940 in Frederick, MD, is the Mallinckrodt Professor of Engineering Sciences and Geophysics at Harvard, appointed jointly in its School of Engineering and Applied Science and Department of Earth and Planetary Sciences. From 1965 to 1981 he was a faculty member in the Division of Engineering at Brown. His prior education was at Lehigh, with a 1962 Sc.B. in engineering mechanics, and a 1963 Sc.M. and 1964 Ph.D. in applied mechanics.

Rice’s research focuses on the mechanics and related hydrologic, materials and thermal science underlying earth and environmental processes. That has included analyses of earthquake nucleation, dynamic rupture propagation, and aseismic deformation transients in fault zones, landslide processes, and more recently, tsunami propagation and meltwater interactions with glacier and ice sheet dynamics. Earlier, his work addressed plastic deformation and cracking processes in mechanical and materials engineering, and related analytical and finite-element computational methodology. His path-invariant integral studies, originally focused on understanding crack tip stress fields in non-linear engineering materials, principally metallic alloys, were quickly adapted to slip weakening descriptions of rupture surfaces in landslides and earthquakes, and later to atomic scale treatments of dislocation nucleation from crack tips in crystal lattices, for assessing the origins of ductile vs. brittle response.

Rice’s contributions have been recognized by numerous awards, including the Timoshenko and Nadai Medals of the American Society of Mechanical Engineers, the von Karman and Biot medals of the American Society of Civil Engineers, the Bucher Medal of the American Geophysical Union, the Néel Medal of the European Geosciences Union, and the Reid Medal of the Seismological Society of America. He has been elected to the USA National Academies of Engineering and of Science, to foreign membership in the Royal Society, London, and in the French Académie des Sciences, and has received honorary doctorates from several universities.

For Rice’s publications, see http://esag.harvard.edu/rice/RicePubs.html, and/or a full cv, see http://esag.harvard.edu/rice/RiceCV.html.
Plenary Talk Presentations

San Gorgonio Pass Special Fault Study Area, Michele L. Cooke, David D. Oglesby, and John D. Yule
Monday, September 14, 2015 (10:30)

The largest irregularity along the San Andreas fault occurs in the San Gorgonio Pass (SGP) region where active strands disaggregate into a distributed zone of faulting, rather than having deformation restricted to a single active strand. Forecasting the earthquake hazards in this complex region requires addressing three fundamental questions: 1) What is the subsurface geometry of active faulting through the SGP? 2) What is the earthquake potential in the SGP region? 3) What is the probability of a through-going San Andreas rupture? The SGP SFSA has taken a multi-disciplinary approach to address these three questions. One focal point throughout SCEC4 has been the activity level of the northern route through the pass along the Mill Creek and Mission Creek strands of the SAF. The role of this route in passing slip through the pass is critical for understanding potential earthquakes in the region. Through field studies, investigations of microseismicity, geodetic inversions for slip rate and crustal deformation models, we have vastly increased the data available to assess the activity of the Mill Creek/Mission Creek strand and honed our understanding of the partitioning of deformation throughout the fault system. New strike-slip rates have filled a critical gap within previous data along the SAF. Microseismicity shows anomalously high stress drops within the SGP that may reveal stress levels critical for rupture dynamics. Dynamic rupture models of realistically geometrically complex faults demonstrate that the development of earthquake rupture through the pass is highly sensitive to initial stress levels as well as fault geometry. The important question of through-going rupture history has been addressed with deep trenches that show that the last event to rupture through the SGP may have been ~1400 AD. The emerging view from the work reveals a fault system that typically arrests ruptures as they approach the pass, yet occasionally allows through-going, very large events. This view is consistent with lowered strain accumulation, measured strike-slip rates and strike-slip rates from kinematically consistent models within the SGP. The SGP workshops have showcased the impressive collection of collaborative research emerging from the SFSA. Through such interdisciplinary dialog we are successfully integrating a variety of datasets to form a clearer understanding of active faulting in this region that has the potential for devastating earthquakes.

Monday, September 14, 2015 (10:30)

The SCEC Ventura Special Fault Study Area (SFSA) promotes interdisciplinary science investigating the prospects for large, multi-segment thrust fault earthquakes in southern California. The SFSA is centered on the north-dipping Ventura – Pitas Point fault and overlying anticline, which are located at the juncture of several of the largest and fastest slipping faults in the Transverse Ranges. Holocene marine terraces above the anticline suggest that it deforms in discrete 7-9 m uplift events, with the latest event occurring ~950 years ago.

Recent excavations across the fold scarp above the blind Ventura fault show evidence for at least two large-displacement (4.5 to 6m uplift), paleo-earthquakes in the Holocene that may be correlated with uplift of marine terraces along the coast. Geophysical studies of the larger fault system that extends offshore also document discrete Holocene seafloor deformation. Current efforts are focused on developing a comprehensive understanding of coastal uplift and subsidence patterns that record both the activity of the 140 km long Ventura – Pitas Point – North Channel fault system and a series of active north- and south-dipping faults in its hanging wall and football. Seismological studies show that thrust and strike-slip earthquakes occur throughout the region, and are consistent with NNESW compression. Geodetic observations (GPS, InSAR, and leveling studies), and fault system models also indicate rapid shortening (2.7 to 8 mm/year) and uplift (~2 mm/yr) rates across portions of this structure. Mechanical models of the Ventura fault system predict slip rates that agree with geologic estimates of fast slip, with the maximum slip predicted near the coast. Together, these results support the occurrence of large thrust fault earthquakes involving the Ventura fault system.
To assess the hazards posed by these earthquakes, the SFSA has supported numerical simulations that suggest ruptures of the Ventura – Pitas Point fault system will produce large surface displacements and significant, long duration ground motions (> 0.5 m/s, PGV) over a large area of southern California. As these ruptures will likely extend offshore, they also pose the threat of generating tsunamis. Recent studies examining sedimentary deposits along the coast have suggested possible paleo-tsunami deposits, as well as rapid coastal subsidence events that may be caused by paleo-earthquakes. Numerical modeling of tsunamis shows significant run-ups (up to 8 m) along large areas of the coastline for equivalent modeled seafloor offset. These studies confirm that large thrust fault earthquakes pose considerable seismic and tsunami hazards to coastal southern California. SCEC is at the forefront of efforts to better characterize these hazards.

The Community Geodetic Model. Jessica R. Murray, Rowena Lohman, and David Sandwell

Monday, September 14, 2015 (14:00)

The SCEC Crustal Motion Map (CMM) provided average geodetic velocities from southern California data collected through 2004. Core SCEC4 science targets require input that captures spatiotemporal variations at high resolution. The Community Geodetic Model (CGM) aims to provide this by leveraging the complementary features of Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) data. Advances since the completion of the CMM, including a larger continuous GPS network, the launch of new SAR satellites, and development of InSAR time series analysis techniques, provide essential CGM building blocks. Raw GPS and InSAR data are being analyzed and combined via appropriate models to generate GPS station time series, spatially gridded InSAR time series, and a self-consistent integration of the two.

Creating the CGM requires synthesis of existing analyses and development of new methodologies. In a series of in-person and virtual workshops, geodesy experts and potential users have defined the target CGM product, identified important decision points in CGM development, evaluated candidate methodologies, and adjusted the plan accordingly.

By comparison of continuous GPS time series from several processing centers we have uncovered and addressed discrepancies. We are finalizing a consensus approach for merging these time series and incorporating campaign data. GPS-derived secular velocities are needed to constrain some InSAR analyses and have intrinsic value to the broader SCEC community for interseismic deformation studies. Calculating these rates is complicated by factors such as long term postseismic signals, particularly in regions with little pre-earthquake GPS data, and the potential for bias introduced by the scale term applied during GPS reference frame alignment. These are topics of ongoing evaluation and decision-making by CGM contributors.

An important finding is that some InSAR time series derived without GPS constraints show good agreement with GPS even at long spatial scales and thus might provide deformation time series in regions with sparse GPS coverage. The new Sentinel-1a and ALOS-2 satellites now supply ascending and descending data for southern California with short baselines and frequent repeats, opening exciting new avenues for improved InSAR time series analysis and atmospheric corrections. Through the CGM effort thus far we have laid the groundwork to capitalize on these unique observations in the coming years.

Blending data and dynamics into equilibrium for the Community Stress Model. Peter Bird

Monday, September 14, 2015 (14:00)

With 3-D tensor models of stress in the lithosphere in southern California, SCEC could: (a) determine the shear stress on active faults to constrain the physics of slip; (b) predict Coulomb stress changes for operational earthquake forecasting; and (c) test the realism of long-term earthquake sequence simulators. One basis for models is data: stress directions (from focal mechanisms and boreholes), and stress intensity (only from boreholes). But earthquakes rarely occur deeper than 15~20 km, and boreholes rarely deeper than ~6 km. Therefore, data must be supplemented by dynamic models using: laboratory flow laws, a geotherm model, a Moho model, relative plate motions, and locations of active faults. One dynamic model uses code Shells, which solves for 2-D equilibrium of vertically-integrated stresses using 2-D velocity models and 3-D structure. While this model predicts full stress tensors, they are discontinuous and noisy. A newer approach is to model the stress anomaly field as the sum of topographic and tectonic stress anomaly fields. In program FlatMaxwell, the topographic stress is defined as the convolution of topography (and deep density anomalies) with analytic solutions for an elastic half-space. The tectonic stress is modeled by sums of derivatives of a Maxwell vector potential field. The whole stress field is then best-fit (by weighted least squares) to both data and the dynamic model. In practice, FlatMaxwell models are limited in spatial resolution to no more than 6 wavelengths along each side of the model domain. Thus they are quite smooth, and cannot represent stress
discontinuities at the Moho predicted by the Shells model. Results to date show a low-amplitude stress anomaly, with peak shear stress of 120 MPa and peak vertically-integrated shear stress of 2.9×10^12 N/m. Channeling of deviatoric stress along the strong Peninsular Ranges and Great Valley is seen. In southern California, deviatoric stress and long-term strain-rate are negatively correlated because regions of low heat-flow act as stress guides while deforming very little. In contrast, active faults lie in areas with higher heat-flow, and their low strength keeps deviatoric stresses locally modest. Opportunities for future CSM advances include: [1] collecting more data; [2] tuning the Shells dynamic model; [3] using a different dynamic modeling code; and/or [4] applying a similar Maxwell equilibrium filter to models of the interseismic stress rate.

**Plenary Talk Presentations**

**FARockM Perspectives on Earthquake Processes from the Lab to the Field.**
*Greg H. Hirth*

Tuesday, September 15, 2015 (08:00)

Laboratory rock mechanics and complimentary analyses of fault zone microstructures provide numerous constraints on processes that promote or limit earthquake nucleation and rupture. I will provide my perspective on how SCEC has fostered important directions in rock mechanics, where we stand currently and the role that rock mechanics and structural studies can play in future SCEC initiatives. (1) Preceding the Annual Meeting, we will be holding a workshop on the Community Rheology Model (Convened by Hearn, Becker, Fialko, Fuis, Hirth and Thatcher) to discuss, among several topics, how to integrate our understanding of rheology and physical properties into a practical model of lithospheric deformation in Southern California. Here, I will provide a brief summary of the efficacy (and limitations) of using laboratory based flow laws in such models, and how to integrate observations of microstructures from exhumed fault rocks and xenoliths into a systems-based analysis of deformation in the lithosphere. (2) Perhaps the biggest role that SCEC has played in the rock mechanics community is through its impact on focusing effort towards understanding (and applying) the processes that promote dynamic fault weakening. I will provide an update on where this field stands and highlight areas where a combination of laboratory and theoretical studies need to advance, drawing from our own work and that of the community. One issue that stands out as particularly important is constraining the processes that lead to strain localization during both interseismic/quasi-static and dynamic fault slip. (3) A common link between these topics is identifying the deformation conditions at the "brittle-ductile transition". Here I will discuss recent experimental work from our lab, in which we analyze how grain-scale plasticity influences the “effectiveness” of the effective pressure law, and how these processes may control the depth of the seismogenic zone and how it evolves with changing temperature, strain rate and lithology. In addition, I will illustrate why higher temperature/higher pressure experiments may be a key for not only constraining these processes, but also understanding the apparent discrepancy between interpretations regarding the strength/effective viscosity of major faults in California.

**Shallow structure of the San Jacinto fault zone and detailed catalog of seismic sources based on spatially-dense array data.**
*Yehuda Ben-Zion*

Tuesday, September 15, 2015 (08:00)

I review results (*) on imaging the shallow structure of San Jacinto fault zone and detection/location of seismic energy sources using data of a spatially-dense Nodal array centered on the Clark branch of the fault. The array operated at the Sage Brush site south of Anza for about 4 weeks in 2014 with 1108 vertical (10 Hz) geophones in about 650 m x 700 m box configuration. Continuous waveforms with signals generated by the ambient seismic noise, earthquakes, and Betsy gunshots were recorded with useable frequencies up to 200 Hz. The shallow structure imaging is done with surface and body waves extracted from the ambient noise, arrivals from local and teleseismic earthquakes, and waves generated by the gunshots. The results document very low seismic velocities and attenuation coefficients, strong lateral and vertical variations, seismic trapping structure, local sedimentary basin, and overall lithology contrast across the fault. The detection/location techniques include stacking, beamforming, matched field processing, and templates generated by these methods. The analysis uncovers many hundred of daily earthquakes not detected by the regional networks and several different types of surface noise sources.

*The research was done in collaboration with F. Vernon, Z. Ross, P. Roux, D. Zigone, G. Hillers, H. Meng, M. Campillo & others*
Getting Real: The Promise and Challenges of 3D Ground-Motion Simulations, Arthur Frankel and William Stephenson

Tuesday, September 15, 2015 (10:30)

3D ground-motion simulations improve our prediction of ground shaking for future large earthquakes. For the Seattle basin, there are clear observations of basin-edge focusing and basin-edge generated surface waves that we have successfully modeled using the 3D finite-difference method. In 2007, we published probabilistic seismic hazard maps for Seattle of 1 Hz spectral accelerations, based on 3D simulations for 540 earthquake rupture scenarios for sources that dominate the probabilistic hazard. These maps were derived from synthetic seismograms at 7200 receiver sites spaced 280m apart. We also investigated how 3D random heterogeneities in seismic velocities can affect forward directivity pulses and basin surface waves. The Hanford basin in eastern Washington is another case where basin-edge generated surface waves are observed in recordings and matched by 3D simulations. Our current challenge is producing broadband (0-10 Hz) synthetic seismograms for M9 earthquakes on the Cascadia subduction zone using 3D simulations up to 1 Hz, as part of the M9 project of the University of Washington. The central task of this study is to consider a variety of rupture scenarios and provide realistic synthetic seismograms to structural and geotechnical engineers so that they can evaluate the range of performance of buildings and soils. Strong-motion and teleseismic recordings of the M9.0 Tohoku and M8.8 Maule earthquakes, as well as observations of some large crustal earthquakes, indicate that higher frequency (≥ 0.5 Hz) radiation is generated at localized portions of the fault that are not the same as where the maximum slip occurs. This implies that the wavenumber spectra of stress and slip on a fault vary along the fault plane, with smooth and rough patches. For the M9 Cascadia simulations, we use high stress drop M8 sub-events combined with background slip with relatively long rise times. We present an example for the Seattle basin that demonstrates the importance of geologic information to constrain inversions for seismic velocities based on Rayleigh wave phase velocities. A 3D simulation using the smoothed southern edge of the Seattle basin determined from the surface-wave inversion cannot reproduce the basin-edge focusing observed during the Nisqually earthquake. This focusing is well explained by a 3D simulation with a velocity model containing an abrupt southern edge of the basin derived from geologic information and seismic reflection profiles.

Physics-based Earthquake Forecasting: Encouraging Results from a Retrospective CSEP Evaluation of Forecasting Models during the 2010 Canterbury, New Zealand, Earthquake Sequence, Maximilian J. Werner and the CSEP Canterbury Working Group

Tuesday, September 15, 2015 (10:30)

Despite much progress in our understanding of the physical mechanisms of earthquake nucleation, clustering and triggering, physics-based earthquake forecasting remains a major challenge. For instance, evaluations of the predictive power of the static Coulomb stress change hypothesis for earthquake clustering have up to now concluded that Coulomb-based forecasts could not compete with statistical models, which exploit statistical regularities of observed seismicity patterns. In sharp contrast to previous results, a recent experiment by the Collaboratory for the Study of Earthquake Predictability (CSEP) suggests that newly developed and improved Coulomb-based models are now competitive alternatives that can outperform statistical models. The CSEP experiment consisted of a retrospective evaluation of time-dependent forecast models during the complex and fatal 2010-12 Canterbury, New Zealand, earthquake cascade. Fourteen models were developed by groups in New Zealand, Europe and the US, including statistical, physics-based and hybrid models. We evaluated the models from the time just after the Mw7.1 Darfield earthquake until February 2012 using three forecast durations (1-year, 1-month and 1-day). We found that the information content of physics-based and hybrid model forecasts is greater than or comparable to that of statistical model forecasts at all forecast horizons. Differences are greatest for 1-yr horizons, where variants of the Coulomb model and a hybrid model outperform a reference ETAS model by a probability gain per earthquake of about 7. These results offer some encouragement for a physical basis for earthquake forecasting. We speculate on further model developments as well as the use of finite earthquake rupture simulators for the purpose of earthquake forecasting.

From Seismic Hazard to Risk: Summary of Critical Issues and How SCEC Research Can Foster New Solutions, Christine A. Goulet

Tuesday, September 15, 2015 (14:00)

Seismic risk analysis is gaining popularity as a tool for civil engineering design. It is not only the basis for the performance-based earthquake engineering (PBEE) design approach, it is now included, in a simplified fashion, into the latest building codes and design guidelines. Risk combines
hazard, exposure and vulnerability to provide probabilities of various outcomes such as structural collapse, loss of life, and exceedance of given threshold repair costs or downtime. Overall, better risk quantification helps stakeholders make better decisions and will contribute to a more sustainable society. Example applications of risk-informed decision include the design of new critical facilities, such as hospitals, dams and bridges, and the prioritization of retrofitting for our aging building stock and infrastructure.

In this presentation, I will cover a “big picture” view of seismic hazard risk. The presentation is focused on risk from ground-motion hazard, but the take-away points are applicable to other types of seismic hazard as well, such as from surface fault rupture, liquefaction, or earthquake-triggered landslides. Often, the factor controlling risk, especially at long return periods, is the seismic hazard itself, and more specifically its associated uncertainty and variability. After showing examples on how hazard impacts risk, I will explore different avenues that SCEC researchers can take to help improve hazard quantification and thus, lead to better risk assessment. The combination of fundamental and applied research conducted under the SCEC umbrella is unique. With contributions from both the core research program and the special projects, the SCEC community can have a meaningful impact on seismic resilience.

**Managing Earthquake Hazards and Risks to Implement an Infrastructure Resilience Program**, Craig A. Davis

Tuesday, September 15, 2015 (14:00)

The Los Angeles Water System is implementing a Seismic Resilience Program as part of a larger city-wide plan to improve the City’s seismic resilience as outlined by the Mayor in his “Resilience by Design” report. The Water System Resilience Program comprehensively covers all aspects of water system business. Some key components to the program are aqueduct crossings of the San Andreas Fault, fire following earthquake, and developing a seismic resilient pipe network. This presentation provides a brief overview of the resilience program. The Los Angeles Water System is a large and complicated geographically distributed system exposed to many different seismic hazards posing different risks to the loss of services and ability to restore them following an earthquake. A significant problem exists on how to quantify the different hazards (e.g. liquefaction, landslide, faulting, ground shaking), having a wide range of probabilities of occurrence, that threaten large spatially distributed systems. Each hazard is quantified differently and there is no accepted methodology for uniform incorporation across the systems. This problem is compounded when system dependencies and cascading effects must be considered, such as the interaction of water, power, and gas systems associated with fire following earthquakes. A seismic resilient pipe network (SRPN) is designed and constructed to accommodate damage with ability to continue providing water or limit water outage times tolerable to community recovery efforts. An SRPN is an attempt to optimize pipe replacements in an existing network to reduce risks to communities from future earthquake impacts on the water system. The ability to understand the true risks of service losses is inhibited by hazard quantification and how to distribute across the network. Los Angeles intends to implement the seismic resilience program with risk-informed decisions. Improved mapping of geologic earthquake hazards incorporating the magnitudes of ground deformations and improved quantification allowing application of all hazards with uniform confidence in system models are aspects which can greatly improve community resilience.

**Plenary Talk Presentation**

**The Gorkha Mw=7.8 earthquake: an incomplete Himalayan rupture**, Roger Bilham

Wednesday, September 16, 2015 (08:00)

Although an earthquake near Kathmandu had been anticipated for more than two decades, the Mw7.8 Gorkha earthquake of 25 April 2015 was smaller than expected and in the wrong place. Within ten seconds of shaking its 150x60 km² rupture had lifted Kathmandu 1m, and shifted it bodily 1.8m to the south (http://youtu.be/VS6WVz4V0ps). Yet local accelerations (≈0.25g) were lower than in historical Himalayan earthquakes, thereby avertting a much worse disaster. The official death toll exceeded 8700, half a million homes were damaged or destroyed, and 4.5 million rendered homeless. Had the earthquake occurred, not at midday on Saturday, but 12 hours earlier, or during school hours the death toll could have been 4-6 times larger. The main tectonic feature of the earthquake is that it failed to rupture the entire Himalayan décollement to the surface, a feature we now recognize as common to half a dozen Himalayan Mw<7.9 earthquakes in the past several centuries, including one that ruptured almost the same area in 1833.

The remote scientific response to the earthquake (global seismic data and InSAR) was immediate and effective, but public knowledge in Nepal about the earthquake in the weeks following the mainshock remained hazy. Government and University researchers, anxious not to alarm citizens...
during the rumble of frequent aftershocks were reluctant to mention the growing realization that a
large earthquake could still occur to the west of Kathmandu. Amid the information vacuum many
survivors began to reassemble the wreckage of their homes using identical methods that led to their
collapse, under the impression that no future earthquake would occur.

A strong and immediate scientific presence in the mezzoseismal zone of a large earthquake is
essential to capture time sensitive seismic data, and to inform the public and local officials of the
best available seismic information as it becomes known. With a few notable exceptions the
response to the Nepal earthquake was slow, with earthquake investigative teams arriving more than
a month after the event. Delays were caused by the absence of funds for an instantaneous
response, and by the mistaken perception that scientists would impede rescue and recovery
missions. As a result important macroseismic indicators of mainshock intensities were lost when the
Mw=7.3 aftershock destroyed already weakened buildings. Fortunately many photos and videos of
damage in the mainshock captured some of this lost information.

The high frequency ‘anomaly’ that saved lives: Site effects and damage
patterns of the 2015 Gorkha Earthquake, Domniki Asimaki

Wednesday, September 16, 2015 (08:00)

Although the M7.8 Gorkha mainshock ruptured a segment of the Main Himalayan Thrust directly
below Katmandu, structural damage across the valley was much lower than expected. Strong
motion data prominently featured a 5-sec pulse that reverberated in the basin, but were severely
depleted of high frequency components that would have been catastrophic for the typical low-rise,
non-ductile structures in Katmandu. By contrast, systematic damage was observed on the tops of
hills and ridges and at the basin edges, most likely the result of ground motion amplification due to
three-dimensional site effects. Isolated cases of liquefaction and lateral spreading of the
unconsolidated sediments were also observed, but have not yet revealed a systematic damage
pattern. To date, several questions linger about the causative factors of the high frequency
‘anomaly’, which limited structural damage to the very few high-rise buildings in Katmandu, and
triggered localized liquefaction and widespread slope stability failures. In this talk, I will use
observational evidence from earthquake reconnaissance by several individuals and organizations
and a new dataset of strong motion records from an array across Katmandu to shed light to some of
these questions, raise some more, and highlight the lessons learned in Nepal that can help build a
safer Los Angeles.
Poster Session Schedule

Sunday, September 13, 2015
21:00 – 22:30 Poster Session 1

Monday, September 14, 2015
16:00 – 17:30 Poster Session 2
21:00 – 22:30 Poster Session 3

Tuesday, September 15, 2015
16:00 – 17:30 Poster Session 4
21:00 – 22:30 Poster Session 5

Earthquake Engineering Implementation Interface (EEII)

001 Validation and Insights of Utilizing Simulated Ground Motions for Building Response Assessments, Nenad Bijelic, Ting Lin, and Gregory Deierlein

002 Engineering Validation of Simulated Ground Motions for Skewed-bridges Response Assessment, Carmine Galasso, Farzin Zareian, Peyman Kaviani, and Alexandra Tsioulou

003 Considering rupture directivity in selecting ground motion ensembles for seismic response analysis in the near-fault region, Karim Tarbali

004 Using Building Strong Motion Data to Quantify Blast Pressure Fields in Urban Environments, Anthony T. Massari

005 Damage Maps for the 2015 M7.8 Gorkha Earthquake from Spaceborne Radar Interferometry, Sang-Ho Yun, Kenneth Hudnut, Susan Owen, Frank Webb, Mark Simons, Patricia Sacco, Eric Gurrola, Gerald Manipon, Cunren Liang, Eric Fielding, Pietro Millillo, Hook Hua, Alessandro Coletta

Ground Motion Prediction (GMP)

006 On the Use of Simulated Ground Motions as a Means to Constrain Near-Source Ground Motion Prediction Equations in Areas Experiencing Induced Seismicity, Samuel A. Bydlon, Eric M. Dunham, Abhineet Gupta, N. Anders Petersson, and Ossian O’Reilly

007 Broadband (0–8 Hz) Ground Motion Variability From Ensemble Simulations of Buried Mw 6.7 Thrust Earthquakes Including Rough Fault Descriptions and Q(f), Kyle Withers

008 Quantification of ground motion reductions by fault zone plasticity, Daniel Roten, Kim B. Olsen, Steven M. Day, and Yifeng Cui

009 0-5 Hz Verification and Validation of Deterministic Ground Motion Prediction of the 2014 M5.1 La Habra, CA, Earthquake, Kim B. Olsen, Jacobo Bielak, Scott Callaghan, Po Chen, Yifeng Cui, Steven Day, David Gill, Robert Graves, Tom Jordan, Naem Khoshnevis, En-Jui Lee, Phil Maechling, Daniel Roten, William Savran, Fabio Silva, Zheqiang Shi, Ricardo Taborda, Kyle Withers,

010 Kinematic Ground Motion Simulations on Rough Faults Including Effects of Random Correlated Velocity Perturbations, Robert W. Graves and Arben Pitarka

011 Toward a 3D Kinematic Rupture Generator Based on Rough Fault Spontaneous Rupture Models, William H. Savran and Kim B. Olsen

012 Testing the SH1D Assumption for Geotechnical Site and Basin Response Using 3D Finite Difference Modeling, Arthur J. Rodgers and Arben Pitarka

013 Physics-based and empirical models of site response for SCEC ground motion simulations, Carlos Gonzalez, Albert Yang, Jian Shi, and Dornnik Asimaki

014 Stochastic characterization of 3D mesoscale seismic velocity heterogeneity in Long Beach, California, Nori Nakata and Gregory C. Beroza

015 3D Canterbury Velocity Model (CantVM) – Version 1.0, Brendon A. Bradley, Robin Lee, Ethan Thomson, Francesca Ghisetti, Christopher McGann, and Jarg Pettinga

016 Improvements of ground motion duration metrics with empirically derived scattering impulse response functions, Jorge G. F. Crempien, Ralph J. Archuleta, and Chen Ji

017 Progress Report on Improvements to the Composite Source Model for the Broadband Platform, With Emphasis on High Frequencies, John G. Anderson

018 Hybrid broadband ground motion simulation of the 2010-2011 Canterbury earthquakes, Hoby N.T. Razafindrakoto, Brendon A. Bradley, Ethan Thomson, and Robert W. Graves

019 Broadband ground motion modelling of a major Alpine Fault Earthquake (New Zealand), Caroline Holden and Anna Kaiser

020 A non-ergodic Ground-Motion Prediction Equation for California with Spatially Correlated Coefficients, Nicolas M. Kuehn and Niels Landwehr

021 Uncertainty, variability, and earthquake physics in GMPEs: The source component, Annemarie S. Baltay, Thomas C. Hanks, and Norm A. Abrahamson


023 Impact of Uncertainty in Magnitude-Area Scaling Relations on BBP Broadband Simulations, Andreas Skarlatoudis, Jeff Bayless, and Paul Somerville
024 IDA Demonstrates nSpectra as a Valuable New IM, William P. Graf, Yajie J. Lee, and Jeff Bayless
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Meeting Abstracts

Earthquake Stress drop Measurements – Variability and Resolution, Rachel E. Abercrombie (Poster 163)

Measuring the stress drop during an earthquake is fundamental to understanding the physics of the rupture process, and in calculating seismic hazard. Although it is superficially simple to calculate an estimate of stress drop from the radiated spectrum, it is much harder to ensure that measurements are reliable and accurate. The large number of seismological studies of earthquake stress drop, the high variability in results (~0.1-100 MPa), the large uncertainties, and the ongoing controversy of whether stress drop changes with earthquake magnitude are evidence for this. I use earthquakes in the 3 sequences targeted by the San Andreas Fault Observatory at Depth (SAFOD), to investigate resolution and uncertainties of earthquake stress drops calculated using an empirical Green’s function (EGF) approach. I used multiple borehole stations and multiple EGFs.

The source spectra of earthquakes in cluster T1 (M=2.1) are well-fit by a circular source model. The earthquakes stress drops (25-65 MPa) gradually increase, decrease following the 2004 M6 earthquake, then return to previous levels. They correlate with those from previous studies implying that the inter-event variability is resolvable. The spectra of the cluster T2 (M=1.9) include high frequency energy not fit by simple source models and so stress drops are unreliable, and probably under-estimated. There is no correlation with previous studies, and inter-event variation is not resolvable. The earthquakes in the smallest magnitude cluster (M=1.8, T3) have the highest corner frequencies, but similar stress drops (4-120 MPa). The stress drops exhibit the same temporal variation as the first cluster, but there is poor correlation with surface measurements, probably because the frequency bandwidth of the latter is too limited.

I use earthquakes in cluster T1 to quantify the likely uncertainties to arise in less optimal settings. I use EGF earthquakes with a range of cross-correlation values and separation distances from the main earthquakes. Decreasing the either the quality of the EGF assumption required, or the high-frequency limit of the signal bandwidth, both result in underestimates of the corner frequency and stress drop. Using either multiple stations or EGFs both increase the reliability of the stress drop measurements.

Ongoing work involves extending the approach to larger data sets, and investigating stacking over multiple stations or high-quality EGFs to improve resolution.

Determining the uncertainty range of coseismic stress drop of large earthquakes using finite fault inversion, Mareike N. Adams, Chen Ji, Cedric Twizardik, and Ralph Archuleta (Poster 161)

A key component in understanding the physics of earthquakes is the resolution of the state of stress on the fault before, during and after the earthquake. A large earthquake’s average stress drop is the first order parameter for this task but is still poorly constrained, especially for intermediate and deep events. Classicallly, the average stress drop is estimated using the corner frequency of observed seismic data. However a simple slip distribution is implicitly assumed; this assumed distribution is often not appropriate for large earthquakes. The average stress drop can be calculated using the inverted finite fault slip model. However, conventional finite fault inversion methods do not directly invert for on-fault stress change; thus it is unclear whether models with significantly different stress drops can match the observations equally well. We developed a new nonlinear inversion to address this concern. The algorithm searches for the solution matching the observed seismic and geodetic data under the condition that the average stress drop is close to a pre-assigned value. We perform inversions with different pre-assigned stress drops to obtain the relationship between the average stress drop of the inverted slip model and the minimum waveform misfit. As an example, we use P and SH displacement waveforms recorded at telesismic distances from the 2014 Mw 7.9 Rat Island intermediate depth earthquake to determine its average stress drop. Earth responses up to 2 Hz are calculated using an FK algorithm and the PREM velocity structure. Our preliminary analysis illustrates that with this new approach, we are able to define the lower bound of the average stress drop but fail to constrain its upper bound. The waveform misfit associated with the inverted model increases quickly as pre-assigned stress drop decreases from 3 MPa to 0.5 MPa. But the misfit varies negligibly when the pre-assigned stress drop increases from 4.0 MPa to 50 MPa. We notice that the fine-scale roughness of the inverted slip distributions changes dramatically. Future investigations using velocity recordings, which should be more sensitive to fine scale roughness on the fault surface, will be conducted.

Filling the paleoseismic gap between Bidart and Frazier Mountain: Exploration of Van Matre Ranch (VMR) paleoseismic site in the Carrizo Plain, Sinan O. Akcoz, Matthew Marin, Juliet O. Olsen, Eui-jo Marquez, Barrett J. Salisbury, Alana Williams, Tom Rockwell, J Ramon Arrowsmith, Lisa Grant-Ludwig (Poster 085)

In August 2015, we opened one exploration trench at the Van Matre Ranch (VMR) paleoseismic site (35.146321°, -119.688535°) to confirm and expand the Holocene earthquake history of the Carrizo section of the San Andreas Fault (SAF). Trench 1 is located across the simple and subtle 1857 scar of the San Andreas Fault in an area which appears to receive alluvial fan units including well-laminated fine sand and silts originating from the Temblor Range. In trench 1, a 3 m deep, 1 m wide and 30 m long trench, we observed evidence for the last two or three paleoearthquakes in sequence and another one earlier, but potentially out of sequence, event. Apparent vertical offsets, filled fissures, upward terminations and fault-bounded were used to identify these earthquakes. In Trench 1, we found the surface scarp to coincide with a featureless ~3m-wide fault zone. No major bioturbation zones were observed. Detrital charcoal pieces were not as abundant as the Bidart Fan site, ~ 20 km to the NE, but 3 individual charcoal pieces and 1 bulk sample from an organic-rich paleosol layer were collected. In addition, samples from six different quartz-rich fine- to coarse-sand layers near earthquake event horizons were collected for Infra-red stimulated luminescence (IRSL) dating. With the presence of good, undisturbed stratigraphy with abundant datable layers and good access on private property, VMR has the potential to be developed into a high quality paleoseismic site, providing much needed earthquake event data between the Bidart Fan and Frazier Mountain sites.

Velocity contrast and 10km vertical Moho offset across the Denali fault from double-difference tomography and fault zone head wave analysis, Amir A. Allam, Natalia Ruppert, Zachary E. Ross, and Yehuda Ben-Zion (Poster 184)

We present tomographic images of lithospheric structure along the Denali fault in central Alaska based on double-difference inversions of earthquake arrival times. We discretize the region with a uniform grid spacing of 3km within a 600km by 500km by 60km volume. We invert for VP, VS, and hypocenter location using data from 5634 earthquakes recorded at 326 stations, incorporating 715,000 P and 229,000 S wave phase arrivals. The use of this large dataset provides resolution throughout the crust and into the upper mantle up to depths of 75km, with diminishing resolution below 50km depth as determined with checkerboard tests and calculation of the inversion derivative weight sum. The tomographic results indicate that the Moho is offset by approximately 10km along the entire resolved length of the Denali fault, with the northern side having the shallower Moho depths around 30km. This indicates that the Denali fault is likely a deep lithospheric structure which penetrates into the upper mantle. The shallow crustal velocity structure of the Denali fault is more complicated with high-velocity plutonic bodies and low-velocity subsidiary fault zones, though the northern side of the fault generally has slightly lower velocities. In order to bolster the tomographic images we analyze more than 100 events recorded at 55 near-fault stations to find fault zone head waves, which offer a clear indication of a sharp across-fault velocity contrast. In addition to picking head waves manually using horizontal particle motion, we run an automated picker over the entire dataset using no assumptions about likely head wave distributions. Most
of the head wave detections are located on the northern side of the fault near the town of Healy, though the source-receiver geometry may be suboptimal for detection in other portions of the fault zone. Taken together, the tomographic and head wave results have important implications for the shallow crust, deeper lithospheric structure, and tectonic history of the Denali fault and the Central Alaskan Interior.

**Earthquake Cycle Simulations of the Imperial Fault with Viscoelasticity and Rate-and-State Friction**, Kali L. Allison, Brittany A. Erickson, and Eric M. Dunham (Poster 249)

The Imperial fault, which crosses the border between California and Mexico, accommodates almost 80% of the relative motion between the North American and Pacific plates (Lyons et al., 2002). It cuts through the Salton Trough, where the two plates are pulling apart, resulting in a shallow Moho and a thick layer of loosely consolidated sediments near the surface. Two major earthquakes have occurred on this fault in the recent past. In 1940, a magnitude 7.1 earthquake ruptured the entire length of the fault. This was followed 39 years later by a magnitude 6.6 in which surface slip occurred on only the northern third of the fault and most of the slip was confined beneath the layer of sediment (Rockwell and Klinger, 2013). In this study, we explore how the material structure in this region influences characteristics of the earthquake cycle on this fault, such as the recurrence interval and the coseismic and postseismic slip distributions.

We have implemented a parallel code that simulates earthquake cycles on a strike-slip fault in two dimensions. Both rate-and-state friction on the fault and Maxwell viscoelastic deformation are modeled. The method uses a spatial discretization that accommodates variable off-fault material properties and depth-dependent frictional properties. Idealized simulations focusing on the effects of the sedimentary basin, represented as an elliptic region of decreased shear modulus and density, show that a sufficiently deep and compliant basin will prevent ruptures from propagating through the basin to the surface, producing an alternating sequence of sub-basin and surface-rupturing events. To test if the Salton Trough sedimentary basin can produce this sequence, we ran a simulation using wave speed and density distributions from SCEC’s Community Velocity Model. This simulation showed that the basin significantly slows the upward-propagating rupture, even with velocity-weakening frictional properties in the basin. This means that if velocity-strengthening properties are included on the shallowest part of the fault, then it may be possible to produce both sub-basin and surface-rupturing events. Preliminary simulations with a layered viscosity structure and uniform shear modulus show that viscosities ranging from 1e18 - 1e21 Pa s in the lower crust only slightly impact the recurrence interval and surface slip of each event, but do significantly reduce the amount of postseismic slip that occurs on the fault at depth.

**EZ-FRISK implementation of the USGS 2014 NSHM seismic source model and ground motion prediction equations**, Jason Altekruze, Alireza Haji-Soltani, Katherine Reyes, and Osman El Menchawi (Poster 047)

The major objective of this project is to implement the updated USGS 2014 NSHM seismic source models and ground motion prediction equations (GMPEs) into EZ-FRISK seismic hazard software, comparing the results to the USGS 2014 NSHM data and demonstrating the software’s seismic hazard analysis capabilities (probabilistic and deterministic hazard curves, seismic hazard maps, and deaggregation of seismic hazard). We validate the results of the EZ-FRISK implementation at over 120 sites across the U.S. to the published USGS 2014 NSHM data and discuss the results in terms of different modeling approaches such as logic trees, fault geometry, gridded seismicity, and uncertainties. The USGS 2014 NSHM model incorporates the third generation of the Uniform California Earthquake Rupture Forecast (UCERF3) model, which is not easily used for classic probabilistic seismic hazard calculations for arbitrary sites, and cannot be implemented directly in EZ-FRISK. The magnitude frequency distributions (MFD) from UCERF3 include participation of fault segments in ruptures on adjacent faults, and these MFD must be individually adjusted on a site-specific basis to avoid double counting seismic hazard. We compare the results for sites in California using the EZ-FRISK implementation of the USGS 2008 NSHM California source model (UCERF2) with the 2014 NSHM data for California.
However, the Bryce Canyon erosion rate (6-13 m per millennium) that they refer to is the horizontal progression of the canyon rim, not the erosion of the Hoodoos themselves. The 6-13 mm/yr rate they refer to is consistent with another rim erosion rate of 10 mm/yr at Bryce Canyon that has been determined accurately by dating tree rings that survive at its perimeter (Chronic and Chronic, 2004). The erosion rate of hoodoos must be slower than the basin scale erosion rate, which is in turn slower than the progression of the rim. The mechanism of hoodoo’s superior resistance to erosion compared to the basin erosion rate (and in turn the rim erosion rate) is well described by “fabric interlocking”, that is, increased strength as a result of vertical loading prior to and during their emerging from the basin (Bruthans et al., 2014). Time-lapse photographs taken at the Red Rock Canyon State Park hardly show any differences in the landscape in 66 years (1933-1999). Similarly, time-lapse photographs of the two hoodoos investigated in Anooshehpoor et al. (2013) show no visible changes in their shapes in 21 years (1984-2015). Evidence for thinning of two sets of hoodoos at Bryce Canyon exposed 17500 years apart, suggest an erosion rate of 0.017 mm/yr, more than two orders of magnitude smaller than that of the canyon rim. At this rate, the hoodoos at Red Rock canyon would erode less than two centimeters per millennium, thus rendering them useful to constraining seismic hazard.

**Impact from Magnitude-Rupture Length Uncertainty on Seismic Hazard and Risk**, Trey Apel, Deborah Kane, Natanya Porto, and Marleen Nyst (Poster 148)

In probabilistic seismic hazard and risk assessments seismic sources are typically divided into two groups: fault sources and background sources. Background sources can be modeled as areas, points or pseudo-faults. When background sources are modeled as pseudo-faults, magnitude-length or magnitude-area scaling relationships are required to construct these pseudo-faults. However the uncertainty associated with these relationships is often ignored or discarded in hazard and risk models, particularly when faults sources are the dominant contributor. Conversely, in areas like the Central and Eastern United States and Hawaii the hazard and risk is driven primarily by background sources and these uncertainties are much more significant. Stirling et al. (2013) showed that for a given suite of magnitude-rupture length relationships the variability can be quite large. In this study we test the impact of using various relationships and the resulting epistemic uncertainties on the seismic hazard and risk in the Central and Eastern United States and Hawaii. The 2014 US National Seismic Hazard Maps (Petersen et al., 2014) used only one magnitude-rupture length relationship (Somerville, et. al., 2001) in the Central and Eastern United States and did not consider variability in the seismogenic rupture plane width. We use a suite of metrics to compare the USGS approach with these variable uncertainty models to assess 1) the impact on hazard and risk and 2) the epistemic uncertainty associated with choice of relationship. In areas where the seismic hazard is dominated by larger crustal faults (e.g. New Madrid) the choice of magnitude-rupture length relationship has little impact on the hazard or risk. However away from these regions the choice of relationship is more significant and may approach the size of the uncertainty associated with the ground motion prediction equation suite.

**Interseismic strain accumulation in metropolitan Los Angeles in the context of oil and water management**, Donald F. Argus, Piyush Shanker Agram, Christopher Rollins, Sylvain Barbot, and Jean-Philippe Avouac (Poster 203)

**MAIN POINT.** InSAR measurements from 1992 to 2012 are detecting deformation due to oil pumping and groundwater changes throughout metropolitan Los Angeles. This is allowing elastic strain build up on blind thrusts beneath the city to be accurately evaluated using GPS.

**OIL FIELDS.** Pumping and repressurization of oil fields have generated substantial displacement in metropolitan Los Angeles, causing Beverly Hills, downtown, and Whittier to subside at 3–10 mm/yr and Santa Fe Springs and La Mirada to rise at 5–9 mm/yr.

**AQUIFERS.** Displacements of the Santa Ana and San Gabriel Valley aquifers accumulate in response to sustained changes in groundwater over periods of either drought or heavy precipitation. Santa Ana aquifer has subsided nearly 0.1 m in response to lowering of the groundwater level by about 25 m over the past 18 years.

**ANTHROPOGENIC VS. TECTONIC MOTION.** We are assessing horizontal motions due to changes groundwater using an empirical relationship established on the basis of seasonal oscillations of Santa Ana aquifer. Anthropogenic horizontal motion is estimated to be proportional to the directional gradient in vertical motion inferred with InSAR. We are finding this rough approximation to be quite useful for evaluating deviations of GPS position from a constant velocity.

**EARTHQUAKE STRAIN BUILDUP ON BLIND THRUST FAULTS.**

NNE contraction perpendicular to the big restraining bend in the San Andreas fault is fastest not immediately south of the San Andreas in the San Gabriel Mountains, but instead 50 km south of the fault in northern Los Angeles. Stereographic models of interseismic strain accumulation fit to GPS data and incorporating a 1D approximation of the rheology of the Los Angeles basin indicates the deep segment of the Puente Hills (~upper Elysian Park) Thrust to be slipping at 9 ±2 mm/yr beneath a locking depth of 12 ±5 km. Please see also our complementary study [Rollins et al., AGU 2015] exploring elastic models with 3D geometry. This 9 mm/yr geodetic slip rate for the Puente Hills Thrust system is faster than the 3–5 mm/yr cumulative geologic slip rate for the upper Elysian Park and Puente Hills Thrust, indicating that M 6.5 and M 7 earthquakes in metropolitan Los Angeles are more frequent than forecast.

**Paleogeodesy of the Southern Santa Cruz Mountains Frontal Thrusts, Silicon Valley, CA**, Felip Aron, Samuel A. Johnstone, Andreas P. Mavrommatis, Robert M. Sare, and George E. Hilley (Poster 227)

We present a method to infer long-term fault slip rate distributions using topography, by coupling a three-dimensional elastic boundary element model with a geometric incision rule. In particular, we used a 10 m-resolution digital elevation model (DEM) to calculate channel steepness (kSN) throughout the actively deforming southern Santa Cruz Mountains in Central California. We then used these values with a power-law incision rule and the Poly3D code to estimate slip rates over seismogenic, kilometer-scale thrust faults accommodating differential uplift of the relief throughout geologic time. Implicit in such an analysis is the assumption that the topographic surface remains unchanged over time as rock is uplifted by slip on the underlying structures. The fault geometries within the area are defined based on surface mapping, as well as active and passive geophysical imaging. Fault elements are assumed to be traction-free in shear (i.e., frictionless), while opening along them is prohibited. The free parameters in the inversion include the components of the remote strain-rate tensor (cij) and the bedrock resistance to channel incision (K), which is allowed to vary according to the mapped distribution of geologic units exposed at the surface. The nonlinear components of the geomorphologic model required the use of a Markov chain Monte Carlo method, which simulated the posterior density of the components of the remote strain-rate tensor and values of K for the different mapped geologic units. Interestingly, posterior probability distributions of cij and K fall well within the broad range of reported values, suggesting that the joint use of elastic boundary element and geomorphic models may have utility in estimating long-term fault slip-rate distributions. Given an adequate DEM, geologic mapping, and fault models, the proposed paleogeodetic method could be applied to other crustal faults with geological and morphological expressions of long-term uplift.

**The high frequency ‘anomaly’ that saved lives: Site effects and damage patterns of the 2015 Gorkha Earthquake**, Domniki Asimaki (Invited Talk Wed 08:00)

Although the M7.8 Gorkha mainshock ruptured a segment of the Main Himalayan Thrust directly below Katmandu, structural damage across the valley was much lower than expected. Strong motion data prominently featured a 5-sec pulse that reverberated in the basin, but were severely depleted of high frequency components that would have been catastrophic for the typical low-rise, non-ductile structures in Katmandu. By contrast, systematic damage was observed on the tops of hills and ridges and at the basin edges, most likely the result of ground motion amplification due to three-dimensional site effects. Isolated cases of liquefaction and lateral spreading of the unconsolidated sediments were also observed, but have not yet revealed a systematic damage pattern. To date, several questions linger about the causative factors of the high frequency ‘anomaly’, which limited structural damage to the very few
Evaluation of the SCEC Seismic Velocity Models through Simulation and Validation of Past Earthquakes, Shima Azizzadeh-Roodpish, Ricardo Taborda, Naeem Khoshtonevis, and Keli Cheng (Poster 037)

SCEC scientists have devoted significant effort over the last two decades to the development of various seismic velocity models for southern California. These models are mostly used in forward wave propagation simulation, but also as reference for tomographic and source inversions, and in other seismology and engineering problems. Two of these models, CVM-S and CVM-H, are among the most commonly used. This includes alternative variations such as the recently released model CVM-S4.26, which incorporates results from a sequence of tomographic inversions, and the user-controlled option of CVM-H to replace the near-surface profiles with a Vs30-based geotechnical layers (GTL) model. All four alternatives are thought acceptable, yet they have distinctions that lead to different results in forward simulations. The present study evaluates the accuracy of these models to predict the ground motion in the greater Los Angeles region through the validation of a series of past earthquake simulations. We present results for simulations of 30 moderate-magnitude earthquakes (3.5 < Mw < 5.5), and compare synthetics with data using a goodness-of-fit (GOF) method. The simulations are done with a finite element parallel code, with numerical models that satisfy a maximum frequency of 1 Hz and a minimum shear wave velocity of 200 m/s. We analyze the regional distribution of the GOF results for all events and all models, and search for correlations between the results and the characteristics of the models. Based on our comparisons, we identify which model consistently yields better results and present arguments that help explain why this is the case.

Dynamic Rupture Simulation of the Mw7.7 Balochistan Earthquake, Kangchen Bai, Jean-Paul Ampuero, Amaury Vallage, and Yann Klinger (Poster 241)

The 2013 Mw7.7 Balochistan Earthquake occurred at the junction of a strike slip fault and a reverse fault. Coseismic slip as is constrained by seismic and geodetic observations shows a strike slip to dip slip ratio of 6:1. While the long term kinematics revealed by fault zone geomorphology shows a systematic variation from strike-slip dominating to dip-slip dominating from north to south. By applying dynamic rupture simulations over such a geologically complicated fault system, we are trying to prove the possibility that dynamic stress can make a fault deviate from its long-term kinematics during an earthquake. We are using a regional stress field derived from measurements of surface crack orientation distribution, which is indicating a north-south compressional regime in the fault area. We test the dynamic effect caused by the variations in nucleation locations. It only causes second order variations on final slip distribution whether the rupture is nucleating at the reverse fault segment or the strike slip segment under a slip weakening friction law. We further emphasize the dynamic effect on a fault with spatial varying oblique slip by using a rate-and-state friction law with friction law. We further emphasize the dynamic effect on a fault with spatial varying oblique slip by using a rate-and-state friction law with friction law. We further emphasize the dynamic effect on a fault with spatial varying oblique slip by using a rate-and-state friction law with friction law. We further emphasize the dynamic effect on a fault with spatial varying oblique slip by using a rate-and-state friction law with friction law.
residuals (“event terms”) for individual clusters of earthquakes, and compare them to spatially dependent, seismologically determined stress drops to highlight how physical parameters can be incorporated into GMPEs.

The Performance of Triangular Fault Elements in Earthquake Simulators, Michael Barall and Terry E. Tullis (Poster 051)
An earthquake simulator is a computer program that generates a synthetic earthquake catalog spanning thousands of years, or longer. Most of the computational effort in an earthquake simulator goes into computing how slip on one part of a fault affects stresses on other parts of the fault, and on other faults. The computation is done by discretizing the fault system into a large number of fault elements, and using Greens functions to determine how a pattern of slip on some fault elements affects the stresses on all the fault elements. Traditionally, earthquake simulators have used rectangular fault elements, chosen so that the Okada Greens functions can be used. Recently, due to the development of new Greens functions for triangular dislocations, it has become practical to use triangular fault elements. The purpose of this project is to assess the accuracy of stress calculations performed with triangular fault elements, as compared to the accuracy of the same calculations done with rectangular fault elements. For planar faults, rectangles and triangles can be expected to give the same results. But when a fault is curved, partitioning it into rectangular fault elements will necessarily create gaps and overlaps between adjacent elements. In contrast, partitioning a curved fault into triangular fault elements can be done using a triangular mesh which has no gaps or overlaps between adjacent elements. Because triangles can represent curved fault geometry more accurately than rectangles, one intuitively expects that stress calculations performed with triangles should be more accurate than stress calculations done with rectangles. However, our results are contrary to the intuitive expectation. In our tests, triangles are not superior to rectangles. One or the other may be superior in a particular case, but, overall, rectangles perform as well as or better than triangles. Another unexpected result is that one triangulation of a fault surface may perform significantly better than another triangulation with a different pattern of triangles.

Sources of Subsidence at the Salton Sea Geothermal Field, Andrew Barbour, Eileen Evans, Stephen Hickman, and Mariana Eneva (Poster 235)
Earlier PS-InSAR analysis of satellite data collected over the Salton Sea geothermal field (SSGF) between 2003 and 2010 showed that the ground surface subsided continuously within a ~25 km<sup>2</sup> anomaly, reaching a maximum absolute rate of ~52 mm/yr. After finding that this pattern of observed subsidence is not consistent with aseismic fault-slip across tectonic structures inferred from seismic data, we compared the same geodetic observations with predictions based on a poroelastic model that simulated the industrial injection and production activities in this geothermal field. This model, which expresses the surface subsidence in terms of volumetric strain coupled with fluid-mass loss from a simplified model of the reservoir at depth, appears to be capable of replicating the geodetic data in a way that is consistent with subsidence due to geothermal operations in this field. Based on parameter estimates obtained through nonlinear inversion, we find that at least 95% confidence levels the source of this mass loss is at depths comparable to those of both the generalized boundaries of the geothermal reservoir and the zone of peak seismicity rates in the vicinity. While these results do not necessarily implicate industrial operations at the SSGF, they underscore the need for further study on the effects that varying injection and production rates have on the state of stress, temperature, and pore-fluid pressure in the reservoir. Although this geothermal field is within a region of active tectonics, analysis of dense high-resolution geodetic data reveals that the observed subsidence is almost certainly a consequence of the net pressure in the reservoir. Although this geothermal field is within a region of active tectonics, analysis of dense high-resolution geodetic data reveals that the observed subsidence is almost certainly a consequence of the net pressure in the reservoir. However, our results are contrary to the intuitive expectation. In our tests, triangles are not superior to rectangles. One or the other may be superior in a particular case, but, overall, rectangles perform as well as or better than triangles. Another unexpected result is that one triangulation of a fault surface may perform significantly better than another triangulation with a different pattern of triangles.

Paleoearthquake evidence from Elizabeth Lake and constraints on rupture patterns for the Mojave section of the south-central San Andreas Fault, Sean P. Bemis, Kate Scharer, James F. Dolan, Edward Rhodes, Alex Hatem, and Crystal Wesppestad (Poster 082)
The extent and variability of latest Holocene paleo-ruptures along the south-central San Andreas Fault has been the focus of numerous paleoseismologic studies which have resulted in both key constraints on the patterns of prehistoric earthquakes and highlighted where critical ‘gaps’ in data remain. We developed the Elizabeth Lake paleoseismic site in the center of the Mojave section of the south-central San Andreas Fault, near the middle of the 100 km span between the Frazier Mountain and Pallett Creek sites, to fill a gap in the understanding of paleoearthquake extent along the SAF. We have completed three field campaigns at the site, ultimately excavating and documenting 10 trenches that span portions of an elongate (~40 x 350 m) geomorphic depression that has been filled due to a bedrock-cored shutter ridge on the NW (downhill) side. Radiocarbon dates establish that the excavations expose >2000 years of stratigraphy deformed by a relatively narrow fault zone. The best stratigraphic resolution occurs within the past ~800 years where we have documented evidence for 4–5 earthquakes. We have good evidence for the 1857 event and another earthquake after the mid 1700s. We have strong evidence for two more events during the preceding 500 years. The stratigraphic position (relative age) of a possible fifth paleoearthquake is unclear due to lateral slip and fault overprinting; this event will be dated using luminescence (pIR IRSL). Comparison to adjacent paleoseismic records permits only one ~300-km-long, 1857-like rupture during the past 800 years. Our ongoing efforts are focused on improving the age control within the upper stratigraphic section (~1250 cal AD) and finalizing our catalog of evidence for each event. Radiocarbon age control illustrates a significant detrital component to charcoal ages, with up to 500 year variability for samples from the same layer. Pending pIR IRSL ages from key stratigraphic horizons should clarify the age of some events, improve our age constraints on the timing of the latest Holocene paleoearthquakes, and provide a test for luminescence dating of young sediments in organic rich environments.

Complexities in cosmogenic dating of arid region alluvial fans, Whitney M. Behr, Peter Gold, Warren Sharp, Dylan Rood, Tom Rockwell, Katherine Kendrick, Tom Hanks (Poster 095)
Cosmogenic exposure dating of alluvial fans can be used to inform a wide range of tectonic and geomorphic processes, but requires simplifying assumptions about the local geologic processes that contribute to exposure history. Here we describe three case studies in which common-practice assumptions for estimating exposure age yield precise but erroneous results. We focus on multi-component datasets from three debris-flow- dominated arid region alluvial fans (one Holocene, two late Pleistocene) located along the San Andreas in the Coachella Valley of southern California. These include the Qfr and Qoa3 fans along the Banning fault recently discussed by Gold et al. (JGR, 2015) and the Bisnark fan along the Mission Crags fault described by (GSAB, 2010). All three fans yield model exposure ages obtained from sand collected from depth profiles that are >40-60% younger than the minimum depositional age constrained by U-series dating on pedogenic carbonate and degrees of soil development in the same profile. Cobbles and boulders on the fan surfaces yield exposure ages that are much closer to the minimum ages derived from U-series dates and soils. These seemingly disparate datasets may be reconciled through consideration of geologic processes that are common during alluvial fan construction and degradation. We use forward models to explore two possible scenarios: 1) incremental deposition of the dated profiles, and 2) progressive fan-surface lowering by erosion of fine-grained matrix. Both mechanisms predict nearly uniform 10Be concentrations in the profiles at depths below ~100 cm, effectively mimicking the nuclide distribution expected for much younger deposits. The 10Be profile from the Holocene fan can be fit by either non-uniform inheritance in the sand-sized fraction or incremental deposition of the dated profile. The data from the older Pleistocene fans are consistent with up to 1.5 m of progressive surface lowering and some inheritance in the sand-sized fraction, but cannot be explained by incremental growth. These case studies illustrate some of the real-Earth complexities that can complicate cosmogenic exposure histories and demonstrate the advantages of combining soils observations, U-Th and 10Be geochronometry, and multiple cosmogenic sampling strategies, in order to more reliably date alluvial fans.

Shallow structure of the San Jacinto fault zone and detailed catalog of seismic sources based on spatially-dense array data, Yehuda Ben-Zion (Invited Talk Tue 08:00)
I review results (*) on imaging the shallow structure of San Jacinto fault zone and detection/location of seismic energy sources using data of a spatially-dense Nodal array centered on the Clark branch of the fault. The array operated at the Sage Brush site south of Anza for about 4 weeks in 2014 with 1108 vertical (10 Hz) geophones in about 650 m x 700 m box configuration. Continuous waveforms with signals generated by the ambient seismic noise, earthquakes, and Betsy gunshots were recorded with useable frequencies up to 200 Hz. The shallow structure imaging is done with surface and body waves extracted from the ambient noise, arrivals from local and teleseismic earthquakes, and waves generated by the gunshots. The results document very low seismic velocities and attenuation coefficients, strong lateral and vertical variations, seismic trapping structure, local sedimentary basin, and overall lithology contrast across the fault. The detection/location techniques include stacking, beamforming, matched field processing, and templates generated by these methods. The analysis uncovers many hundred of daily earthquakes not detected by the regional networks and several different types of surface noise sources.

*The research was done in collaboration with F. Vernon, Z. Ross, P. Roux, D. Zigone, G. Hillers, H. Meng, M. Campillo & others

**Great ShakeOut Earthquake Drills, Mark L. Benthien, Jason E. Ballmann, and John E. Marquis (Poster 302)

Great ShakeOut Earthquake Drills began in southern California in 2008, to involve the general public in a large-scale emergency management exercise based on an earthquake on the San Andreas fault (the USGS “ShakeOut Scenario” developed by a team of more than 300 experts led by Dr. Laura F. Lentini). While no longer focused on the ShakeOut scenario, ShakeOut worldwide continues to communicate scientific and preparedness information based on 30 years of research about why people choose to get prepared. Its purpose is to motivate everyone, everywhere to practice earthquake safety (“Drop, Cover, and Hold On”), and to get prepared at work, school, and home.

SCEC has hosted the ShakeOut website (www.ShakeOut.org) since the beginning and created a registration system. In 2008 more than 5.4 million Californians participated. Though originally intended to be held only once, requests from ShakeOut participants prompted partners and state agencies to expand the event statewide as an annual ShakeOut drill on the third Thursday of October. This date is ideal for schools and follows National Preparedness Month in September, allowing for significant media exposure prior to the drill. While K-12 and college students and staff comprise the largest number of participants, the ShakeOut has also been successful at recruiting participation of businesses, non-profit organizations, government offices, neighborhoods, and individuals. Each year participants are encouraged to incorporate additional elements of their emergency plans into their ShakeOut drill. More than 10.4 million Californians participated in October, 2014.

In addition to its lead role in organizing the California ShakeOut, SCEC manages a growing network of ShakeOut Regions across the country (with support from FEMA) 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. In total more than 26.5 million people registered to participate in 25 Official ShakeOut Regions in 2014. ShakeOut websites are now online in English, Spanish, French, Italian, and Japanese. SCEC now also manages TsunamiZone.org and supports FEMA’s America’s PrepareAthon multi-hazard campaign (ready.gov/prepare), both which are based on the ShakeOut model.

**Foraminifera Zonations in Southern California Salt Marshes, John M. Bentz, Alex Simms, and Pamela Buza-Stephens (Poster 106)

Salt marsh foraminiferal species live in distinct elevation zones relative to tidal and sea level datums. Their strict vertical zonation can be used as a tool in recognizing rates of sea-level rise as well as tectonic activity along the coast. Although foraminifera have been used worldwide to reconstruct past sea levels, no such elevation zonations have been produced for southern California salt marsh foraminifera. We sampled foraminifera from three southern California estuaries: Carpenteria Slough, Mugu Lagoon, and Sweetwater Marsh, for the purpose of establishing a foraminifera zonation for southern California marshes. The results from Carpenteria Slough display a distinct zonation in foraminifera species based on their elevation in relation to tidal datums. The high marsh foraminifera consist primarily of Trocholina inflata and show a small assemblage of Milammina fusca. The low (subtidal) marsh is dominated by textulariids and rotaliids, while also showing an abundance of pelagic foraminifera and several deep-sea benthic species. These results will allow for the construction of a better-defined paleo sea level curve for southern California, as well as providing insights into tectonic activity along the southern California coast.

**Grey Layers in Santa Barbara Basin: measures of earthquake frequency?, William Berelson, Laura Morine, and Nick Rollins (Poster 108)

We have been studying the geochmical nature of grey layers found frequently in Santa Barbara Basin laminated sediment cores. These grey layers have been considered to represent flood deposits as they contain clays and many layers are correlated across the basin. However, we find that many layers are NOT correlated across the basin and think this argues for a submarine landslide source rather than flood. Further, we find marine fossils within the grey layer, suggesting marine source. The grey layers that we’ve examined (8 of them) are very consistent in terms of carbon content and inorganic and organic C isotope value. Relatively few 14C ages indicate that grey layer Corg is a few hundred years older than surrounding Corg but grey layer CInorg is 4,000-7,000 years older than surrounding CInorg. This observation, and the light 13C isotopic composition of the CInorg are difficult to reconcile with either a flood or submarine landslide source. Organic compound analysis is underway.

**Fingerprint and Similarity Thresholding (FAST) for Computationally Efficient Earthquake Detection, Karianne Bergen, Clara Yoon, Ossian O’Reilly, Yihe Huang, and Gregory Beroza (Poster 132)

Cross-correlation based earthquake detection methods have been shown to be sensitive and able to detect low-magnitude events by identifying similar waveforms in continuous seismic data. Existing methods have limitations; template matching can only find new events that are similar to known templates, and autocorrelation has poor scaling properties that make its use for long-duration data sets prohibitive. We have developed a computationally efficient method for waveform correlation-based detection called Fingerprint and Similarity Thresholding (FAST). FAST performs a blind search for similar waveforms without relying on known template events, and has potential to scale to long-duration continuous seismic data. The method involves two key steps: extracting discriminative features from waveforms to create compact representations called “fingerprints,” and using locality-sensitive hashing to construct and efficiently search a database to identify similar waveform fingerprints. We demonstrate the ability of FAST to detect uncataloged earthquakes using single and multi-station data during an aftershock sequence near the Calaveras fault, with a significant speed-up compared with autocorrelation. We will present initial results for uncataloged earthquakes in the Guy-Greenbrier, Arkansas, earthquake sequence identified using FAST that have not been identified in previous template-matching studies. We will also present on-going algorithmic improvements for network-based detections using foreshocks of 2014 Iquique earthquake as a test case.

**Constraints from xenoliths on the rheology of the Mojave lower crust and lithospheric mantle, Rachel E. Bernard and Whitney M. Behr (Poster 234)

We use xenoliths from young (3 Ma to present) cinder cones in the tectonically active Mojave region of southern California to characterize the rheological properties of the lower crust and upper mantle beneath the Eastern California Shear Zone (ECSZ). The xenoliths, which include spinel and plagioclase facies peridotites and lower crustal rocks (representing a depth range of ~25-60 km), were collected from two localities ~80 km apart: the Cima and Dish Hill volcanic fields. We document how stress, temperature, water content, deformation mechanism, lattice preferred orientation, and style of localization vary spatially and with depth. Key findings include the following:

(1) Both xenolith suites exhibit a wide range of deformation textures, ranging from granular, to protogranular, to porphyroclastic and mylonitic.
Higher strain fabrics show no evidence for static annealing, thus are likely reflecting youthful deformation. These high strain fabrics are localized and may represent the ductile extensions of ECSZ faults into the lithospheric mantle.

(2) Both xenolith suites show abundant dynamic recrystallization and other evidence for dislocation creep as the dominant deformation mechanism.

(3) Water contents—from Fourier transform infrared spectroscopy (FTIR) and Secondary Ion Mass Spectrometry (SIMS)—range from 115-254 ppm for clinopyroxene, 35-165 ppm for orthopyroxene, and less than 10 ppm for olivine.

(4) Deformation in most lower crustal gabbros is weak, but some show strong fabrics associated with plagioclase-rich zones. Water content from clinopyroxene in one highly-deformed gabbro is <1 ppm.

(5) Recrystallized grain size paleopiezometers for olivine and plagioclase indicate stress magnitudes of 16-21 MPa for the uppermost mantle, and 0.1 MPa for the lowermost crust.

These data can be used as inputs for the SCEC Community Rheology and Stress Models for the Mojave region, as well as in long-term post-seismic relaxation models of earthquakes in the Mojave region.

**Alternative Rupture Basis for UCERF3, Glenn P. Biasi (Poster 046)**

UCERF3 was the most comprehensive earthquake rupture forecast yet produced for California. Notable innovations in UCERF3 included removing explicit fault segmentation and including fault-to-fault rupture topologies. Faults were discretized into ~7 km long “subsections”, and, subject to certain compatibility rules, ruptures in the forecast consist of all unique combinations of two or more subsections. The “unique combinations” rule allows the forecast to model all possible ruptures on the fault system, but it comes with unintended consequences. Two are most important. First, because California faults are so connected, there are far more long ruptures than short ones input to the inversion, while there must be far fewer long ruptures in the output to recover a Gutenberg-Richter magnitude-frequency distribution (MFD) for regional seismicity. This creates computational stress on the inversion process. Second, the process results in over 550,000 ruptures. The shear size of the forecast has slowed model adoption by the seismic hazard community. We investigate an alternative rupture basis that addresses both of these difficulties.

Our approach instead seeks a rupture set that produces all possible ground motions. Observed from a single subsection, ground motion scales with magnitude, so ruptures that span the magnitude space will span the corresponding hazard space. Similar rupture sets starting at adjacent subsections involve the initial subsection in an interconnected web of ruptures. Uniform magnitude spacing leads to a power-law distribution of rupture lengths and an estimated 60% reduction in the number of necessary ruptures to model the fault system. Power-law spacing also allows smaller subsection discretization, which will help with engineering-scale model applications where the hazard is dominated by M6 to 6.8 size ruptures. The key tool for model evaluation is the subsection MFD. Rupture collections resulting in the same subsection MFDs produce equivalent hazards. This provides a mechanism to benchmark alternative rupture bases. Later in the project we will test the sensitivity of the method to GMPE and magnitude-area relations. The ultimate goal will be an algorithm suitable for implementation by UCERF4.

**Validation and Insights of Utilizing Simulated Ground Motions for Building Response Assessments, Nenad Bijelic, Ting Lin, and Gregory Deierlein (Poster 001)**

This work focuses on the utilization of earthquake ground motion simulations for the design and response assessment of buildings, with the specific goals to (1) help validate results of earthquake simulations through comparative assessments of building performance, and (2) demonstrate the unique advantages that earthquake simulations offer over conventional approaches. The first part of the study examines a validation case study performed using ground motion simulations of historic earthquakes generated as part of the SCEC Broadband Platform (BBP) validation effort. A 20-story concrete frame building is analyzed under comparable sets of simulated and recorded motions at ground motion intensity levels up to collapse to check for statistically significant differences between the responses to simulated and recorded ground motions. These comparisons, which yielded similar results in most cases, reveal that under specific circumstances biased responses can be obtained from simulated motions even when the mean and variability of hazard-consistent parameters are properly accounted for; the source of bias is traced back to correlations of spectral values across periods as simulated by both “deterministic” and “stochastic” methods.

A second, on-going part of the study has a broader goal of exploring where simulated earthquakes can offer unique insights to questions of engineering concern that cannot be adequately addressed using conventional hazard analysis. A comparative analysis of seismic hazards and demands for two sites located within the Los Angeles basin is performed by: a) using “conventional” approaches relying on recorded motions coupled with probabilistic seismic hazard assessments; and b) by completely relying on physics-based 3D simulations generated as part of the SCEC CyberShake project. Opportunities and potential pitfalls involved with estimation of hazard targets, e.g., the Conditional Spectra, from simulations are discussed. In terms of seismic demands, the two approaches yield similar estimates for one site, while being drastically different for the other. Extent and sources of these discrepancies are investigated and opportunities for future work are discussed.

**The Gorkha Mw=7.8 earthquake: an incomplete Himalayan rupture, Roger Bilham (Invited Talk Wed 08:00)**

Although an earthquake near Kathmandu had been anticipated for more than two decades, the Mw7.8 Gorkha earthquake of 25 April 2015 was smaller than expected and in the wrong place. Within ten seconds of shaking its 150x60 km2 rupture had lifted Kathmandu 1m, and shifted it bodily 1.8m to the south (http://youtu.be/VS6WZ40Vps). Yet local accelerations (~0.25g) were lower than in historical Himalayan earthquakes, thereby averting a much worse disaster. The official death toll exceeded 8700, half a million homes were damaged or destroyed, and 4.5 million rendered homeless. Had the earthquake occurred, not at midday on Saturday, but 12 hours earlier, or during school hours the death toll could have been 4-6 times larger. The main tectonic feature of the earthquake is that it failed to rupture the entire Himalayan décollement to the surface, a feature we now recognize as common to half a dozen Himalayan Mw<7.9 earthquakes in the past several centuries, including one that ruptured almost the same area in 1833.

The remote scientific response to the earthquake (global seismic data and InSAR) was immediate and effective, but public knowledge in Nepal about the earthquake in the weeks following the mainshock remained hazy. Government and University researchers, anxious not to alarm citizens during the rumble of frequent aftershocks were reluctant to mention the growing realization that a large earthquake could still occur to the west of Kathmandu. Amid the information vacuum many survivors began to reassemble the wreckage of their homes using identical methods that led to their collapse, under the impression that no future earthquake would occur.

A strong and immediate scientific presence in the mezzoseismal zone of a large earthquake is essential to capture time sensitive seismic data, and to inform the public and local officials of the best available seismic information as it becomes known. With a few notable exceptions the response to the Nepal earthquake was slow, with earthquake investigative teams arriving more than a month after the event. Delays were caused by the absence of funds for an instantaneous response, and by the mistaken perception that scientists would impede rescue and recovery missions. As a result important macroseismic indicators of mainshock intensities were lost when the Mw=7.3 aftershock destroyed already weakened buildings. Fortunately many photos and videos of damage in the mainshock captured some of “as lost inform” insights.

**Blending data and dynamics into equilibrium for the Community Stress Model, Peter Bird (Invited Talk Mon 14:00)**

With 3-D tensor models of stress in the lithosphere in southern California, SCEC could: (a) determine the shear stress on active faults to constrain the physics of slip; (b) predict Coulomb stress changes for operational earthquake forecasting; and (c) test the realism of long-term earthquake sequence simulations. One basis for models is data: stress directions (from
focal mechanisms and boreholes), and stress intensity (only from boreholes). But earthquakes rarely occur deeper than 15–20 km, and boreholes rarely deeper than ~6 km. Therefore, data must be supplemented by dynamic models using: laboratory flow laws, a geotherm model, a Moho model, relative plate motions, and locations of active faults. One dynamic model uses code Shells, which solves for 2-D equilibrium of vertically-integrated stresses using 2-D velocity models and 3-D structure. While this model predicts full stress tensors, they are discontinuous and noisy. A newer approach is to model the stress anomaly field as the sum of topographic and tectonic stress anomaly fields. In program FlatMaxwell, the topographic stress is defined as the convolution of topography (and deep density anomalies) with analytic solutions for an elastic half-space. The tectonic stress is modeled by sums of derivatives of a Maxwell vector potential field. The whole stress field is then best-fit (by weighted least squares) to both data and the dynamic model. In practice, FlatMaxwell models are limited in spatial resolution to no more than 6 wavelengths along each side of the model domain. Thus they are quite smooth, and cannot represent stress discontinuities at the Moho predicted by the Shells model. Results to date show a low-amplitude stress anomaly, with peak shear stress of 120 MPa and peak vertically-integrated shear stress of 2.9x10^12 N/m. Channeling of deviatoric stress along the strong Peninsular Ranges and Great Valley is seen. In southern California, deviatoric stress and long-term strain-rate are negatively correlated because regions of low heat-flow act as stress guides while deforming very little. In contrast, active faults lie in areas with higher heat-flow, and their low strength keeps deviatoric stresses locally modest. Opportunities for future CSM advances include: [1] collecting more data; [2] tuning the Shells dynamic model; [3] using a different dynamic modeling code; and/or [4] applying a similar Maxwell equilibrium filter to models of the interseismic stress rate.

**Strike slip tectonics in the Inner California Borderlands, Lasuen Knoll, and the southern termination of the Palos Verdes fault, Jayne M. Bormann, Graham M. Kent, Neal W. Driscoll, and Alistair J. Harding (Poster 219)**

Lasuen Knoll is a prominent bathymetric high in the Inner California Borderlands (ICB) that is bounded on the west by the northwest striking, right-lateral Palos Verdes fault. Lasuen Knoll is commonly interpreted to be a northwest trending, westward verging anticline that formed as a result of oblique right-lateral reverse slip on the northeast dipping, southernmost section of the Palos Verdes fault. However, interpretations of ICB structure are complicated by the overprinting of modern strike-slip deformation on topography formed as a result of large-scale extension of ICB structure are complicated by the overprinting of modern strike-slip and tectonic stress anomaly fields. We present observations from a focused, high-resolution 2D multichannel seismic (MCS) reflection and multibeam bathymetric survey to constrain the architecture of and tectonic evolution of Lasuen Knoll. We supplement our data with industry and USGS MCS surveys. We use sequence stratigraphy to identify discrete episodes of deformation in the MCS data and present the results in a fault map and tectonic model of the Palos Verdes fault, Lasuen Knoll, and the Carlsbad Ridge fault to the southeast.

We interpret the most recent deformation at Lasuen Knoll to result from right-lateral slip at the southern termination of the Palos Verdes fault. Mapping of structures within Lasuen Knoll shows an east-west trending series of compressional folds and faults thrusting sediments southward on to a preexisting structural high that extends more than 20 km southeast from Lasuen Knoll. The western margin of compressional deformation is sharply bounded by the Palos Verdes fault, with no evidence of compressional deformation southwest of the fault. South of Lasuen Knoll, the Palos Verdes fault becomes difficult to distinguish in the seismic data, suggesting that compressional deformation at Lasuen Knoll is related to the southern termination of the fault. The structural high that underlies Lasuen Knoll is bounded on its southeastern margin by the inactive Carlsbad Ridge fault. We interpret this structural high to be formed in part by a compressional, left-lateral stepover between the two strike slip fault systems. We acknowledge that the orientation of strike-slip faults in the ICB is likely influenced by inherited basement topography, and we conclude that modern fault geometry and plate boundary kinematics enhance this topographic structure at Lasuen Knoll.

**Modeling and removal of non-tectonic loading in GPS time series for improved vertical rate estimates in Southern California, Adrian A. Borsa, Thorsten W. Becker, and Duncan C. Agnew (Poster 035)**

We have reanalyzed continuous GPS position time series in Southern California, using an improved methodology to estimate vertical crustal velocities for the region. In addition to standard displacement corrections for atmospheric loading and coseismic/postseismic effects, we apply a new non-parametric seasonal filter that is effective at removing amplitude-modulated periodic signals that are characteristic of GPS time series. From the deseasoned displacements of all GPS stations in the western U.S., we also estimate the common-mode signal due to GPS satellite ephemeris and processing errors and remove this signal from the raw displacements of stations within the SCEC footprint. To further isolate tectonic/mantle processes from those due to hydrology, we invert for the time-varying elastic loading across the western U.S. that is consistent with observed displacements, forward model the load-related vertical displacements at each GPS site in Southern California, and remove these displacements from the vertical time series. These reanalyzed time series represent our best effort at removing known transient signals, particularly the seasonal and interannual hydrological loading that represents the largest contribution to variability in vertical displacement. Finally, we estimate secular velocities from the reanalyzed time series and compare them to vertical rate estimates from UNAVCO’s GAGE processing. We will deliver both secular velocities and time-varying displacement to the SCEC Community Geodetic Model (CGM) working group for discussion and vetting, with the hope that these new estimates will help to better constrain tectonic processes in Southern California.

**A 3D Seismic Velocity Model Offshore Southern California from Ambient Noise Tomography of the ALBACORE OBS Array, Daniel C. Bowden, Monica D. Kohler, and Victor C. Tsai (Poster 218)**

The Pacific-North America plate boundary in Southern California extends far west of the coastline, and a temporary ocean bottom seismometer (OBS) array, ALBACORE, spanned the western side of the plate boundary in 2010 and 2011. Here, velocities are modeled through stacked cross correlations of ambient noise data. Twelve months of continuous data were used from 22 OBS stations and ~30 coastal and island Southern California Seismic Network stations. Particular attention has been paid to improving signal-to-noise ratios in the noise correlations with OBS stations by removing the effects of instrument tilt and infragravity waves. Different applications of preprocessing techniques allow us to distinguish the fundamental and first higher order Rayleigh modes, especially in deep water OBS pairs where the water layer dominates crustal sensitivity of the fundamental mode. Standard time domain and frequency domain methods are used to examine surface wave dispersion curves for group and phase velocities between 5 and 50 second periods, and these are inverted for 3D velocity structure. The results define the transition in three dimensions from continental lithospheric structure in the near-shore region to oceanic structure west of the continental boundary. While the most prominent features of the model relate to thinning of the crust west of the Patton Escarpment, other notable anomalies are present north-to-south throughout the continental borderland and along the coast from the Los Angeles Basin to the Peninsular Ranges. The velocity model will help describe the region’s tectonic history, as well as provide new constraints for determination of earthquake relocations and rupture styles.

**Structure and Mineralogical Characterization of Multiple Fault Traces in Painted Canyon Area, Mecca Hills, Southern San Andreas Fault System, California, Kelly K. Bradbury, James P. Evans, Amy C. Moser, and Sarah A. Schulties (Poster 258)**

We examine the structure and composition of 4 faults that are part of a subsidiary system of north-striking right lateral faults of the Southern San Andreas Fault (SSAF) within the Mecca Hills south of southern California. The variably oriented and anastomosing fault system is part of a positive flower structure that forms a broadly distributed zone of fault-related damage within the northeastern block of the SSAF. Here, active creep appears to be localized along the main trace of SSAF during the interseismic period. Exhumed exposures of fault-related rocks and juxtapose Tertiary to Quaternary sedimentary rocks against Precambrian (?) and Cretaceous granitic gneiss and Oroopia Schist.

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Detailed characterization of textural, compositional, and geochemical features and variations across representative faults and related damage zones are conducted using a combination of field, microstructural, XRD, XRIF, SEM, and isotopic methods. Evidence for multiple episodes of slip and complexly related fluid flow at variable orientations is recorded by the geometry and distribution of slip surfaces, cataclasite, recompression bands, cataclasites, breccia, iron oxide-stained gouge, calcite and quartz veinlets, and hematite-coated fracture surfaces. Alteration phases vary between fault surfaces and may include chlorite-serpentinite, clays (Illite, gypsum), quartz, calcite, ankerite, zeolites, iron oxides/hydroxides, and/or sulfides, or some combination thereof, suggestive of complex fluid-rock and hydrothermal geochemical reactions. Major vein systems include a predominately north-northwest striking quartz set, a north-south striking calcite set, and an east-west striking calcite set, where locally these sets are complexly interwoven, finely interlayered with other minerals, and/or brecciated.

The scale of variations in structural complexity and rock properties of the SSAF are important input parameters for developing realistic models for the attenuation of near-fault wave amplification.

3D Canterbury Velocity Model (CantVM) – Version 1.0, Brendon A. Bradley, Robin Lee, Ethan Thomson, Francesca Ghisetti, Christopher McGann, and Jarg Pettinga (Poster 015)

This poster presents features of the Version 1.0 3D high-fidelity seismic velocity model of Canterbury, New Zealand (CantVM). The intention of the model is to provide the 3D crustal structure in the region at multiple length scales for seismic wave propagation simulations, such as broadband then-reflection. Velocities within sedimentary units are prescribed using depth-dependent functions based on interval velocities from seismic reflection, petroleum wells, and locations with active and passive surface wave analyses. The shallow velocity structure utilizes 3D travel-time tomography. Five geologic surfaces provide the key stratigraphic variation over the region based on seismic reflection information. An additional seven geologic surfaces are also explicitly modeled in the urban Christchurch area with inter-bedded Quaternary deposits based on constraints from 1,500 hydrologic well logs and shallow seismic reflection. Velocities within sedimentary units are prescribed using depth-dependent functions based on interval velocities from seismic reflection, petroleum wells, and locations with active and passive surface wave analyses. The shallow velocity structure is variable geographically, as well as with depth, due to sufficiently detailed observations. Shallow (<30 m) shear wave velocities are primarily variable geographically, as well as with depth, due to sufficiently detailed observations. Shallow (<30 m) shear wave velocities are primarily variable geographically, as well as with depth, due to sufficiently detailed observations. Shallow (<30 m) shear wave velocities are primarily variable geographically, as well as with depth, due to sufficiently detailed observations. Shallow (<30 m) shear wave velocities are primarily variable geographically, as well as with depth, due to sufficiently detailed observations.

Crustal Strike-Slip Faulting along Small Circle Paths in the Northwestern United States, Thomas M. Brocher, Ray E. Wells, Richard J. Blakely, Brian L. Sherrod, Andrew P. Lamb, and Craig S. Weaver (Poster 215)

Late Cenozoic and Quaternary faults, seismicity lineaments, and focal mechanisms provide evidence that clockwise rotation of Washington and Oregon is accommodated by north-directed thrusting and strike-slip deformation in the Washington segment of the Cascadia forearc. Curvilinear NW- to NNW-trending high-angle strike-slip faults and seismicity lineaments define small circles around an Euler pole (117.7°W, 47.9°N) of rotation relative to North America that approximates GPS-derived poles for the rotation of eastern Washington and the Snake River Plain. Although the lengths of strike-slip faults that follow small circle paths suggest maximum earthquake magnitudes of M6.6 to M7.2, their slip rates calculated from the Euler pole are low (0.3 to 0.3 mm/yr). Many normal faults in the Lewis and Clark Zone in Montana, the Centennial fault system north of the Snake River Plain, west of the Wasatch Front, in the northern Basin and Range, and locally east of the Oregon Cascade arc are radial to this pole of rotation, suggesting that these normal faults help accommodate this crustal rotation. Regions undergoing contraction in western Washington and northwestern Oregon are separated from those to the east undergoing extension by lines radial to the Euler pole. In our regional kinematic model, dextral faults along small circles connect SW-directed crustal extension in the Intermountain Seismic Belt and E-directed extension in the Cascade arc south of Mount Hood to N-directed contraction in the Olympic Peninsula, Puget Lowland, and the Yakima Fold and Thrust Belt. The lack of Quaternary faulting and seismicity in the Oregon segment of the forearc is consistent with its clockwise rotation as a rigid block. Potential drivers of the crustal rotation include westward slab rollback and the Yellowstone geoid high, and the overall velocity field may integrate the response of rotating blocks and distributed deformation between them.

Observations of luminescence signals from bedrock feldspars as low temperature thermochronometers, Nathan D. Brown, Ed J. Rhodes, and T. Mark Harrison (Poster 081)

Luminescence measurements from feldspars which have cooled in the Late Pleistocene may offer a means of assessing thermal histories for geomorphically or tectonically active landscapes. The proportion of electron-trapping sites within the crystal lattice which are naturally filled by ionizing radiation is strongly dependent on temperature. Given that optically- or thermally-stimulated luminescence derives from these trapped electrons, luminescence signals from bedrock feldspar can be measured to determine whether a sample is in thermal steady state or disequilibrium. We therefore examine the degree of signal saturation samples taken from a glacial valley within the Beartooth Mountains (Montana), which was excavated during the Last Glacial Maximum; and the Yucaipa Ridge Block, a rapidly-uplifting tectonic block along the San Andreas Fault.

One key observation is that luminescence properties can vary widely across different lithologies, even within a single metamorphic province; in general, the more felsic samples are better behaved. This should dictate field sampling. The degree to which a measured signal fades during laboratory timescales is another important concern. We present measurements from various samples which have implications for luminescence thermochronology, as well as for the dating of sedimentary feldspars.

Finally, we speculate on the near future of the technique. K-feldspars have proven to be much brighter than quartz, but the complicated reaction kinetics of feldspar preclude the simple assignment of a closure temperature. Preliminary modeling work in this study and previously by other workers suggests that signals from quartz and feldspar should accumulate at temperatures near or slightly below those involved in Apatite Heun or Apatite Fission Track thermochronology. The fact that the signals begin to accumulate only after cooling to such low temperatures is opportune for the study of Late Quaternary landscape evolution.

Rupture complexity and the supershear transition on rough faults, Lucile Bruhat and Eric M. Dunham (Poster 272)

Past field investigations [e.g., Bouchon et al., 2010] suggest that supershear earthquakes occur on simple, smooth fault segments. However, numerical simulations show that heterogeneity of stress, strength, and fault geometry can also trigger various rupture styles, including supershear transitions. Our work examines 2D plane strain dynamic ruptures on fractally rough faults subject to strongly rate-weakening friction laws.

We analyze the ensemble rupture catalog of Fang and Dunham (2013) and document the effect of the fault roughness and background shear stress on the rupture behavior. This ensemble contains 3000 simulations for five different values of roughness and various background shear stress levels. We first show that fault roughness can explain the broad diversity in rupture styles observed in nature, such as rupture arrests, re-rupturing of the same fault section with slip pulses propagating in opposite directions, second pulses or supershear transitions. Indeed, despite a very high seismic S ratio, far above the Borrud-Andrews threshold for planar faults with uniform stress and strength conditions, supershear transitions are observed. When exploring the distribution of rupture velocities for all the simulations, we find that the percentage of the fault that ruptures at supershear speeds increases not only with the background shear stress, as expected, but surprisingly also with the fault roughness.
We also examine individual ruptures to identify recurrent patterns for the transition to the supershear regime. Some transitions happen notably at the initiation of a less favorable bend, or, after the propagation through a restraining bend. The rupture is first temporarily delayed by the bend, storing strain energy in the surrounding medium. When the rupture breaks through the bend, it taps this energy and impulsively surges forward at a supershear speed. This mechanism might explain how supershear ruptures can occur on faults with high seismic S ratio.

**Update of PBR comparison with hazard maps for the line between the San Jacinto and Elsinore faults, James N. Brune and Richard Brune (Poster 026)**

In a previous study Brune et al., (Geology, 2006) compared precariously balanced rocks (PBRs) along a line between the San Jacinto and Elsinore faults with 2002 USGS and CDMG hazard maps, and concluded the hazard maps were too high. They suggested that this could be caused in part by an inappropriate use of the ergodic assumption (Anderson and Brune, 1999). The 2006 and then 2014 hazard maps have successively somewhat reduced the hazard estimates, bringing them closer to being consistent with PBRs. Reduction of the aleatory Sigma for hard rock sites and for source variability (Yagoda – Biran and Anderson, SSA, 2015a and 2015b) could further reduce the hazard estimates. Some hazard estimates may also be reduced by correcting for the effects of stepovers (San Jacinto Valley, Lozos et al., SSA, 2015, and the San Bernardino Valley stepover, Ludwig et al., 2015). In addition hazard estimates for the northern half of the line may be reduced by eliminating the effects of smoothing seismicity into the area, where there are essentially no mapped capable faults.

Here we summarize results of a comparison of new PBR data using more precise modeling (PHOTOMODELER) of a number of PBRs, with hazard maps based on the recent UCERF3 estimate of shaking probabilities. We also calculate PBR responses to broadband waveforms from previous studies. The new results show reduced inconsistency between the PBRs and the 2% in 50 yr hazard maps, but some inconsistencies remain to be explained. Future studies should use actual waveforms which reflect the effects of rupture directivity, source complexity and ground motion directionalities at each PBR site.

**Comparing Precariously Balanced Rocks to synthetic seismograms: A scale model approach, Richard J. Brune and James N. Brune (Poster 027)**

New innovations in 3d modeling, 3d printing and the development of 3d shake tables open opportunities for comparison of Fragile Geologic Features to physics-based ground motion models. Experiments with physical scale models on shake tables can be used to validate site-specific earthquake ground motion models via their seismograms. A few 3d numerical models of Precariously Balanced rocks (PBRs) have already been produced, with the use of Software available from Photomodeler, Autodesk123dCatch and Lidar, and accurate scale models of the rocks can be constructed. We made several physical scale models of a Precariously Balanced Rock near Perris, CA., that was field tested and accidentally broken by Anoosheshpoor, Brune and Purvance on July 27, 2007. This involved analyzing the original field test data and photographing the toppled Perris rock in 2015 to accurately model the rock and its complex multiple axis basal contact and then constructing a 1/14 physical scale model of the rock and pedestal. We constructed two types of simple shake tables, and also used the University of Nevada Reno’s ANCO mini shake table, to test the scale models. When the measured accelerations from the three shake tables’ motions were applied in computer simulations, they produced the results observed in the scale model. Numeric broadband three component seismograms from the Lozets et al 2015 rupture and ground motions simulations were applied to numeric models of Perris area rocks, scaled so the accelerations matched the 2014 USGS hazard map peak for the 2% in 50 year probability of the Perris location. The 3d directionalities of the waveforms was preserved and applied to the azimuth-correct 3d computer models of the rocks. The result was a prediction of toppling for several Perris area rocks. Scaling to the 2014 USGS hazard SA(1) produced a similar result, with more rocks toppled due to a higher scaling factor. Future studies will now be able to use actual waveforms which reflect the effects of rupture directivity, source complexity and ground motion directionalities at each PBR site.

**Observations of vertical deformation across the western Transverse Ranges and constraints on Ventura area fault slip rates, Reed J. Burgette, Kaj M. Johnson, and William C. Hammond (Poster 201)**

The Ventura Special Fault Study Area (SFSA) project provides a multidisciplinary approach to understanding seismic hazard posed by the fault network in the western Transverse Ranges. We contribute to this effort by estimating a vertical deformation rate field with repeated leveling, tide gauges, InSAR, and GPS and estimate fault slip rates across the Ventura area. Here, we have expanded our analysis to encompass the entire western Transverse Ranges with GPS and InSAR. A new time-series analysis of repeated leveling yields relative deformation rates between tide gauges at Santa Monica and Port San Luis, and a route north from Ventura. Rates from terrestrial techniques are aligned with the space-based rate field. Agreement between techniques suggests deformation rates have been steady over the past century, and that imaged vertical deformation rate signals are robust. Notably, the vertical deformation rate field includes rapid subsidence in the Ventura basin and a broad gradient of > 2 mm/yr over 20-25 km to uplift in the Santa Ynez range. Anthropogenic signals are present as well, including subsidence in the Oxnard area at rates > 1 cm/yr. Work in progress will identify the anthropogenic part of the rate field using seasonal deformation and other criteria to minimize its effects on interpretation of tectonic deformation. We are modeling the new vertical deformation rate field with a previously published horizontal velocity field (UCERF3, CMM4). We model the present-day rates and the long-term, geologic surface uplift rates using a model in which faults are forced to slip in an elastic plate under gravitational restoring forces. Fault slip rates are constrained by published geologic slip rates and the UCERF3 geologic slip model. Monte Carlo inversions are conducted to produce ranges of slip rates consistent with data. Near Ventura, the sum of reverse dip-slip across the Mission Ridge, Oak Ridge, Red Mountain and Ventura faults must be at least 12 mm/yr to match the ~6 mm/yr of observed horizontal shortening across the Ventura Basin. Inversion of the geodetic data suggests the observed tilting rate between the Ventura Basin and Santa Ynez range is produced by a ~6 mm/yr slip rate on the Ventura fault (ramp-flat-ramp geometry proposed by Hubbard et al). The model predicts 1-2 mm/yr of long-term surface uplift (integrated over multiple earthquake cycles) that can be compared with rates from geologic markers.

**Sounding the Alert: Designing an Effective Voice for Earthquake Early Warning, Erin R. Burkett and Douglas D. Given (Poster 066)**

The USGS is working with partners to develop the ShakeAlert Earthquake Early Warning (EEW) system (http://pubs.usgs.gov/fs/2014/3083/) to protect life and property along the U.S. West Coast, where the highest national seismic hazard is concentrated. EEW sends an alert that shaking from an earthquake is on its way (in seconds to tens of seconds) to allow recipients or automated systems to take appropriate actions at their location to protect themselves and/or sensitive equipment. ShakeAlert is transitioning toward a production prototype phase in which test users might begin testing applications of the technology. While a subset of uses will be automated (e.g., opening fire house doors), other applications will alert individuals by radio or cellphone notifications and require behavioral decisions to protect themselves (e.g., “Drop, Cover, Hold On”). The project needs to select and move forward with a consistent alert sound to be widely and quickly recognized as an earthquake alert. In this study we combine EEW science and capabilities with an understanding of human behavior from the social and psychological sciences to provide insight toward the design of effective sounds to help best motivate proper action by alert recipients. We present a review of existing research and literature, compiled as considerations and recommendations for alert sound characteristics optimized for EEW. We do not yet address wording of an audible message about the earthquake (e.g., intensity and timing until arrival of shaking or possible actions), although it will be a future component to accompany the sound. We consider pitch(es), loudness, rhythm, tempo, duration, and harmony. Important behavioral responses to sound to take into account include that people respond to discordant sounds with anxiety, can be calmed by harmony and softness, and are
innately alerted by loud and abrupt sounds, although levels high enough to be auditory stressors can negatively impact human judgment.

On the Use of Simulated Ground Motions as a Means to Constrain Near-Source Ground Motion Prediction Equations in Areas Experiencing Induced Seismicity, Samuel A. Bydion, Eric M. Dunham, Abhineet Gupta, N. Anders Petersson, and Ossian O’Reilly (Poster 006)

Recent increases in seismic activity in historically quiescent areas such as Oklahoma, Texas, and Arkansas, including large, potentially induced events such as the 2011 Mw 5.6 Prague, OK, earthquake, have spurred the need for investigation into expected ground motions associated with these seismic sources. The neoteric nature of this seismicity in-crease, however, corresponds to a scarcity of ground motion recordings within 50 km of earthquakes Mw 3.0 and greater, with increasing scarcity at larger magnitudes. Gathering additional near-source ground motion data will result in better constraints on regional ground motion prediction equations (GMPEs) and will happen over time, but this leaves open the possibility of damaging earthquakes occurring before potential ground shaking and seismic hazard in these areas are properly understood. To aid the effort of constraining near-source GMPEs associated with induced seismicity, we aim to integrate synthetic ground motion data from simulated earthquakes into the process. Using the dynamic rupture and seismic wave propagation code wavelslab3d developed by our research group, we perform verification and validation exercises intended to establish confidence in simulated ground motions for use in constraining GMPEs. Verification exercises include accuracy tests for point moment tensor sources, using a new discretization method developed by members of our group and LLNL, and comparison to the PEER/SCC layer-over-halfspace problem LOH1. Validation exercises include comparisons between recorded ground motions for earthquakes in Oklahoma between Mw 3.0 and 3.5 and simulated ground motions using point moment tensor sources embedded in the plane layered velocity structure of Keranen et al. (2013). Future work on this problem will likely include the addition of small-scale heterogeneity to the velocity model and dynamic ruptures on finite-area faults for large magnitude earthquakes, where point source representations may be inappropriate.

Paleoseismologic evidence for Holocene activity on the Pinto Mountain fault, Ana Cadena, Thomas K. Rockwell, Charles M. Rubin, Scott Lindvall, Chris Walls, and Chris Madugo (Poster 113)

Excavations across the Pinto Mountain fault in Twentynine Palms, California exposed faulted strata across a 32-m wide zone. Trench wall exposures revealed clear evidence for five ground rupturing events during the Holocene, and two additional events in the late Pleistocene. Optically stimulated luminescence ages from alluvial sediments suggest that the most recent event occurred between 1.7-2.9 ka B.P. and the penultimate event between 2.7-4.2 ka B.P.. Prior to the penultimate event, there were five ground rupturing earthquakes on the eastern Pinto Mountain fault between 3.5-13.6 ka B.P.. The average recurrence interval between 13.3-13.6 ka B.P. is 1510-1650 years, and 1200-1500 years in the last 8.3-9.4 ka B.P.. Geomorphic evidence from offset streams southeast of Donnell Hill and offset gravel bars south and east of the Oasis of Mara suggests two to four meters of slip in the most recent event. Assuming three meters as characteristic displacement and seven events in 13.6 ka yields a Holocene slip rate of 1.59-1.80 mm yr-1. This rate greatly improves upon previously reported slip rate estimates inferred from the cumulative offset of crystalline bedrock contacts and structure.

Using CyberShake Workflows to Calculate a 1 Hz Urban Seismic Hazard Map on Large-Scale Open-Science HPC Resources, Scott Callaghan, Philip Maechling, Gideon Juve, Karan Vahi, Robert W. Graves, Kim B. Olsen, Kevin Milner, David Gill, Yifeng Cui, Thomas H. Jordan (Poster 042)

The CyberShake computational platform, developed by the Southern California Earthquake Center (SCEC), is an integrated collection of scientific software and middleware that performs 3D physics-based probabilistic seismic hazard analysis (PSHA) for Southern California. CyberShake integrates large-scale parallel and high-throughput research codes to produce probabilistic seismic hazard curves for individual locations of interest and hazard maps for an entire region. A recent CyberShake calculation produced about 500,000 two-component seismograms for each of 336 locations, resulting in over 300 million synthetic seismograms in a Los Angeles-area probabilistic seismic hazard model.

A series of scientific software programs are run to perform a CyberShake calculation. Early computational stages produce data used as inputs by later stages, so we describe CyberShake calculations using a workflow definition language. Scientific workflow tools automate and manage the input and output data and enable remote job execution on large-scale HPC systems.

To provide broad impact users of CyberShake data, such as seismologists, utility companies, and building code engineers, seismic hazard estimates of improved accuracy, we successfully completed CyberShake Study 15.4 in May 2015. This series of simulations calculated a 1 Hz urban seismic hazard map for Los Angeles, intended as a candidate map for the USGS Urban Seismic Hazard Mapping Project. We distributed the calculation between the NSF Track 1 system NCSC Blue Waters, the DOE Leadership-class system OLCF Titan, and USC’s Center for High Performance Computing. This study ran for over 5 weeks, burning about 1.1 million node-hours and producing over half a petabyte of data. CyberShake Study 15.4 results doubled the maximum simulated seismic frequency from 0.5 Hz to 1.0 Hz as compared to previous studies, representing a factor of 16 increase in computational complexity.

We will describe how our workflow tools supported splitting the calculation across multiple systems. We will explain how we modified CyberShake software components, such as with GPU implementations and use of MPI messaging, to greatly reduce the I/O demands and node-hour requirements of CyberShake. We will also present performance metrics from CyberShake Study 15.4, and discuss future challenges in running CyberShake at even higher frequencies and migrating to the UCERF 3 ERF.

The minimum scale of grooving on faults, Thibault Candela and Emily Brodsky (Poster 247)

The roughness of fault surfaces is the fingerprint of past slip events and a major parameter controlling the resistance to slip. The most obvious slip indicator and record of tractions are the grooves and striations with elongate axes in the direction of slip. We focus on this roughness feature by analyzing the micro-roughness of slip surfaces from natural and experimental fault zones at scales of several millimeters down to one micron. For each topographic map acquired by White Light Interferometry, an average Fourier spectrum is computed in the slip parallel and slip perpendicular direction seeking to define the scale dependence of the roughness anisotropy. We show that natural and experimental fault surfaces have a minimum scale of grooving at 4-500 micrometers. Below this scale, fault surfaces are isotropic. We have systematically measured this minimum scale of grooving on 42 topographic maps of eight different natural fault zones and 25 topographic maps of eight experimental fault zones. Our results are interpreted in terms of the aspect ratio H/L with H the average asperity height and L the observation scale. This aspect ratio is proportional to the strain necessary to completely flatten the asperities. H/L systematically increases with the decreasing of L. The transition between anisotropic and isotropic is well predicted by a critical aspect ratio. With the scale of observation decreasing the grooves become steeper and once they reach a critical aspect ratio they fail. At all scales, evidence of failure of the slip surfaces are observed and we interpret the minimum scale of grooving as a manifestation of the change in deformation mode from brittle- to plastic-dominated. As the scale of observation decreases, the aspect ratio of the grooves increases and the resulting higher stress concentrations at micro-asperities favor plasticity. The transition is dependent on the rock properties and faulting history, and for each fault one unique critical aspect ratio (between 0.1-8%) maps the transition scale. This transition in deformation mode will control the asperity distribution and therefore be an important factor in controlling the frictional strength. The observations underline the crucial role that plasticity might play at the micrometer scale in controlling sudden large-scale brittle failures along faults.

Constraining the most recent surface rupture on the Garnet Hill Fault, Coachella Valley, CA, Jose E. Cardona, Doug Yule, Kate Scharer, and Brittany Huerta (Poster 075)
The grain-scale dynamics is described by the Shear-Transformation-Zone environment, causing the flow of entropy between them. The peculiar phenomenon of autoacoustic compaction—whose shape and frictional characteristics may have important applications—fits to experimental data obtained within the fault and rock mechanics model. Our methods are based on a physics-based framework for constitutive laws. Our model accounts for the observed autoacoustic compaction, and interpret the effect of friction as an acoustic noise strength. In addition, we observe a threshold vibration intensity above which vibrations induce significant frictional weakening by clock-advancing large slip events. Furthermore, as the vibration intensity is increased we observe slow slip. The model and its results shed important light on the physical mechanisms of earthquake triggering and slow slip, and provide essential elements for the multiscale modeling of earthquake ruptures.

Systematic detection of remotely triggered seismicity in Salton Sea with a waveform matching method, Bridget Casey, Xiaofeng Meng, Dongdong Yao, Xiaowei Chen, and Zhigang Peng (Poster 310)

To better understand the dynamic triggering behavior in the Salton Sea Geothermal Field and to improve the current earthquake catalogs in 2007-2014, we perform a matched-filter detection of microseismicity around the occurrence time of 5 distant earthquakes found in an earlier study to be candidates for triggering in Salton Sea. We use waveforms recorded by the EN borehole network and generated by 6958 relocated events as templates, and scan through five days before and five days after each distant mainshock. We apply a 10-25 Hz filter to the continuous waveforms, from which we subsequently cut the template waveforms, and then use a 6-s window around the arrival of the P-wave.

Out of all earthquakes examined, only the 2009/08/30 Mw 6.9 Baja event from a 2001 Geonics geophysical engineering report. As it crosses the surface wave, despite the swarms in the days before the main event that initially hid the triggered activity. The 2008 Mw 6.0 Nevada earthquake and the 2010 Mw 8.8 Chile earthquake both show potential dynamic triggering in the seismic rate immediately following the main events, but further evidence in the spectrograms and continuous waveform data has not been found. The Salton Sea Geothermal Field also experiences a significant increase in seismic activity 18 to 24 hours after the 2008 Mw 6.0 Nevada and the 2010 Mw 8.8 Chile earthquakes, but whether this is due to delayed triggering or a spontaneous swarm remains to be investigated.

Imaging the San Jose Fault with Resistivity on the California State Polytechnic University, Pomona Campus, Kevin J. Chantrapornlert and Jascha Polet (Poster 096)

The San Jose fault is a reverse left-lateral separation fault located east of the Los Angeles Basin. The 1988 (M4.6) and 1990 (M5.2) left-lateral strike-slip Upland earthquakes have been attributed to this fault and it has been suggested that it is capable of producing a magnitude M6.0-6.5 earthquake. Sections of the fault are considered to run through the campus of California State Polytechnic University, Pomona, as inferred from cross sections and aerial photography. As it cuts across the campus, this report concluded that it has a reverse component of motion. Ascertaining the precise location of the San Jose fault traces on campus is crucial as the university plans its future buildings. Resistivity surveys were conducted across several suggested traces of the fault.

The surveys consisted of 24 electrodes in a Wenner electrode configuration with an electrode spacing that varied between 1-5m. An IRIS Instruments Syscal KID switcher unit provided the power source and data recording hardware. The data was processed with the IRIS Prosys II software suite before using Geotomo’s Res2Dinv software to obtain 2D images of subsurface resistivity for these profiles. A total of 23 surveys was conducted throughout the campus. Surveys were performed before and after rainfall to assess the effect of water content on the resistivity measurements. Preliminary results indicate shallow, north-dipping contrasts in resistivity across many of the areas where the fault was previously identified in the geotechnical report. The profiles will be further analyzed to develop an enhanced understanding of the San Jose fault in the vicinity of the Cal Poly Pomona campus.

Potential, limits, and best practices for characterization of interseismic deformation with InSAR, Estelle Chaussard, Christopher W. Johnson, Heresh Fattahi, and Roland Bürgmann (Poster 200)

The evaluation of interseismic strain accumulation using long-wavelength deformation signals traditionally relies on GPS data, providing precise but spatially sparse measurements, or on high spatial-resolution InSAR velocity fields aligned to a GPS-based model. However, in this approach InSAR contributes only short-wavelength deformation constraints and the two datasets become dependent, thereby preventing the characterization of the long-wavelength displacement from the InSAR products, the evaluation of the InSAR uncertainties, and the justification of corrections

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(For tropospheric noise). Here, we present an analysis of InSAR data for the characterization of interseismic strain accumulation rates along the southern San Andreas Fault (SAF) and the San Jacinto Fault (SJF) in southern California, where the SAF is split into the Mission Creek (MCF) and the Banning (BF) fault strands. We lay out best practices for the use of InSAR alone for characterizing short- and long-wavelength deformation. We evaluate the sensitivity of the InSAR velocity field and the need for additional corrections relying on independent GPS data. We use forty-one descending SAR acquisitions from the Envisat satellite spanning seven years and continuous GPS data. InSAR line-of-sight (LOS) and GPS velocities agree within ~1 mm/yr over the 200-km-long Envisat swath, suggesting a low noise level and a high accuracy of the mean InSAR velocity map in this region. This result demonstrates that InSAR can be independently used to successfully characterize interseismic deformation with higher spatial resolution than GPS. We use simple dislocation models to investigate the ability of the obtained dataset to constrain fault slip rates. A mean LOS velocity field can help distinguish between different slip-rate scenarios on the SAF and SJF (~35 km apart) but cannot provide constraints on the MCF and BF (at most ~12 km apart). Current and future satellite missions should focus on acquiring multiple viewing geometries so the signal can be decomposed in its vertical and horizontal components and interseismic models of strain accumulation used for seismic hazards assessment should generally consider InSAR mean velocity maps.

Site Response along the Hollywood Fault Zone, Terry M. Cheifetz and Jascha Polet (Poster 187)

Site characteristics are a critical factor in seismic hazard assessment. To better understand site response differences on a small scale, we applied both the Refraction Microtremor (ReMi) and the Horizontal-to-Vertical spectral ratio (HVSR) methods to sites along the Hollywood Fault Zone (HFZ) in a heavily urbanized geologic setting. The HFZ is within the central portion of the Santa Monica-Hollywood-Raymond Fault system, which is collectively part of a ~200 km long west-trending system of oblique, reverse and left-lateral faults. The HFZ extends for ~17 km beneath densely populated communities. Hollywood has ~22,193 people/mi² making it imperative to map and compare the local site response across the HFZ.

We have collected seismic waveform data for ReMi analysis at 3 initial sites and will invert this data to determine shallow S-wave velocity profiles. Our other preliminary results are based on the application of the HVSR technique, in which the ratio between the vertical ambient noise component of ground motion to the horizontal components is computed as a function of frequency. By applying this method and the criteria from the Site Effects Assessment Using Ambient Excitations (SESAME) guidelines, we can determine a fundamental frequency and corresponding site amplification at individual sites. We deployed broadband seismometers on both sides of the HF along its 5 mapped segments. The sites are all within the finalized earthquake hazards zone map from the California Geological Survey Fault Evaluation Report 253. Two hours of waveform data were recorded at each individual site. Using the Geopsy software to analyze these waveforms, we produced spectral ratio curves and determined the peak frequencies and the amplitudes of those main peaks. Based on a comparison with the most recent published geological map from the U.S. Geological Survey, our preliminary results from each fault segment display prominent H/V curves with distinctly different peak frequencies on either side of the fault zone. The entire area is covered by various geomorphic Holocene deposits that tend to produce localized significant spectral peaks that range in fundamental frequencies between approximately 0.33Hz to 6.0Hz, with a minimum amplification factor of ~2.2 to 10. We will present a series of preliminary site response parameter maps, one for fundamental frequencies and one for minimum site amplification factors at each recorded site.

Integrated UAV (drone) Imaging and SFM Computing for Rapid Detection of Seismic Rupture in the Aftermath of the 2014 South Napa Earthquake, Zhichiang Chen, Mohammed Alabasi, and Jianfei Chen (Poster 188)

Extreme earthquake disasters can overwhelm capacities of societies and built infrastructure, leading deadly losses in a short time. Rapid disaster response, which is a key component of the general notion of disaster resilience, greatly relies on remote sensing technologies for achieving rapidity in damage assessment and recovery preparation at a geospatial scale. However, a devastated earthquake-disaster scene is far more complex than what is likely captured by orbital or high-altitude optical or Radar imagery, due to the limitation in spatial resolution and overcoming occlusions. For performing a thorough post-disaster assessment, ground-based reconnaissance stands out as the typical means, in which individual geologists or engineers use manual methods (e.g., digital cameras, markers, and tape measures) for inspecting and archiving geological or structural damage within a small-scale region, which is, however, time-consuming and faces challenge for hard-access areas. In this paper, a new approach, titled UAV Imaging and SFM computing for rapid post-disaster damage assessment is proposed, which is based on the integrated use of micro-unmanned airborne vehicles (UAV, a.k.a drones) based remote sensing and structural from motion (SfM)-based multi-view imaging modeling.

This poster presentation starts with a basic review of traditional computational damage detection methods using remote sensing data. Then we will propose a flight-imaging-computing framework that starts with the use of drone at a community or moderate geospatial scale. To process multi-view UAV-based imagery, it challenges the traditional photogrammetric approach, wherein a large number of image sequences without accurate geo-registrations and with significant imaging distortion are involved. The basic SFM algorithm will be reviewed and used as the basis in the modeling component of the framework.

We will demonstrate the use of the proposed framework and the drone images captured in the aftermath of 2014 South Napa Earthquake. On Aug 30, 2015, we flew our drone starting from the Stone Bridge School following the fault rupture southward, through the school playground, the Los Cameros Avenue, the vineyard, the South Avenue, and down to the vineyard again, till we lost the light of sight. With a resolution of about 0.9 inch / pixel in collected thousands of high-resolution images, we could recognize ruptures in the high-resolution images. Through 3D reconstruction, focus will be on demonstrating a new algorithm in tracking non-consecutive linear rupture features in the 3D constructed image model. In the end, we will remark the advantages and disadvantages of using drone-based multi-view imaging for post-earthquake disaster reconnaissance.

How does strain rate relate to the precursory time in the EEPAS model? Results from RSQSim synthetic catalogues, Annemarie Christophersen, David A. Roahdes, and Harmony V. Colella (Poster 053)

The EEPAS (Every Earthquake a Precursor According to Scale) model is a medium-term earthquake likelihood model. It is based on the precursory scale increase phenomenon Ψ, which manifests itself as an increase in the magnitude and rate of minor earthquakes before most major earthquakes. The onset of the Ψ-phenomenon occurs with a precursor time that, in active seismic regions, ranges from months to decades before the major event. The precursory time seems to depend on the earthquake magnitude, and perhaps on other factors, such as strain rate. The 2010 M7.1 Darfield, New Zealand earthquake occurred in a region of low geodetic strain rate, and without an observable precursory scale increase. Is the Darfield earthquake a rare exception to the Ψ-phenomenon, or is the historical earthquake catalogue not long enough to detect it?

To investigate this question we use the earthquake simulator, RSQSim, in which the strain rate is represented by the slip rate on faults. A fault network representative of the crustal faults in the Wellington region was employed to generate seismicity catalogues, where the slip rates are systematically reduced by ¼. We present results, where the EEPAS model is fit to simulated catalogues, showing that the precursor time is inversely proportional to the slip rate. Our results support the hypothesis that the New Zealand earthquake catalogue is not sufficiently long to observe the Ψ-phenomenon for the Darfield earthquake.

Crowd-Sourcing Seismic Data: Lessons Learned from the Quake-Catcher Network, Elizabeth S. Cochran, Danielle F. Sumy, Robert de Groot, and Robert Clayton (Poster 130)

The Quake Catcher Network (QCN; qcn.caltech.edu) uses low cost micro-electro-mechanical system (MEMS) sensors hosted by volunteers to
collect seismic data. Volunteers use accelerometers internal to laptop computers, phones, tablets or small (the size of a matchbox) MEMS sensors plugged into desktop computers using a USB connector to collect scientifically useful data. Data are collected and sent to a central server using the Berkeley Open Infrastructure for Network Computing (BOINC) distributed computing software. Since 2003, when the first citizen scientists joined the QCN project, sensors installed in museums, schools, offices, and residences have collected thousands of earthquake records. We present and describe the rapid installations of very dense sensor networks that have been undertaken following several large earthquakes including the 2010 M8.8 Maule Chile, the 2010 M7.1 Darfield, New Zealand, and the 2015 M7.8 Gorkha, Nepal earthquake. These large data sets have been used to develop new rapid earthquake detection capabilities and closely examine source, path, and site properties that impact ground shaking at a site. QCN has engaged a wide sector of the public in scientific data collection, providing the public with insights into how seismic data are collected and used. Furthermore, students use data recorded by QCN sensors installed in their classrooms to explore and investigate earthquakes that they felt, as part of ‘teachable moment’ exercises.

Constructing a Late Pleistocene southern Alpine Fault earthquake record from soft sediment deformation structures, Genevieve L. Coffey, Christopher M. Moy, Virginia Toy, and Christian Oheiser (Poster 124)

New Zealand’s southern Alpine Fault is a strike-slip dominated structure, capable of producing earthquakes of Mw 7 or larger. Past paleoseismic studies on the southern Alpine Fault have recorded a record of these events extending over the last 8,000 years and indicate a recurrence interval of 329 + 68 years. However, no records extend past this into the late Pleistocene, limiting our understanding of earthquake recurrence over longer timescales and under different boundary conditions. The tectonically complex Cascade River runs along part of the southern Alpine Fault and here, planar laminated lacustrine silts are exposed. These silts are interpreted, using radiocarbon dating and layer counting, to be varved and contain continuous folded “seismite” horizons bound above and below by undeformed sediment. X-ray computed tomography has been used to identify these horizons, which contain a variety of fold geometries, all of which display significant asymmetry. These horizons are interpreted to form as a result of Alpine Fault seismic activity. Earthquake shaking causes the pore fluid pressure of the lake sediments to increase, destabilizing the slope and trigger slumping and the release of silt into the sedimentary system. Subsequently, displacement of silt causes the formation of seisite waves, which apply shear stress to lake floor sediments causing further deformation. Three separate earthquake events are identified to have deformed the silt sequence and the dominance of slump folds and lack of fluid escape structures suggests that these earthquakes were likely of magnitude Mw 7 – 8. Radiocarbon dating and varve counting has constrained the maximum ages of these events to 16,530 – 16,880, 16,290 – 16,710, and 16,950 – 16,345 cal yr BP, with an average recurrence interval calculated to be 370 ± 77 years, consistent with the average recurrence interval previously calculated for the Holocene. The consistency of these recurrence intervals suggests that the timing of large earthquakes on the southern Alpine Fault has remained relatively constant from the Late Glacial to present day. This is the first report globally of characteristic fault behavior on such a long interval that has remained relatively constant from the Late Glacial to present day. This suggests that the timing of large earthquakes on the southern Alpine Fault extending over the last 8,000 years and indicate a recurrence interval of 329 + 68 years. However, no records extend past this into the late Pleistocene, limiting our understanding of earthquake recurrence over longer timescales and under different boundary conditions.

Reorganization of the San Andreas Fault system near Tejon Pass in the Late Miocene and implications for drainage development and long-term slip rates, Hannah Cohen, Vincent Zhao, Richard Heermann, and Robinson Cecil (Poster 083)

Fault reorganization along transform plate boundaries is a fundamental part of the evolution of active margins. For example, fault slip along the San Andreas Fault (SAF) system was transferred eastward from the San Gabriel Fault (SGF) onto the present SAF in the late Miocene and early Pliocene. Two outstanding questions related to this restructuring include: 1) did slip migrate from one fault to the other over a long period of time (105-106 years), or was this a relatively short event and 2) how did slip transfer influence drainage and deposition in the region? Understanding this late Miocene event may provide a useful analog for the future of the SAF, such as in southern California where strain is migrating east onto the Eastern California Shear Zone. To elucidate the timing, rate, and implications for fault rearrangement, we investigated the Hungry Valley Formation (HVF), which was deposited at the top of the Ridge Basin Group during the waning stages of slip on the SAF and the onset of slip along the SAF. Our research uses detailed sedimentology, paleocurrent analyses, geochemical mapping, and detrital zircon geochronology to define major depositional changes within the basin resulting from fault interactions. Our preliminary data indicates the HVF can be split into three members by clast type. The lowest member contains granitic and gneissic clasts of exposed basement in the San Gabriel Mountains (SGM). The middle member contains Mojave basalt clasts in addition to SGM clasts. The upper member is dominated by clasts of basalt, quartzite, tuff, and other lithologies not found in the SGM. Detrital zircon analysis of samples from the HVF and major drainages within the SGM, San Bernardino Mountains, and the Mojave Desert, will provide evidence for the provenance of the HVF as well as potentially provide maximum ages for deposition. Our current interpretation of the HVF is that the lower member was deposited while the SFG was still active. The middle member defines the onset of dextral slip on the SAF when major drainage reorganizations allowed Mojave clasts to penetrate the HVF. During deposition of the upper member, continued uplift along the SAF provided a source for Mojave and potentially San Bernardino material into the basin. This study will provide a fingerprint for the HVF sediment that will be used to infer sources on the NE side of the SAF, and thus use the HVF as a piercing point to constrain long-term slip and slip rates of the SAF.

Modeling of off-fault deformation with the earthquake simulator RSQSim, Harmony V. Colella and J Ramon Arrowsmith (Poster 248)

Field observations and image differencing after strike-slip earthquakes in California are regularly utilized to quantify off-fault deformation (OFD). Improved field techniques indicate deformation is partitioned both along and off the fault, in which the width of the corresponding OFD is often referred to as the “damage zone” and varies from fault to fault. While some hypotheses such as the age of the fault and rock properties have been put forth to explain the observed OFD, the characteristics of OFD and the parameters that control it remain poorly understood. Here the earthquake simulator, RSQSim, is employed to explore a variety of scenarios, which include different configurations (i.e., spacing, distribution) of secondary faults parallel to the main fault, secondary faults that dip and are oriented en echelon to the primary fault, and depth required for secondary fault to result in the observed surface displacement. Additionally, we investigate whether shallow faults with rate-strengthening (or creeping) behaviors are enough to generate the OFD observed or whether some (or all) of the faults must possess a component of rate-weakening behavior. Results from the simulations are compared to field observations of OFD from recent earthquakes (e.g., Landers, Izmit, Hector Mine) and the tectonic geomorphology of faults in California as indicated by high-resolution topography to determine potential physical properties and spatial distribution of off-fault faults necessary to reproduce observations.

San Gorgonio Pass Special Fault Study Area, Michele L. Cooke, David D. Oglesby, and John D. Yule (Invited Talk Mon 10:30)

The largest irregularity along the San Andreas fault occurs in the San Gorgonio Pass (SGP) region where active strands disaggregate into a distributed zone of faulting, rather than having deformation restricted to a single active strand. Forecasting the earthquake hazards in this complex region requires addressing three fundamental questions: 1) What is the subsurface geometry of active faulting through the SGP? 2) What is the earthquake potential in the SGP region? 3) What is the probability of a through-going San Andreas rupture? The SGP SFSF has taken a multi-disciplinary approach to address these three questions. One focal point throughout SCEC4 has been the activity level of the northern route through the pass along the Mill Creek and Mission Creek strands of the SAF. The role of this route in passing slip through the pass is critical for understanding potential earthquakes in the region. Through field studies, investigations of microseismicity, geodetic inversions for slip rate and crustal deformation models, we have vastly increased the data available to assess the activity of the Mill Creek/Mission Creek strand and honed our understanding of the partitioning of deformation throughout the fault...
system. New strike-slip rates have filled a critical gap within previous data along the SAF. Microseismicity shows anomalously high stress drops within of the SGP that may reveal stress levels critical for rupture dynamics. Dynamic rupture models of realistically geometrically complex faults demonstrate that the development of earthquake rupture through the pass is highly sensitive to initial stress levels as well as fault geometry. The important question of through-going rupture history has been addressed with deep trenches that show that the last event to rupture through the SGP may have been ~1400 AD. The emerging view from the work reveals a fault system that typically arrests ruptures as they approach the pass, yet occasionally allows through-going, very large events. This view is consistent with lowered strain accumulation, measured strike-slip rates and strike-slip rates from kinematically consistent models within the SGP. The SGP workshops have showcased the impressive collection of collaborative research emerging from the SGP. Through such interdisciplinary dialog we are successfully integrating a variety of datasets to form a clearer understanding of active faulting in this region that has the potential for devastating earthquakes.

Improvements of ground motion duration metrics with empirically derived scattering impulse response functions, Jorge G. F. Crempien, Ralph J. Archuleta, and Chen Ji (Poster 016)

At high frequencies (>1Hz), ground motion is not only stochastic in nature but also nonstationary in both time and frequency. Multiple lapse-time window analysis is a successful method that can estimate scattering loss and intrinsic absorption parameters for particular regions. However, this method relies on the large assumption that these parameters do not vary azimuthally. Using small earthquakes recorded on the Northridge fault after the mainshock in 1994, we estimated scattering impulse response functions (SIRF’s) by stacking the normalized recorded coda envelopes at different frequency bands. This approach is similar to the one used by Baltay et al. (2009). With these SIRF’s, we generate synthetic scatterograms and convolve them with deterministic Green’s functions to produce scattering Green’s functions (SGF’s). With the UCSB method (Schmedes et al., 2010; Crempien and Archuleta, 2015) we simulate 16 stochastic realizations of kinematic rupture on a finite fault with the same location, magnitude and dimensions of the 1994 Northridge earthquake. We then compute ground acceleration for all 16 kinematic rupture scenarios using the SGF’s. We compute ground motion duration based on the evolutionary Arias intensity for each synthetic seismogram and compare these simulations to the actual recorded ground motion for this event. The bias of duration is quite small and shows no trend with distance away from the fault.

Effective Friction Laws for Fault-Scale Dynamic Rupture, Eric G. Daub (Poster 268)

I study dynamic rupture on complex faults, with the goal of understanding how to construct friction laws appropriate for studying rupture propagation and ground motion at larger scales with a coarser spatial resolution. My simulations examine two-dimensional plane strain models on complex faults, and incorporate continuum viscoplasticity and fault friction based on STZ Theory, a physics-based friction law for deformation and failure in amorphous materials. I examine the off-fault ground motions to construct effective friction laws that capture the larger-scale details of rupture propagation. In this work, I test a method for estimating the frictional length scale based on work of Mikumo et al. (2003), and find that the resulting frictional length scale estimates are spatially heterogeneous. This heterogeneity is due to strong ground motion pulses that arrive at unpredictable times in the seismograms, making the results strongly dependent on the small-scale details of rupture propagation. For a fault that does not resolve the finest scale details of heterogeneity, we find fairly uniform values for the frictional length scale estimate for distances away from the fault greater than roughly the slip breakdown distance. This suggests that using larger values of the frictional length scale on coarser resolution faults may be a reasonable first approximation for the frictional behavior at larger scales. However, this does not fully capture the rupture process in the high resolution model, suggesting further modification to the frictional weakening behavior may be necessary in deriving more accurate effective friction laws.

Managing Earthquake Hazards and Risks to Implement an Infrastructure Resilience Program, Craig A. Davis (Invited Talk Tue 14:00)

The Los Angeles Water System is implementing a Seismic Resilience Program as part of a larger city-wide plan to improve the City’s seismic resilience as outlined by the Mayor in his “Resilience by Design” report. The Water System Resilience Program comprehensively covers all aspects of water system business. Some key components of the program are aqueduct crossings of the San Andreas Fault, fire following earthquake, and developing a seismic resilient pipe network. This presentation provides a brief overview of the resilience program. The Los Angeles Water System is a large and complicated geographically distributed system exposed to many different seismic hazards posing different risks to the loss of services and ability to restore them following an earthquake. A significant problem exists on how to quantify the different hazards (e.g. liquefaction, landslide, faulting, ground shaking), having a wide range of probabilities of occurrence, that threaten large spatially distributed systems. Each hazard is quantified differently and there is no accepted methodology for uniform incorporation across the systems. This problem is compounded when system dependencies and cascading effects must be considered, such as the interaction of water, power, and gas systems associated with fire following earthquake. A seismic resilient pipe network (SRPN) is designed and constructed to accommodate damage with ability to continue providing water or limit water outage times tolerable to community recovery efforts. An SRPN is an attempt to optimize pipe replacements in an existing network to reduce risks to communities from future earthquake impacts on the water system. The ability to understand the true risks of service losses is inhibited by hazard quantification and how to distribute across the network. Los Angeles intends to implement the seismic resilience program with risk-informed decisions. Improved mapping of geologic earthquake hazards incorporating the magnitudes of ground deformations and improved quantification allowing application of all hazards with uniform confidence in system models are aspects which can greatly improve community resilience.

Citizen Science With The EPIcenter and Quake-Catcher Networks: Promoting Seismology Research and Activities in Formal and Free-Choice Learning Environments, Robert M. de Groot, Elizabeth Cochran, Danielle Sumy, Rob Clayton, Brian Blake, Marc Moya, Demoree Deocales, Michaelaenn Gallagher, Bernadette Vargas, Amelia Mouri, Elisa Shea, Kevin Chan, Mark BentHEN (Poster 313)

The Quake Catcher Network (QCN) uses low-cost seismic sensors to record data in real-time on volunteer computers and engages participants in authentic science. The Southern California Earthquake Center, the Incorporated Research Institutions for Seismology, the United States Geological Survey, and the California Institute of Technology, manages QCN. The Central U.S. Earthquake Consortium (CUSEC), the EarthScope Program, and the Chaffey Joint Union High School District (CJUHSD) are major QCN partners. The primary goal of this project is to develop a comprehensive program to facilitate the marketing, installation, and sustainability of QCN stations for research and broader impacts activities in K-16 schools and free-choice learning institutions such as museums. The Earthquake Country Alliance partners with QCN to integrate earthquake and tsunami preparedness including promotion of and participation in The Great ShakeOut. As of fall 2015 over 140 schools and free-choice learning institutions are members of the QCN-Education and Public Information Center (EPIcenter) Seismic Network in Alabama, Arkansas, California, Oregon, Tennessee, Mississippi, Maine, Missouri, Tennessee, and Washington. Expansion of QCN into the Central United States during summer 2015 was co-facilitated by CUSEC. QCN partners are developing promotional and informational products including new software tools, installation guides, hands-on activities, and an enhanced website. The CJUHSD and Sunnyside Center and Gardens are serving as test beds for new QCN products, programs, and engagement activities.

Plate boundary seismic hazard near New Zealand’s Alpine Fault - recent South Westland Fault Zone's activity further questions Australian Plate stability, Gregory P. De Pascale, Nicholas Chandler-Yates, Federico Dela Pena, Pam Wilson, Elijah May, Checheng, Amber Twiss (Poster 125)
The at least 300 km long Australian plate South Westland Fault Zone (SWFZ) is immediately west (from 8-20 km) of the Central section of the New Zealand’s Plate Boundary Alpine Fault, has 3500 m of dip slip displacement based on borehole observations and seismic reflection stratigraphy, however recency of activity was unknown prior to this study. Here we present the first evidence for multiple Quaternary surface ruptures via reverse (thrust) faulting along SWFZ immediately west of the Central Alpine Fault within the “stable” Australian Plate. Field stratigraphic observations in an exposure of a faulted river terrace and local mapping combined with cone penetration testing (CPT) across the fault scarp along the terrace allows us to document subsurface stratigraphy and faulting relationships.

We discovered a faulted terrace exposure, coincident with the geophysical surface trace of the SWFZ with a 28 degree SE dipping fault with cumulative dip-slip (reverse) offsets up to ~ 6 m (with 3 m of throw) on the oldest unit (i.e. the Old Man Gravels), evidence for at least three discrete surface ruptures and folding observed of the hanging wall alluvium overlying the Old Man Gravels within 150 m from the surface trace of the fault. Subsurface stratigraphy adjacent to the natural exposure was revealed by a transect of CPTs and shows repeating sequences of silt, sand, silt within the fault scarp (consistent with thrust faulting), and coincident with the terrace exposure stratigraphy. This clearly demonstrates that the SWFZ is an active structure (forming the coastal monocline adjacent to the Alpine Fault with earthquake scaling relationships suggesting SWFZ earthquakes up to Mw 7.3 are possible).

Importantly, the SWFZ-bounding Westland basin is likely forming due to reverse motion along the SWFZ and not due to isostatic subsidence, which has previously been a source of debate. Finally, this new site demonstrates that there are other seismic sources very close to the non-isolated Central Alpine Fault that are responsible for accommodating plate boundary deformation and seismicity off of the Alpine Fault. Ultimately this and other recently discovered active faults adjacent to the Alpine Fault (in both the Pacific and Australian Plates) likely influence regional paleoseismic records (i.e. not all paleoseismic off-fault shaking records which has previously been a source of debate. Finally, this new site demonstrates that there are other seismic sources very close to the non-isolated Central Alpine Fault that are responsible for accommodating plate boundary deformation and seismicity off of the Alpine Fault. Ultimately this and other recently discovered active faults adjacent to the Alpine Fault (in both the Pacific and Australian Plates) likely influence regional paleoseismic records (i.e. not all paleoseismic off-fault shaking records near the Alpine Fault are from Alpine Fault earthquakes), which has important implications for understanding plate boundary behaviour.

USGS GPS Network in Southern California, Daniel N. Determan, Aris G. Aspiotes, Derek T. Barseghian, Ken W. Hudnut, and Keith F. Stark (Poster 069)

The USGS Pasadena field office currently operates more than 140 permanent, continuously-operating GPS stations in the Southern California GPS Network. The network recently acquired 41 new NetR9 GPS receivers with Zephyr Geodetic II antennas, through Caltech and the 2014 Urban Area Security Initiative (UASI) project. The new equipment not only includes Global Navigation Satellite System (GLONASS) tracking capability, like the Net-G3A receivers purchased through the 2009 American Recovery and Reinvestment Act, but they also have the onboard RTX software option. The new RTX software allows for Precise Point Positioning with Ambiguity Resolution (PPP-AR) on the receiver. This new capability is best suited to support the West Coast Earthquake Early Warning (WC-EEW) system at sites close to an active fault. We therefore installed the new NetR9 receivers at existing “zipper area” and other sites close to the San Andreas Fault (SAF), to determine displacements quickly after a large event. We also installed GPS at more than 30 new UASI funded sites, where the removed equipment (from “zipper area” and other sites) has been re-installed and co-located with seismic sensors. Some of the new sites are close to critical faults, including the San Jacinto and Elsinore. Before the UASI project, our GPS network in southern California consisted of 104 permanent, continuously-operating GPS stations, which included 95 sites with real-time data telemetry and 26 co-located with seismic equipment. As a result of support from UASI and re-installation of the removed equipment, our network has increased to more than 140 permanent, continuously-operating GPS stations. The network now has more than 130 sites with real-time data telemetry and more than 60 sites co-located with seismic equipment. The larger network now utilizes three types of geodetic grade GPS receivers: 89 have NetG3A receivers; 10 utilize NewAge receivers; and 41 use the new NetR9 receivers with RTX software (PPPAR). In the coming year, we plan to replace the NetRS receivers and continue integrating with the Northern California GPS Network and the Southern California Seismic Network (SCSN). We also plan to improve our data telemetry, to increase the robustness and reliability of all of our real-time data streams.

Designing a Regional Scale Simulation and Data System for Enhanced Earthquake Hazard and Risk Assessments of Electrical and Gas Systems, Carola Di Alessandro, David McCallen, Norman Abrahamson, Philip Harben, and Shawn Larsen (Poster 038)

The need for a better understanding of spatial variations of earthquake ground motion hazard and risk at a regional scale is particularly relevant to distributed energy systems, including both electrical and gas, and related infrastructure. Recently conducted probabilistic seismic hazard analysis (PSHA) for critical facilities in the western U.S. indicated that, when the effect of repeatable recording sites and source-to-station paths is accounted for, there are very large epistemic uncertainties which lead to a large spread in the exceedance probabilities at long return periods. Current advances in seismic waveform modeling in 3-D geologic structures suggests that better quantifying regional fault effects may be the most tractable way to significantly reduce uncertainties in seismic risk assessment.

Here, we present the considerations and insights gained during the initial planning of a full-system design concept for regional simulation and ground motion data acquisition applied to a test area. The approach is founded on a rigorous feasibility assessment and system-design trade study conducted by a team of multidisciplinary experts to provide clear insight into the system requirements and technology readiness.

The feasibility discussion includes: (1) Determination of the frequency resolution for a regional-scale computational model that is required to capture the frequency ranges of structural systems of interest in a regional electric/gas energy system; (2) Evaluate the density of seismic instrumentation which would be required to provide travel path information that can be used to constrain and optimize the geologic characterization in a regional-scale model and to provide a basis for model validation; (3) Develop sensor and communication system engineering design concepts based on emerging nontraditional sensor technologies and the existing PG&E RF communication backbone links; (4) Leveraging of the high-performance computing capabilities at LBNL to perform full frequency bandwidth simulations progressively augmented by the constraint insights obtained from inversion of big data acquired through massive deployment of nontraditional stations; (5) Assimilate data in a PSHA framework and validate the reduction on the hazard uncertainty as a result of accounting for repeatable site and path effects, and (6) Develop an appropriate approach to propagate seismic hazard assessment through a regionally distributed infrastructure risk evaluation.

A High-Resolution Dynamic Approach to Identifying and Characterizing Slow Slip and Subduction Locking Processes in Cascadia, Lada L. Dimitrova, A. John Haines, Laura M. Wallace, and Noel Bartlow (Poster 253)

Slow slip events (SSEs) in Cascadia occur at ~30-50 km depth, every 10-19 months, and typically involve slip of a few cm, producing surface displacements on the order of a few mm up to ~1cm. There is a well-known association between tremor and SSEs; however, there are more frequent tremor episodes that are not clearly associated with geodetically detected SSEs (Wech and Creager, 2011). This motivates the question: Are there smaller SSE signals that we are currently not recognizing geodetically? Most existing methods to investigate transient deformation with continuous GPS (cGPS) data employ kinematic, smoothed approaches to fit the cGPS data, limiting SSE identification and characterization.

Recently, Haines et al (2015) showed that Vertical Derivatives of Horizontal Stress (VDoHS) rates, calculated from GPS data by solving the force balance equations at the Earth’s surface, represent the most inclusive and spatially compact surface expressions of subsurface deformation sources: VDoHS rate vectors are tightly localized above the sources and point in the direction of push or pull. We adapt this approach to daily cGPS time series from Cascadia and compare our results with those from the Network Inversion Filter (NIF) for 2009 (Bartlow et al., 2011) and selected SSEs from 2010 to present day.
In both NIF and VDoHS rate inversions, the main 2009 SSE pulse reaches a peak slip value and splits into northern and southern sections. However, our inversion shows that the SSE started prior to July 27-28, compared to August 6-7 from the NIF results. Furthermore, we detect a smaller (~1 mm surface displacement) event from June 29-July 7 in southern Cascadia, which had not been identified previously. This demonstrates the potential of our method to lower the threshold of SSE detection with cGPS data. VDoHS rates also reveal the boundaries between the locked and unlocked portions of the megathrust, and we can track how this varies throughout the SSE cycle. Above the locked interface, the pull of the subducted plate generates shear tractions in the overlying plate in the direction of subduction, while above the creeping section shear tractions are in the opposite direction, which is reflected in the VDoHS rates. We show that sections of the Cascadia megathrust unlock prior to some SSEs and lock thereafter, with the locked zone propagating downdpip and eastward after the SSEs over weeks to months.

In the future, we would like to apply this method to timeseries in California to detect transient deformation.

**A new mid-Holocene slip rate for the central Garlock fault: Implications for the constancy of fault slip rates and system-level fault behavior**, James F. Dolan, Sally F. McGill, and Edward J. Rhodes (Poster 114)

New post-IR50-IRSL225 luminescence dates from an alluvial fan that has been offset ~9.5 m along the central Garlock fault at our Summit Range East site (35 deg 29.17’ N, 117deg 31.77’ W) indicate a slip rate averaged over the past 6.8 ky of ~5.5 mm/yr. This age range overlaps with the age range of the last six surface ruptures documented at the El Paso Peaks (EP) paleoseismic site of Dawson et al. (2003), which is located 14 km to the west. These data, together with our earlier SCEC-funded results (Dolan et al., in review), allow us to constrain more fully the incremental slip rate of the central Garlock fault. The fault slipped at an average rate of ~12 mm/yr over the past 2 ka - a period encompassing the 0.5-2.0 ka cluster of four earthquakes documented at the EPP trench - with a total of ~23-24 m of left-lateral slip. The new 6.8 ka slip rate is much slower than this late Holocene rate, reflecting the absence of any earthquakes on this stretch of the fault during the ca. 3300-year-long lull documented at EPP between 2-5.3 ka. The ~13-14 m difference between the 24 m of slip accommodated during the past 2 ka and the 37.5 m of slip accommodated during the past 6.8 ka is consistent with the notion that the two oldest earthquakes documented at EPP (4.9-5.3 ka & 6.7-7.3 ka) each accommodated ~6-7 m of slip. Collectively, these data reveal millennial-scale strain super cycles along the Garlock fault, with the fault experiencing alternating fast (e.g., 0.5-2.0 ka, 6.8-4.9 ka) and slow (e.g., 0 mm/yr slip rate 2.0-5.1 ka) modes. We suggest that these strain super cycles are a manifestation of system-level controls on elastic strain accumulation and release within the complicated network of faults around the Mojave, including the Garlock, San Andreas, and eastern California shear zone faults. Currently, both the Garlock and San Andreas Mojave segment are in seismic lulls, and both are storing elastic strain energy at rates that are much slower than their long-term average rates.

**Studying Recent California Earthquakes with UAVSAR and GeoGateway**, Andrea Donnellan, Jay W. Parker, Margaret T. Glasscoe, Lisa Grant Ludwig, John B. Rundle, Marlon E. Pierce, Jun Wang (Poster 189)

The M 7.2 2010 El Mayor – Cucapah, M 5.1 2014 La Habra, and M 6.0 2014 South Napa earthquake have all been imaged with NASA’s L-band UAVSAR instrument. The 2010 M7.2 El Mayor – Cucapah earthquake ruptured the northern part of Baja, Mexico. The right-lateral rupture terminated near border between Mexico and United States. The magnitude 5.1 La Habra earthquake struck the Los Angeles basin in March 2014 on a northeast striking, northwest dipping left-lateral oblique thrust fault. In August 2014 the M 6.0 South Napa earthquake occurred just north of the California Bay Area. Each of these earthquakes was observed with UAVSAR with images acquired a few months prior to each earthquake an approximately one week after each event. Additional observations, spaced a few month apart, captured postseismic motion following the two larger events. Substantial slip on a network of conjugate faults stepping up to the Elsinore, San Jacinto, and San Andreas fault was observed in the InSAR imagery as a result of the earthquake. The slip decreases northward across the Salton Trough, and becomes more buried to the north at the East Elmore Ranch fault. Postseismic slip is observed on the Yuha and Superstition Hills fault. A M 5.7 aftershock that occurred 2.5 months after the earthquake shows buried slip on a fault connecting the mainshock rupture to the Elsinore fault. In spring of 2014 a M 5.1 earthquake struck the Los Angeles basin in the town of La Habra. UAVSAR and GPS results show a broad pattern of deformation occurred that can be explained by slip on the mainshock rupture and on additional, shallow structures surrounding the event. The M 6.0 South Napa earthquake occurred in August 2014. Inversion of GPS and UAVSAR data suggests that multiple faults ruptured near the surface, but that a single fault can explain most of the regional deformation from the event. Imagery collected in the one week to two months after the event shows substantial afterslip, but that it is confined to a single fault. It is likely that the postseismic slip extends the main rupture upward to the surface following the earthquake. GeoGateway tools were used to analyze and model the data.

**Bay Area Fault Interaction and Progressive Damage in a Risk Modeling Framework**, Jessica R. Donovan, Delphine Fitzenz, Deborah Kane, and Marleen Nyst (Poster 055)

The combination of fault and population densities in the San Francisco Bay Area raises important questions about the potential for fault interaction in this area. Plate motion is distributed across several faults in the northern San Andreas system, and the degree to which these faults interact is an important consideration for quantifying risk in the Bay Area. We therefore investigate the relationship among the major faults in the Bay Area through multi-year simulations from the time-dependent UCERP3 (Field et al., 2014) event set. Within these simulations, we observe periods in which more than one damaging earthquake occurs. When multiple events affect the same area and are closely spaced in time, loss can be amplified in successive events due to damage sustained in a previous event. We model losses for exposures in the Bay Area and include the effects of this progressive damage over the simulated time periods when multiple damaging events occur.

**Seismic structure beneath the Great Valley, central California: Implications for identifying the tectonic origin of the Isabella anomaly**, Sara L. Dougherty and Robert W. Clayton (Poster 180)

The tectonic origin of the Isabella high-velocity anomaly in the upper mantle beneath California’s southern Great Valley is unclear. Previous low-resolution seismic imaging studies of the region have been unable to identify the structural connection between this upper mantle anomaly and the overlying lithosphere. The two dominant hypotheses attribute the Isabella anomaly to a fossil slab or the foundered lithospheric root of the Sierra Nevada batholith. The Central California Seismic Experiment (CCSE) is designed to distinguish between these hypotheses. We present results from the CCSE, which consists of 44 broadband seismometers currently deployed in a quasi-linear array spanning from the Pacific coast, across the Great Valley, to the Sierra Nevada foothills, at an approximate latitude of 36°N. Waveform modeling of the 2D structure of the crust is performed using local earthquakes recorded by the CCSE and a finite-difference algorithm to provide constraints on the geometry and velocity of the Great Valley. This sedimentary basin is suggested to be filled with very low velocity material at shallow depths and partially underlain by a high-velocity ophiolite body. Therefore, a well-constrained basin structure will be important in correcting surface wave tomography and receiver function images. The impact of the Great Valley basin structure on body waves is evident by an observed delay in P-wave arrival times on the radial component relative to the vertical component for stations located within the basin. Surface waves along the CCSE array also show a distinct slowing by the valley at periods <10 sec. Data from teleseismic events recorded by the CCSE reveal scattered waves arriving tens of seconds after the S-wave at stations located across the majority of the valley, with time delays increasing from west to east. We will interpret these waves in terms of the seismic structure of the region by identifying the source location(s) of the scatterer(s). We may also gain insights into the structural connection between the Isabella anomaly and the overlying lithosphere with this analysis.

**3D dynamic rupture simulations on self-similar fractal faults**, Kenneth Duru and Eric Dunham (Poster 243)
Observations indicate that natural faults are self-similar fractal surfaces with deviations from planarity at all scales. As opposed to slip on planar faults, slip on nonplanar faults perturbs the stress field in the vicinity of the rupture front, altering its advance and introducing fluctuations in slip and rupture velocity. This variability, which destroys the coherence of the high-frequency seismic wavefield, is evidently comparable to that occurring in real earthquakes. In this work, we begin generating an ensemble of 3D simulation of shearing a fault layer between two rigid plates has revealed several interesting results including: (1) development of a computational framework in which granular and intact phases of material coexist with the abilities of resolving the different spatial and time scales associated with gouge deformation and the wave propagation in intact rocks; (2) development of a computational framework capable of resolving the slow tectonic loading during the inter-seismic period and the rapid elastoplastic co-seismic response; and (4) a flexible adaptive mesh refinement framework to resolve evolving localization and distributed damage features as a function of progressive loading.

Here we report on our recent progress in addressing some of these challenges. Our starting point is constructing a 2D continuum model for fault gouge plasticity. Our primary theoretical tool is using the Shear transformation zone (STZ) theory, a non-equilibrium statistical thermodynamic formulation for describing the evolution of plastic deformation in amorphous materials. We implement the STZ equations in the finite element software Abaqus through a User Defined Material Model (VUMAT). The momentum balance equations are then solved iteratively informed by the integration of STZ constitutive model. The STZ plasticity model is rate dependent and capable of capturing both hardening and softening behavior. Furthermore, the material model is includes effects such as grain breakage and particle rearrangements which leads to nonlocal yielding and complex strain localization patterns. The 2D simulation of shearing a fault layer between two rigid plates has revealed several interesting results including: (1) development of boundary and Riedel shear, (2) transition from brittle to ductile behavior in the gouge as a function of the gouge maturity level, and (3) identification of zones of tensile mean stress at the boundaries of expanding plastic regions which may leads to cracking or fracturing in cohesive soils and are a potential weakening mechanism that was not previously identified. We discuss the implications of these findings on fault gouge dynamics, gouge-pore fluid interaction as well as dynamic rupture propagation.

The Effects of Plasticity and the Evolution of Damage Zones in Earthquake Cycle Simulations, Brittany A. Erickson and Eric M. Dunham (Poster 270)

How does plastic response during the earthquake cycle affect nucleation and propagation during individual events and the recurrence intervals between events? How do damage zones evolve with increasing cumulative slip and how do they affect subsequent rupture? To explore these questions we are developing a robust, physics-based earthquake cycle model accounting for off-fault yielding over multiple event sequences. The method is developed for the anti-plane framework where interseismic loading is imposed at the remote boundary. Spontaneous, quasi-dynamic events nucleate at the fault governed by rate-and-state friction.

The off-fault volume is discretized with finite difference methods and time-dependent boundary conditions impose the free surface, remote loading and friction law at the fault. Stresses in the domain are limited by a Drucker-Prager yield condition, with depth-dependent normal stresses that remain constant in time during antiplane shear deformation. The constitutive theory furnishes a nonlinear equilibrium equation that makes use of an elastoplastic tangent stiffness tensor. One of the difficulties arising in our application problems is that plasticity reduces the effective shear modulus to values approaching zero and the equilibrium equations undergo a loss of solvability. One possible solution to this is through the incorporation of hardening which can provide a lower bound (away from zero) of the shear modulus. We assume zero initial plastic strain prior to the first event which nucleates down dip near a locking depth of 12 km. Plastic flow ensues when stresses exceed the yield condition. The event ruptures up dip with reduced rupture speed and slip velocity compared to its elastic counterpart, generating a flowerlike plastic strain distribution corresponding to greater damage near Earth’s free surface. Our preliminary exploration of parameter space show that once the first event terminates, an interseismic loading period follows during which no further plastic strain occurs. The incorporation of hardening causes the yield surface to expand during plastic response, thus subsequent ruptures generate a decreasing amount of additional plastic strain. It is likely that this behavior will change if the off-fault material softens, instead of hardens, during plastic straining.

Quantifying variability in geodetic slip rate estimates, Eileen L. Evans, Wayne R. Thatcher, and Fred F. Pollitz (Poster 213)

Current understanding of the seismic potential of faults in California is limited in part by our ability to resolve spatial and temporal changes in fault slip rates across the Pacific-North American plate boundary, and quantify their uncertainties. Fault slip rate can be estimated by modeling fault systems, based on space geodetic measurements of surface ground displacement (GPS and InSAR). However, geodetic slip rate estimates may vary widely for a single fault or region due to measurement and epistemic uncertainties. To examine published geodetic slip rate estimates in California and quantify variability among models, we develop a database compiling published geodetic slip rate estimates in California. Because deformation models may vary in the number of faults represented and the precise location of faults, we combine published geodetic slip rate estimates on a geographic grid and compare models spatially. Within each geographic grid cell, a number of metrics are considered based on the suite of fault slip rates in the cell. These metrics include geometric moment, total slip rate, strain rate, formal uncertainties, and variation among models. This approach assumes that all published geodetic slip rate estimates are equally valid, and therefore the variability among models serves as a proxy for epistemic uncertainties in geodetic slip rates. These uncertainties can then be incorporated into hazard estimates and used to systematically identify regions that may require more careful consideration in terms of modeling available geologic and geodetic data.

How much can we hope to resolve in earthquake rupture processes with back-projection?, Wenyuan Fan and Peter M. Shearer (Poster 169)

Back-projection has been proven to be reliable and effective for unraveling complicated earthquake rupture processes. It is very robust because the method makes few a priori assumptions about the fault geometry or rupture speed, and is relatively insensitive to 3D velocity variations. As most studies use array data at high frequencies for back-projection imaging, the results sometime suffer from artifacts, limited resolution, and unclear physical explanations. We have found that improved back-projection results can be obtained utilizing global data. First, global data often can provide fairly uniform azimuthal coverage, which improves spatial resolution and reduces back-projection artifacts, permitting hidden features in the ruptures to be studied in detail. Second, the good azimuthal coverage also enables back-projection to be performed at relatively low frequencies (0.05 to 0.2 Hz), which can fill in the gap
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between moment tensor/finite-fault inversions (low frequency content) and high-frequency back-projection/beam-forming. Third, P-wave polarity differences among global stations will affect the maximum coherency of back-projected power as a function of source location, which can be used to resolve the spatially varying local-mechanisms of complicated earthquakes involving multiple fault segments. We plan to conduct synthetic tests to explore the resolution and uncertainty limits of global back-projection across multiple frequency bands. Ultimately, we hope to extend the potential of back-projection methods with global array data, while exploring the theoretical limits of the method.

Understanding the granular origins of rate and state friction behavior of fault gouge, Behrooz Ferdowsi, Douglas Jerolmack, and David Goldsby (Poster 265)

Most mature faults contain a granular layer at their core, termed “fault gouge”. Gouge is accumulated through wear and fragmentation of the fault interface and most often is the weakest zone of the fault. The dynamical behavior of gouge thus plays a fundamental role in the stability of the fault system. Granular layers exhibit stick-slip dynamics when subjected to shearing at sufficiently high confining pressures and low shearing velocities in laboratory experiments and simulations. Stick-slip instabilities have been associated with a non-monotonic shear stress vs. shear rate response in granular materials with frictional dissipation. The non-monotonic response has recently been argued to be an important contribution to rate and state dependent frictional behavior. Here, we seek to understand the physics of rate and state friction behavior of simulated fault gouge using theory and methods from the field of granular physics. We use particle dynamics simulations to explore the response of fault gouge to a range of loading conditions, at confining pressures of 0.5 to 50 MPa and shear velocities of 5 to 1000 μm/s. Our granular system is constructed of grains with the mechanical properties of quartz. Grains interact with each other in the contact-normal direction via the Hertz contact law and in the shear direction via Coulomb friction. We show that by varying the shear rate from low to high values, the dynamical behavior of the simulated fault gouge transitions from stick-slip to continuous (steady) sliding. Stick-slip behavior emerges in the absence of permanent deformation at the grain scale, indicating that frictional dissipation and disordered structure are sufficient to produce rate and state frictional behavior and a non-monotonic shear stress vs. shear rate response. We will next examine the response of the system at different states to a change in shear rate (in simulated velocity-stepping tests), providing insight into grain-scale processes at the core of observed velocity-weakening and velocity-strengthening behaviors. We also monitor the energy release and slip initiation mechanisms in simulated gouge in relation to precursory phenomena and triggering of aftershocks. Our results provide important inputs for a granular physics-based view of the mechanics of fault gouge and for formulating physically-based friction laws with predictive power across widely varying length and time scales.

Getting Real: The Promise and Challenges of 3D Ground-Motion Simulations, Arthur Frankel and William Stephenson (Invited Talk Tue 10:30)

3D ground-motion simulations improve our prediction of ground shaking for future large earthquakes. For the Seattle basin, there are clear observations of basin-edge focusing and basin-edge generated surface waves that we have successfully modeled using the 3D finite-difference method. In 2007, we published probabilistic seismic hazard maps for Seattle of 1 Hz spectral accelerations, based on 3D simulations for 540 earthquake rupture scenarios for sources that dominate the probabilistic hazard. These maps were derived from synthetic seismograms at 7200 receiver sites spaced 280m apart. We also investigated how 3D random heterogeneities in seismic velocities can affect forward directivity pulses and basin surface waves. The Hanford basin in eastern Washington is another case where basin-edge generated surface waves are observed in recordings by 3D simulations. Our current challenge is producing broadband (0-10 Hz) synthetic seismograms for M9 earthquakes on the Cascadia subduction zone using 3D simulations up to 1 Hz, as part of the M9 project of the University of Washington. The central task of this study is to consider a variety of rupture scenarios and provide realistic synthetic seismograms to structural and geotechnical engineers so that they can evaluate the range of performance of buildings and soils. Strong-motion and teleseismic recordings of the M9.0 Tohoku and M8.8 Maule earthquakes, as well as observations of some large crustal earthquakes, indicate that higher frequency (≥0.5 Hz) radiation is generated at localized portions of the fault that are not the same as where the maximum slip occurs. This implies that the wavenumber spectra of stress and slip on a fault vary along the fault plane, with smooth and rough patches. For the M9 Cascadia simulations, we use high stress drop M8 sub-events combined with background slip with relatively long rise times. We present an example for the Seattle basin that demonstrates the importance of using geologic information to constrain inversions for seismic velocities based on Rayleigh wave phase velocities. A 3D simulation using the smoothed southern edge of the Seattle basin determined from the surface-wave inversion cannot reproduce the basin-edge focusing observed during the Nisqually earthquake. This focusing is well explained by a 3D simulation with a velocity model containing an abrupt southern edge of the basin derived from geologic information and seismic reflection profiles.

Holocene geologic slip rate for Mission Creek strand of the southern San Andreas Fault, Rosemarie Fryer, Whitney Behr, Warren Sharp, and Peter Gold (Poster 073)

The San Andreas Fault (SAF) is the primary structure accommodating motion between the Pacific and North American plates. The Coachella Valley segment of the southern SAF has not ruptured historically, and is considered overdue for an earthquake because it has exceeded its average recurrence interval. In the northwestern Coachella Valley, this fault splits into three additional fault strands: the Mission Creek strand, which strikes northwest in the San Bernardino Mountains, and the Banning and Garnet Hill strands, which continue west, transferring slip into San Gorgonio Pass. Determining how slip is partitioned between these faults is critical for southern California seismic hazard models. Recent work near the southern end of the Mission Creek strand at Biskra Palms yielded a slip rate of ~14-17 mm/yr since 50 ka, and new measurements from Pushawalla Canyon suggest a possible rate of ~20 mm/yr since 2.5 ka and 70 ka. Slip appears to transfer away from the Mission Creek strand and to the Banning and Garnet Hill strands within the Indio Hills, but the slip rate for the Garnet Hill strand is unknown and the 4-5 mm/yr slip rate for the Banning strand is applicable only since the mid Holocene. Additional constraints on the Holocene slip rate for the Mission Creek strand are critical for resolving the total slip rate for the southern SAF, and also for comparing slip rates on all three fault strands in the northern Coachella Valley over similar time scales. We have identified a new slip rate site at the southern end of the Mission Creek strand between Pushawalla and Biskra Palms. At this site, (the Three Palms Site), three alluvial fans sourced from three distinct catchments have been displaced approximately 80 meters by the Mission Creek Strand. Initial observations from an exploratory pit excavated into the central fan show soil development consistent with Holocene fan deposition and no evidence of soil profile disruption. To more precisely constrain the minimum depositional timing of the most well-defined alluvial fan, we are currently processing samples for U-series analysis of pedogenic carbonate. We expect this to result in a maximum bound of the Holocene slip rate on the Mission Creek Strand. Future Be-10 exposure age measurements from surface cobbles will independently constrain fan age yielding a complementary Holocene slip rate.

Active flower structure along the San Andreas fault zone in Coachella Valley, California: Results from the Salton Seismic Imaging Project, Gary S. Fuis, Klaus Bauer, Mark R. Goldman, Trond Ryberg, Victoria E. Langenheim, Daniel S. Scheirer, Michael J. Rymer, Joann M. Stock, John A. Hole, Rufus D. Catchings (Poster 223)

The southernmost part of the San Andreas fault (SAF) zone, in the Coachella Valley, California, is considered likely to produce a large-magnitude, damaging earthquake in the future. The geometry of the SAF and adjacent sedimentary basins will greatly influence energy radiation and strong ground motion during a future rupture. The Salton Seismic Imaging Project (SSIP) was undertaken, in part, to provide more accurate information on the SAF and basin geometry in this region. We report interpretations of seismic profiles in the Salton Trough (Lines 4, 6) that cross the Coachella Valley normal to the SAF. On Line 4, through
the Mecca Hills, seismic imaging (reflection and refraction), potential-field studies (magnetic and gravity), and microearthquakes (relocated hypocenters and focal mechanisms) provide strong constraints on SAF structure. In the depth range of 7-13 km, the SAF dips ~ 50° NE. At depths less than 5 km, a clear flower structure is seen, where multiple faults generally dip steeply and can be correlated with mapped fault traces in the Mecca Hills. On Line 6, in the northernmost Coachella Valley, seismic data also image a flower structure developed at depths less than 9 km above a NE-dipping SAF. In the depth range of 9-13 km, the SAF dips ~ 55° NE.

Fault zone hydrologic properties and processes revealed by borehole temperature monitoring, Patrick M. Fulton and Emily E. Brodsky (Poster 271)

High-resolution borehole temperature monitoring can provide valuable insight into the hydrogeologic structure of fault zones and transient processes that affect fault zone stability. Here we report on results from a subsurface temperature observatory within the Japan Trench plate boundary fault and discuss methodologies that can be applied to other investigations offshore or on land.

We illustrate how spatial variations in the thermal recovery of the borehole after drilling and other spectral characteristics provide a measure of the subsurface permeability architecture. More permeable zones allow for greater infiltration of cool drilling fluids, are more greatly thermally disturbed, and take longer to recover. The results from the JFAST (Japan Trench Fast Drilling Project) observatory are consistent with geophysical logs, core data, and other hydrologic observations and suggest a permeable damage zone consisting of steeply-dipping faults and fractures overlays a low-permeability clay-rich plate boundary fault.

Using high-resolution time series data, we have also developed methods to map out when and where fluid advection occurs in the subsurface over time. In the JFAST data, these techniques reveal dozens of transient earthquake-driven fluid pulses that are spatially correlated and consistently located around inferred permeable areas of the fault damage zone. These observations are suspected to reflect transient fluid flow driven by pore pressure changes in response to dynamic and/or static stresses associated with nearby earthquakes. This newly recognized hydrologic phenomenon has implications for understanding subduction zone heat and chemical transport as well as the redistribution of pore fluid pressure which influences fault stability and can trigger other earthquakes.

Engineering Validation of Simulated Ground Motions for Skewed-bridges Response Assessment, Carmine Galasso, Farzin Zareian, Peyman Kaviani, and Alexandra Tsoulou (Poster 002)

This study deals with the engineering validation of the hybrid broadband ground-motion simulation methodology by Graves and Pitarka (2010) in terms of seismic response of reinforced concrete (RC) bridges with skewed-angled seat-type abutments (or simply ‘skewed bridges’). Synthetic ground motions, simulated at fine grid spacing, represent an attractive option for estimation purposes, e.g., if transportation networks are of interest. Moderate and strong earthquake events may cause system interruption over a long period of time, resulting in unacceptable socio-economic losses and societal disruption. In order to assure that the damage estimates of a bridge (or a portfolio of bridges in a transportation network) computed using simulated and recorded ground motions exhibit similar statistics, the equality, in statistical sense, between seismic responses to these two types of accelerograms needs to be tested. To this aim, three short bridges located in California are selected as seed bridges here, from which different models are developed by varying key bridge structural parameters such as column-bent height, symmetry of span arrangement, and abutment skew angle. Through extensive nonlinear dynamic analysis conducted using simulations and actual recordings for two historical earthquakes; i.e., 1989 M 6.8 Loma Prieta earthquake and 1994 M 6.7 Northridge earthquake, it is demonstrated that median deck rotations and column drift ratios produced by simulations agree reasonably well with those produced by recorded ground motions. However, the intra-event dispersion in the structural response due to the simulations is generally lower than that for recorded ground motions, consistently with the findings of previous studies on the same topic. Finally, the sensitivity of the two demand parameters to some ground-motion intensity measures, particularly those related to ground-motion directionality and directivity, is investigated for both simulations and recorded waveforms.

Low-frequency basin resonance effects in Kathmandu during the 2015 Mw 7.8 Gorkha earthquake and its aftershocks, Jianghui Geng, Jennifer S. Haase, Diego Melgar, and Yehuda Bock (Poster 179)

On April 25, 2015 an Mw 7.8 thrust earthquake struck Kathmandu, Nepal with about 9000 fatalities. The earthquake initiated northwest of Kathmandu and ruptured southeastward along a 140 km long fault segment with a total duration of about 65 s with peak moment release less than 10 km north of Kathmandu. Half an hour later, an Mw 6.6 aftershock occurred at about 15 km northeast of the mainshock epicenter. On the next day, another aftershock of Mw 6.7 occurred in the northeastern region of Kathmandu, and an even larger event of Mw 7.3 nucleated in nearly the same region on May 12. Kathmandu is located in a basin filled with 500-600 m of fluviolacustrine sediments where the amplitudes of seismic waves are amplified. This would potentially cause substantial damages to local buildings, as in the case of 1985 Mexico City earthquake, from local amplification. However, during the 2015 event the damage to most vulnerable regular dwellings shorter than 4 stories was less severe than that during the 1934 Mw 8.1-8.4 event.Galetzka et al. (2015) reported that the mainshock can be modeled with a simple single slip of 6-7 s duration and smooth onset. The mainshock and three aftershocks were well observed by six 5-Hz GPS stations near the rupture area. Unique high-rate GPS observations at site NAST located within Kathmandu basin illustrate long period resonances (3-5 s) directly in the displacement records when compared to GPS site KKN4 built on bedrock in the hills to the north of the basin. Observed acceleration records for sites in the Kathmandu basin showed resonance effects as well, with peaks at periods of about 5s and 0.3-5s. With these records from 4 events, we will quantify the evidence of long period amplification in displacement records, and test hypotheses for basin resonance using forward modeling based on available information about the basin structure.


Paleoseismic records are often considered incomplete due to the difficulty of detecting ruptures in trenches. Events become increasingly difficult to detect as slip decreases, large earthquakes may be missed if the rupture did not pass through the trench, and it is difficult to differentiate between events that occur very close in space and time. One might assume that these difficulties would result in missing or fewer events. Alternatively, misinterpretation of paleoseismic features could result in over-counting, which may be a more significant problem. We test the effects of different models of event detectability in paleoseismic study sites in the probabilities of large earthquakes in California. We employ the 3D boundary element code RSQSim with a new California fault model, based on the UCERF3 report, to generate synthetic catalogs with millions of events. The simulations incorporate rate-state fault constitutive properties in complex, fully interacting fault systems. Our catalogs are tuned to match the recurrence intervals at the paleoseismic sites in the UCERF3 report by making adjustments to the normal stress in the model. We compare earthquake probabilities at paleoseismic sites using catalogs that were thinned, prior to tuning, based on different models of event detectability. The first catalog was tuned assuming 100% detectability. The second catalog was thinned using the UCERF3 Appendix I probability model of detection, which is based on amount of observed slip at each site. The third catalog was thinned based on a model of detectability that assumes fewer detectable events than given by the UCERF3 model. Finally, the fourth catalog was thinned based on the UCERF3 probability model, but tuned to 25% longer mean recurrence intervals. Comparisons of the different catalogs suggest that the mean recurrence intervals from paleoseismic trenches may be too short resulting in over-estimation of probabilities.

MEETING ABSTRACTS

Three-dimensional (3D) seismic velocity models provide the foundational data for ground motion simulations that calculate the propagation of earthquake waves through the Earth. The Southern California Earthquake Center (SCEC) has developed the Unified Community Velocity Model (UCVM) package for both Linux and OS X. This unique framework provides a cohesive way for querying and visualizing 3D models. The current version, UCVM 14.3.0, supports many Southern California velocity models including CVM-S4, CVM-H 11.9.1, and CVM-S4.26. The last model was derived from 26 full-3D tomographic iterations on CVM-S4. Recently, UCVM has been used to deliver a prototype of a new 3D model of central California (CCA) also based on full-3D tomographic inversions. UCVM was used to provide initial plots of this model and will be used to deliver CCA to users when the model is publicly released.

Visualizing models is also possible with UCVM. Integrated within the platform are plotting utilities that can generate 2D cross-sections, horizontal slices, and basin depth maps. UCVM can also export models in NetCDF format for easy import into IDV and ParaView. UCVM has also been prototyped to export models that are compatible with IRIS' new Earth Model Collaboration (EMC) visualization utility. This capability allows for user-specified horizontal slices and cross-sections to be plotted in the same 3D Earth space.

UCVM was designed to help a wide variety of researchers. It is currently being used to generate velocity meshes for many SCEC wave propagation codes, including AWP-ODC-SGT and Hercules. It is also used to provide the initial input to SCEC's CyberShake platform. For those interested in specific data points, the software framework makes it easy to extract P and S wave propagation speeds and other material properties from 3D velocity models by providing a common interface through which researchers can query earth models for a given location and depth.

Also included in the last release was the ability to add small-scale stochastic heterogeneities to extracted Cartesian meshes for use in high-frequency ground motion simulations. This tool was built using the C language open-source FFT library, FFTW. The stochastic parameters (Hurst exponent, correlation length, and the horizontal/vertical aspect ratio) are all adjustable by the user.


Providing actionable data for situational awareness following an earthquake or other disaster is critical to decision makers to improve their ability to anticipate requirements and provide appropriate resources for response. GeoGateway is a data product search and analysis gateway for scientific discovery, field use, and disaster response focused on NASA UAVSAR and GPS data that integrates with fault data, seismicity and models. E-DECIDER (Emergency Data Enhanced Cyber-Infrastructure for Disaster Evaluation and Response) is a decision support system producing remote sensing and geophysical modeling products relevant to the emergency preparedness and response communities that serves as a gateway to enable the delivery of actionable information to these communities.

Crustal deformation observations can be difficult to access and analyze. The distribution, heterogeneity, and varying quality of the data products are problematic to explore. The complexity of the geodetic imaging data requires a steep learning curve that is inefficient for scientific analysis and infeasible for emergency responders who must act quickly and use intuitive tools to respond to a disaster. GeoGateway allows users to efficiently find and use NASA geodetic imaging data products for analysis of deformation pre- and post-event.

Key information on the nature, magnitude and scope of damage, or Essential Elements of Information (EEI), necessary to achieve situational awareness, are often generated from many organizations and disciplines, using a variety of geospatial and non-geospatial technologies. We are developing actionable products with the CA Earthquake Clearinghouse for use in their response efforts, particularly in exercises such as the May 2015 Capstone and the upcoming June 2016 Cascadia Rising Exercises, as well as for event activations such as the August 2014 South Napa earthquake. We also provided a number of products, services, and consultation to the NASA agency-wide response to the April 2015 Gorkha, Nepal earthquake.

We will present perspectives on developing tools for data discovery and decision support. Products include map layers, delivered through XchangeCore, as part of the common operational data plan for the Clearinghouse that enable users to create merged datasets from multiple providers. For the Nepal response, products included models, damage and loss estimates, and aftershock forecasts that were posted to a NASA site and delivered directly to end-users.

Seismogenic response to fluid injection operations in Oklahoma and California: Implications for crustal stresses, Thomas H. Goebel and Fred Aminzadeh (Poster 142)

The seismogenic response to induced pressure changes provides insight into the proximity to failure of faults close to injection wells. Here, we examine possible seismicity rate changes in response to wastewater disposal and enhanced oil recovery operations in hydrocarbon basins in California and Oklahoma. We test whether a statistically significant rate increase exists within these areas and determine the corresponding timing and location based on nonparametric modeling of background seismicity rates. Annual injection volumes increased monotonically since ~2001 in California and ~1998 in Oklahoma. While OK experienced a recent surge in seismic activity which exceeded the 95% confidence limit of a stationary Poisson process in ~2010, seismicity in CA showed no increase in background rates between 1980 and 2014. A systematic analysis of frequency-magnitude-distributions (FMDs) of likely induced earthquakes in OK indicates that FMDs are depleted in large-magnitude events. Seismicity in CA hydrocarbon basins, on the other hand, shows Gutenberg-Richter type FMDs and b~1. Moreover, the earthquakes and injection operations occur preferentially in distinct areas in CA whereas in OK earthquakes occur closer to injection wells than expected from a random uniform process. To test whether injection operations may be responsible for the strongly different seismicity characteristics in CA and OK, we compare overall well density, wellhead pressures, peak and cumulative rates as well as injection depths. We find that average injection rates, pressures and volumes are comparable between CA and OK and that injection occurs on average 0.5 km deeper in CA than in OK. Thus, the here tested operational parameters can not easily explain the vastly different seismogenic response to injection operations in CA and OK, and may only be of secondary importance for the resulting earthquake activity. The potential to induce earthquakes by fluid injection operations is likely controlled by the specific geologic setting and stress state on nearby faults.

New geologic slip rates for the Agua Blanca Fault, northern Baja California, Mexico, Peter O. Gold, Whitney M. Behr, John Fletcher, Alejandro Hinojosa-Corona, and Thomas K. Rockwell (Poster 097)

Within the southern San Andres transform plate boundary system, relatively little is known regarding active faulting in northern Baja California, Mexico, or offshore along the Inner Continental Borderland. The inner offshore system appears to be fed from the south by the Agua Blanca Fault (ABF), which strikes northwest across the Peninsular Ranges of northern Baja California. Therefore, the geologic slip rate for the ABF also provides a minimum slip rate estimate for the offshore system, which is connected to the north to faults in the Los Angeles region. Previous studies along the ABF determined slip rates of ~4-6 mm/yr (~10% of relative plate motion). However, these rates relied on imprecise age estimates and offset geomorphic features of a type that require these rates to be interpreted as minima, allowing for the possibility that the slip rate for the ABF may be greater. Although seismically quiescent, the surface trace of the ABF clearly reflects Holocene activity, and given its connectivity with the offshore fault system, more quantitative slip rates for the ABF are needed to better understand earthquake hazard for both US and Mexican coastal populations.

Using newly acquired airborne LiDAR, we have mapped primary and secondary fault strands along the segmented western 70 km of the ABF. Minimal development has left the geomorphic record of surface slip remarkably well preserved, and we have identified abundant evidence
meter to km scale right-lateral displacement, including new Late Quaternary slip rate sites. We verified potential reconstructions at each site during summer 2015 fieldwork, and selected an initial group of three high potential slip rate sites for detailed mapping and geochronologic analyses. Offset landforms, including fluvial terrace risers, alluvial fans, and incised channel fill deposits, record displacements of ~5-80 m, and based on minimal soil development, none appear older than early Holocene. To quantitatively constrain landform ages, we collected surface and depth profile samples for Be-10 cosmogenic exposure dating. We also identified sites for new paloseismic excavations, and documented evidence of the last two earthquakes, each of which produced ~2.5 m of surface displacement. We expect new Holocene slip rates for the Agua Blanca Fault to be forthcoming in fall of 2015.

Physically-based and empirical models of site response for SCEC ground motion simulations, Carlos Gonzalez, Albert Yang, Jian Shi, and Dommnik Asimaki (Poster 013)

We present results from two ongoing projects on the integration of site (near-surface path) effects in SCEC broadband and physics-based ground motion simulations. In the first project, we are developing three site response modules for the Broadband Platform (BBP), which, given the velocity profile at a specific site, can estimate the effects of site response on ground motion time series for small to medium intensity shaking. Modules to predict highly nonlinear site response and ground failure will be developed in the next phase of this project. For regional applications, however, geotechnical site characterization data are scarce and sparse, and here the challenge lies in developing site response models that are based on very few input parameters. Within the broader research goals of SCEC, we are tackling this problem in two ways: first, we are developing an improved geotechnical layer (GTL) to approximate the near-surface path layering in 3D physics-based simulations; and second, we are developing empirical complex amplification factors based on Fourier spectral ratios to be used post-facto in broadband ground motion simulations. Both elements of this project are based on simple site and ground motion proxies.

Plate Tectonic Moment Rate at the Pacific-NorthAmerica Border in Las Californias, Jose Javier Gonzalez-Garcia and Javier Alejandro Gonzalez-Ortega (Poster 216)

Utilizing Google Earth, we compare 3 global Tectonic Motion Models: GEODVEL, ITRF2008-TMM and MORVEL56, and the regional model of Gonzalez-Garcia et al (2003), for the Pacific-NorthAmerica border (PANA) at Las Californias. All geodetic models include Isla Guadalupe GPS observation as constraint; MORvel56 is geologic. Our hypothesis is a constant Euler vector, a constant latitudinal angle(s) from pole of rotation and, obviously, rigid plates (i.e., deformation only in the boundary). GEODVEL predicts a better adjustment to the evolution of PANA in terms of geological and geometric constraints. Using the mean location of the San Andreas Fault at Point Reyes (35.7° from pole) and our estimated position of the crossing between Alarcon Rise and Tamayo Transform Zone (37.7°), we estimate that Mendocino Triple Junction (MTJ) is at 40.4°N,124.9°W, and exist a Southern Virtual Triple Junction (VSTJ) NNW from Islas Tres Marias at 22.2°N,107.0°W. Both TJs where together, 29.8 million year ago BP. Considering fixed the MTJ and NA, the SVTJ after following the small circle comprising; north SAF-San Gregorio/Hosgri-San Clemente-Canal de Ballenas-Guaymas transform, "jump" to the small circle comprises San Benito-Tamayo Transform at 12.4 My. The differential motion of northern PANA (from the head of Gulf of California to Mendocino ~1300km) is 5.04 cm/yr, generating a plate tectonic moment rate of 1026.3±0.2 dyne-cm/yr, with sismogenic depth dependence (11±5km). This figure corresponds to a Mw7.85±0.15 earthquake circle of one century if seismicity follow the Gutenberg-Richter Law with b=1.0. This activity predicted by GEODVEL agrees with historic/instrumental earthquakes in the area, probably including postseismic and slow earthquakes. The main parameter to dilucitate for moment rate estimation remains sismogenic depth. More densified, like Anza, seismograph arrays are needed.

Integrated Static and Dynamic Stress Models for Investigating Tremor Source Regions, Hector Gonzalez-Huizar, Sandra Hardy, Aaron A. Velasco, Bridget Smith-Konter, and Karen M. Luttrell (Poster 033)

For active tectonic boundaries, the probability of having an earthquake along a locked zone may depend on the physical conditions at depth, including the frictional and stress state of the underlain aseismic zone; however, frictional and stress states remain difficult to estimate at deep crustal depths. Recent studies have shown that in many tectonic environments, including the San Andreas Fault (SAF) system, dynamic stress changes related to the passage of seismic waves can change local stresses at deep overstressed fault patches, causing sliding and generating seismically detectable tectonic non-volcanic tremor signals. In this work, we present some of our results of using integrated models of the local static and dynamic triggering stresses to investigate the frictional and stress conditions of the SAF where ambient and triggered tremor occurs. Dynamic stress is modeled directly from recorded seismic signals, and static stress is obtained and modeled from existing SCEC Community Stress Model (CSM) contributions. The calculated triggering dynamic stress are added to static stress maps as a proxy to the absolute stresses acting during fault sliding, which is expressed as a seismically detectable tremor signal. Calculating static and dynamic stress for the entire SAF allows for a comparison of the stress and frictional conditions necessary for tremor occurrence.

Space Geodetic Studies in the Southernmost Section of the San Andres fault system in northern Baja California, Mexico, Alejandro J Gonzalez-Ortega, David Sandwell, and Javier Gonzalez-Garcia (Poster 211)

We have studied a dataset of geodetic observations across the Cerro Prieto (CPF) and Imperial (IF) faults, and in the Cerro Prieto Geothermal Field, using Global Position System (GPS) and Interferometric Synthetic Aperture Radar (InSAR). We have installed and conducted dense GPS surveys across these two major faults in the Mexicali Valley from 2011 to 2015, and assembly of a large number of synthetic aperture radar images from ERS, Envisat and ALOS-1 mission satellites, between 1995 and 2010. The GPS data show high velocity gradients of ~35 mm/yr in 40 km across the CPF and IF, however these might be influenced by the 2010 Mw 7.2 El Mayor-Cucapah postseismic relaxation, including the Indiviso Fault (west and ~parallel to CPF) and a possible Northwest continuation of the CPF, which may accommodate slip rates previously only attributed to the CPF and IF. The InSAR data show the characteristic anthropogenic subsidence (~12 cm/yr) and its spatial extent, caused by fluid extraction and recharge at the CPFG, as previously documented in others studies. The substantial anthropogenic subsidence at the Cerro Prieto Geothermal Field and the estimated slip rates across the Cerro Prieto and Imperial faults may contribute to the earthquake hazard assessment in northern Baja California and southern California.

From Seismic Hazard to Risk: Summary of Critical Issues and How SCEC Research Can Foster New Solutions, Christine A. Goulet (Invited Talk Tue 14:00)

Seismic risk analysis is gaining popularity as a tool for civil engineering design. It is not only the basis for the performance-based earthquake engineering (PBEE) design approach, it is now included, in a simplified fashion, into the latest building codes and design guidelines. Risk combines hazard, exposure and vulnerability to provide probabilities of various outcomes such as structural collapse, loss of life, and exceedance of given threshold repair costs or downtime. Overall, better risk quantification helps stakeholders make better decisions and will contribute to a more sustainable society. Example applications of risk-informed decision include the design of new critical facilities, such as hospitals, dams and bridges, and the prioritization of retrofitting for our aging building stock and infrastructure.

In this presentation, I will cover a “big picture” view of seismic hazard risk. The presentation is focused on risk from ground-motion hazard, but the take-away points are applicable to other types of seismic hazard as well, such as from surface fault rupture, liquefaction, or earthquake-triggered landslides. Often, the factor controlling risk, especially at long return periods, is the seismic hazard itself, and more specifically its associated uncertainty and variability. After showing examples on how hazard impacts risk, I will explore different avenues that SCEC researchers can take to help improve hazard quantification and thus, lead to better risk assessment. The combination of fundamental and applied research conducted under the SCEC umbrella is unique. With contributions from
both the core research program and the special projects, the SCEC community can have a meaningful impact on seismic resilience.

IDA Demonstrates nSpectra as a Valuable New IM, William P. Graf, Yajie J. Lee, and Jeff Bayless (Poster 024)

nSpectra [W. Graf, Y. Lee, C. Goulet, ASCE, 2010] has been suggested as a potential new intensity measure (IM). For a given ground motion time series, nSpectra quantifies the number of response cycles “n” for a linear elastic oscillator exceeding a stated threshold, An, as a function of oscillator period. T. nSpectra was designed to capture the effects of magnitude and duration on damage and collapse of building structures, to supplement the use of spectral acceleration (Sa). Incremental Dynamic Analysis (IDA) was used to test nSpectra, which is shown to improve the prediction of ductility demand compared to Sa alone.

For IDA, we selected two oscillators, with T = 0.2s and with T = 2s. For each oscillator, we assigned hysteresic properties with degrading stiffness and strength, similar to nonductile concrete frame buildings. We also evaluated a non-degrading version of the T=2s oscillator. To evaluate the nSpectra, we termed “n” for each IDA solution point. The results show that, for stiffness and strength-degrading structures, high “n” values are associated with higher degradation, and higher ductility demands. Introducing “n” in predictive models like SPO2IDA will reduce the dispersion, and improve damage and collapse predictions.

New radiocarbon dates for refining the slip rate of the San Andreas Fault at Wallace Creek in the Carrizo Plain, CA, Lisa Grant Ludwig, Sinan O. Akciz, J Ramon Arrowsmith, Tsurue Sato, Terry M. Cheifetz, and David E. Haddad (Poster 086)

The slip rate on the San Andreas fault in the Carrizo Plain was first measured at Wallace Creek. Sieh and Jahns’ (1984) slip rate of 33.9 ±2.9 mm/yr was derived from radiocarbon dates of 8 detrital charcoal samples for deposits associated with the offset landforms. The slip rate has been referenced hundreds of times, and provides critical constraint for seismic hazard in California, and many research studies. Paleoseismologic studies at Bidart Fan, ~5 km southeast of Wallace Creek, revealed surface rupture approximately every 88 yrs between ~A.D. 1350 and 1857 (Akciz et al., 2010). Measurements of slip per event for the last 5 or 6 earthquakes at Wallace Creek (Liu et al., 2004; Liu-Zeng et al., 2006), when combined with rupture dates from Bidart Fan, yield slip rates up to 50 mm/yr, well above the widely accepted values of ~35 mm/yr. The apparent discrepancy between slip rates derived from the offset of Wallace Creek and slip per event measurements provided motivation to re-measure Sieh and Jahns’ (1984) slip rate by reopening old trenches and excavating new trenches to collect samples for radiocarbon dating with methods that have improved dramatically since the early 1980s. We re-excavated Sieh and Jahns’ (1984) original trenches WC-2, 7, 9, 10 and 11, and cut a new trench, WC-12. The new trench exposed a rich history of channel cut and erosion, with rupture dates from 8 radiocarbon dates from 35 m depth. Combining these initial ages with structural relief measured from the borehole cross-section allows us to determine a latest Holocene-Holocene uplift rate and, by considering the dip of the fault, a reverse slip rate. The resulting slip rate is somewhat slower than that suggested at our Day Road study site 1.4 km to the west, consistent with slip diminishing eastward toward the Brookshire Avenue site, which lies near the eastern end of the geomorphic expression of the Ventura fault. Eastwards from the Brookshire Avenue site, slip is transferred off the Ventura fault and onto the Southern San Cayetano fault through a “soft” geologic segment boundary. These observations, in combination with ongoing luminescence dating (ages pending) of samples from the boreholes, will provide information on incremental slip rates, as well as the timing and displacement in recent Ventura fault earthquakes. These results add to a growing body of paleoseismic and structural information along the Ventura fault that is changing our view of the hazard posed by this structure. In particular, evidence for large single-event displacements (5-10 m), a rapid fault slip rate, and structural analyses documenting the interconnectivity of major rupture faults of the Western Transverse Ranges demonstrate that the Ventura fault has the potential to generate very large-magnitude (Mw 7.5-8) earthquakes involving multiple faults in the western and central Transverse Ranges. The occurrence of such large magnitude earthquakes has important implications for seismic risk in the densely populated southern California region

Kinematic Ground Motion Simulations on Rough Faults Including Effects of Random Correlated Velocity Perturbations, Robert W. Graves and Arben Pitaraka (Poster 010)

Many recent advances in kinematic rupture characterization have been guided by dynamic spontaneous rupture simulations, which are utilized to develop simplified relations for determining and specifying the required kinematic parameters (e.g., Guatieri et al, 2004). Our methodology follows this same basic approach and starts by generating a spatially random slip distribution that has a roughly wavenumber-squared falloff. The rupture speed is specified to average about 75% of the local shear wave speed and the prescribed slip-rate function has a Kostrov-like shape with a fault-averaged rise time that scales self-similarly with seismic moment. However, both the rupture time and rise time include significant local perturbations across the fault surface that are determined from spatially random fields having roughly wavenumber-squared falloff that are partially correlated with slip. In addition, we incorporate shallow (<5 km) and deep (>15 km) “weak” zones characterized by a decrease in rupture speed and an increase in rise time, which are designed to represent velocity- strengthening regions within the crust. Recent refinements to the approach include the incorporation of geometric perturbations to the fault surface (e.g., Shi and Day, 2013; Trugman and Dunham, 2014), 3D stochastic, correlated perturbations to the velocity structure (e.g. Hartzell et al., 2010), and a ‘damage zone’ surrounding the shallow fault surface characterized by a 30% reduction in seismic velocity (e.g., Cochran et al., 2009). These features all act to reduce the coherency of the radiated higher frequency (0-1 Hz) ground motions, and homogenize radiation pattern effects in this same bandwidth, which move the simulations closer to the statistical characteristics of observed motions. We demonstrate the approach using a suite of simulations for a hypothetical Mw 6.45 strike-slip earthquake embedded in a generalized hard-rock velocity structure (Vs30=1100 m/s). The simulation results are compared with the median predictions from the 2014 NGA GMPEs and show very good agreement over the frequency band 0.1 to 5 Hz for distances out to 25 km from the fault.

Characterizing the recent behavior of the Ventura blind thrust fault: results from the Brookshire Avenue & Day Road sites, Ventura, Jessica R. Grenader, James F. Dolan, Lee J. McAuliffe, Ed J. Rhodes, Judith Hubbard, and John H. Shaw (Poster 116)

Analysis of three continuously cored boreholes and six cone penetrometer tests (CPTs) from strata folded above the thallic of the eastern Ventura fault, together with a high-resolution seismic reflection profile acquired in 2010 along the same transect, reveal the geometry of these deposits and provide information on incremental displacements during latest Pleistocene-Holocene on this major blind thrust fault. The lobe of active folding above the thrust thallic is marked by a prominent 8-m-tall fold scarp at the Brookshire Avenue study site. Preliminary analysis reveals 18 m of relief on a basal clay unit from which we recovered two organic clay samples from a charcoal-rich layer that both yielded latest Pleistocene ages from 35 m depth. Combining these initial ages with structural relief measured from the borehole cross-section allows us to determine a latest Pleistocene-Holocene uplift rate and, by considering the dip of the fault, a reverse slip rate. The resulting slip rate is somewhat slower than that suggested at our Day Road study site 1.4 km to the west, consistent with slip diminishing eastward toward the Brookshire Avenue site, which lies near the eastern end of the geomorphic expression of the Ventura fault. Eastwards from the Brookshire Avenue site, slip is transferred off the Ventura fault and onto the Southern San Cayetano fault through a “soft” segment boundary. These observations, in combination with ongoing luminescence dating (ages pending) of samples from the boreholes, will provide incremental fault slip rates, as well as the timing and displacement in recent Ventura fault earthquakes. These results add to a growing body of paleoseismic and structural information along the Ventura fault that is changing our view of the hazard posed by this structure. In particular, evidence for large single-event displacements (5-10 m), a rapid fault slip rate, and structural analyses documenting the interconnectivity of major rupture faults of the Western Transverse Ranges demonstrate that the Ventura fault has the potential to generate very large-magnitude (Mw 7.5-8) earthquakes involving multiple faults in the western and central Transverse Ranges. The occurrence of such large magnitude earthquakes has important implications for seismic risk in the densely populated southern California region

Improving coverage and updating GPS velocities in Southern California, David L. Guenaga, Gareth J. Funning, and Nader Shakibay Senobari (Poster 306)

Despite improvements in continuous GPS station coverage in Southern California over the past decade, several areas including the Ventura basin, Elsinore fault and central San Jacinto fault have been identified as areas with limited existing GPS coverage. In this continuing project we hope to remedy this by expanding and/or repeating GPS campaign measurements.
in these areas. In this way, our estimates of velocities can be updated and their precisions improved, ultimately providing better constraints on fault slip rates.

During the planning stage, we obtained the coordinates of previously measured sites and various potential new sites for GPS measurement. Sites were selected by considering their ease of access, sites integrity and the need for additional/updated GPS measurements in those areas. With the use of National Geodetic Survey data sheets and photographs, as well as site descriptions provided by geocachers/benchmark-hunters, we were able to effectively evaluate and locate new benchmarks for survey. Once sites were identified and located, we deployed survey-grade GPS equipment at them for a minimum of 8 hours, and in most cases for 18-24 hours. At the time of writing, over 20 sites have already been measured.

We are processing our newly-collected data, along with past campaign data, using the GAMIT software. Velocities will be estimated and rotated into a North American reference frame using the GLOBK software and interpreted using simple 1D dislocation models, once all measurements have been completed. We aim to measure at least 10 additional sites before the conclusion of the project. We also plan to archive the data produced in the UNAVCO Campaign Data archive so that it may be readily available for the SCEC community, for incorporation in the Community Geodetic Model, and for use by other geoscientists in the future.

Performance assessment of a change point model for estimating earthquake rates from induced seismicity, Abhineet Gupta and Jack W. Baker (Poster 065)

A change point model is used to estimate seismicity rates in regions of induced seismicity. Here, we optimize this model for better rate estimation, and assess its performance in Oklahoma compared to other rate estimation models. There has been a marked increase in seismicity in Oklahoma, likely due to wastewater injection in the state. This increase in seismicity can be quantified using a Bayesian change point model. The model is used to first determine whether a change in seismicity is statistically likely to have occurred, and then estimate the date of change, and event rates before and after the change. The goal here is to estimate rates that can be used to reliably predict the earthquake rates in the near future. To tune the degree of spatial smoothing used in the calculations, we use a likelihood comparison methodology. The available earthquake catalog is divided into non-overlapping “training” and “test” catalogs. The seismicity rates estimated using the training catalog are used to compute the likelihood of observing the test catalog, with a higher likelihood indicating a better prediction. Finally, we compare our predictions with a USGS model for induced seismicity hazard, using the same likelihood metric. A better performing model will enable more reliable hazard and risk assessment in a region, and serve as a better decision-support tool for regulators and stakeholders considering operations affecting induced seismicity.

A complete site-specific hazard analysis for a liquid natural gas tank station, Alireza Haji-Soltani and Shahram Pezeshki (Poster 150)

The main purpose of this study is to perform a comprehensive site-specific hazard analysis for a Liquid Natural Gas (LNG) tank station located in New Orleans, LA. Crosshole seismic survey is performed as the first step to evaluate the soil profile. The soil has been assigned a soil-type of E, based on NEHRP soil classification. The associated uncertainties in soil thickness, the shear-wave velocity, and soil dynamic properties will be taken into account. Second, a probabilistic seismic hazard analysis (PSHA) will be performed using both the classical probabilistic seismic hazard analysis (PSHA) approach (National Seismic Hazard Mapping Program codes; the EZ-FRISK software), and the Monte Carlo approach (EQHAZ code). The results from these software packages will be compared and the horizontal and vertical response spectra for Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) conditions will be investigated. Also, the effect of the potentially induced earthquakes on hazard will be studied. In third step, various available procedures will be used to choose the appropriate scaled ground-motions. The earthquake database will consist of both available recorded earthquakes and simulated ground-motions at the reference bedrock. Finally, the ground-motions at the ground surface level will be computed using both equivalent linear and nonlinear approaches. Final results will be used to calculate the design response spectra.
general idea that Roundtop is an area of weak ground shaking, and that since exhumation little weathering has affected this PBR locality.

Microseismic Detection Methods and the Mount St Helens Nodal Array, Steven M. Hansen and Brandon Schmandt (Poster 136)

The Mt St Helens nodal array consisted of ~900 short-period vertical-component geophones that were deployed for a period of two weeks in the summer of 2014. The sensors were located within a 12 km radius of the summit crater of the most active volcano in the Cascade Range. This recording provides an excellent opportunity to test methods for the detection microseismicity in a complex geologic environment. During the recording period, the local monitoring network detected 45 events that occurred directly beneath the summit and above 10 km depth. In this study, we will report on our ongoing efforts to reduce the detection threshold in a challenging large-N array setting.

The first approach that has been investigated for event detection is reverse-time source imaging (RTI). The traces are first processed using the short-term average to long-term average ratio method to mitigate spatial reverse-time source imaging (RTI). The traces are first processed using the short-term average to long-term average ratio method to mitigate spatial variations in the arrival waveform and the resulting traces are back-projected into the image volume. This approach is fully automated and simultaneously detects and locates events but includes a significant computational burden. The RTI method has been applied to the full dataset and has increased the number of detected events by an order of magnitude relative to typical PNSN monitoring efforts. Many of the detected events occur within a narrow vertical lineament beneath the summit which is interpreted as a volcanic conduit.

The second approach to seismicity detection that we have been investigating is waveform correlation. The use of correlation for event detection has been increasing rapidly and has proven to be very effective for identifying events with similar waveform characteristics and travel times. We will show how this method can be improved upon using results from the theory of matched filtering which has been developed primarily within the radar community. These detectors have a statistical derivation and are capable of handling correlated noise which is neglected in the standard correlation approach. The efficacy of these filters is compared with that of the normalized correlation coefficient using a suite of empirical tests with noise derived from actual seismic recordings. It is demonstrated that the matched filters outperform correlation, particularly at low SNR, and can therefore improve the detection of low magnitude events.

Late Quaternary Offset of Alluvial Fan Surfaces along the Central Sierra Madre Fault, Southern California, Austin Hanson, Reed Burgette, Kate Scharer, and Nikolas Midttun (Poster 118)

The Sierra Madre fault (SMF) is an east-west trending reverse fault system along the southern flank of the San Gabriel Mountains near Los Angeles, California. The ~140 km long SMF is separated into four segments, we focus on the multi-stranded, ~60 km long Central Sierra Madre fault (CSMF; W118.3-W117.7) as it lacks a well-characterized long-term geologic slip rate. We combine 1-m lidar DEM with geologic and geomorphic mapping to correlate alluvial fan surfaces along strike and across the fault strands in order to derive fault slip rates that cross the CSMF. We have refined mapping on two sets of terraces described by Crook et al. (1987) and references therein: a flight of Q3 surfaces (after nomenclature of Crook et al., 1987; McCudden, 1982) in Arroyo Seco with distinct terraces ~30 m, ~40 m, ~50 m, and ~55 m above the modern stream and in Piccans Canyon divided a Q3 and Q2 surface, with heights that are ~35 m and ~25 m above the modern stream respectively. Relative degree of clast weathering and soil development is consistent with geomorphic relationships; for example, hues of 7.5 YR to 10 YR are typical of Q3, while hues of 10 YR to 2.5 Y are typical of Q2. A scarp in the Q3 surface extends from ~16 m and a scarp in the Q3 at Piccans Canyon has a vertical offset of ~14 m, while the Q2 surface is not faulted. Our Quaternary dating strategy is focused on dating suites of terraces offset along CSMF scarp in order to provide broader stratigraphic context for the cosmogenic radionuclide and luminescence dating. A better-constrained slip rate for the CSMF will improve earthquake hazard assessment for the Los Angeles area and help clarify the tectonic role of the SMF in the broader plate boundary system. Additionally, the fan chronology will provide information about the timing of alluvial fan aggradation and incision in the western Transverse Ranges.

The SCEC-USGS Dynamic Earthquake Rupture Code Comparison Exercise – Simulations of Large Earthquakes and Strong Ground Motions, Ruth A. Harris (Poster 262)

Our SCEC-USGS Dynamic Rupture Code Comparison Group examines if the results produced by multiple researchers’ earthquake simulation codes agree with each other when computing benchmark scenarios of dynamically propagating earthquake ruptures. These types of computer simulations have no analytical solutions with which to compare, so we use qualitative and quantitative inter-code comparisons to check if they are operating satisfactorily. To date we have tested the codes against benchmark exercises that incorporate a range of features, including single and multiple linked faults, slip-weakening, rate-state, and thermal pressurization friction, elastic and visco-plastic off-fault behavior, complete stress drops that lead to extreme ground motion, heterogeneous initial stresses, and heterogeneous material (rock) structure. Our goal is reproducibility, and we focus on the types of earthquake-simulation assumptions that have been or will be used in basic studies of earthquake physics, or in direct applications to specific earthquake hazard problems. Our group’s goals are to make sure that when our earthquake-simulation codes simulate these types of events, the results are consistent with published results from and supported by simulated strong ground shaking, that the codes are operating as expected.

For more introductory information about our group and our work, please see our group’s overview papers, Harris et al., Seismological Research Letters, 2009, and Harris et al., Seismological Research Letters, 2011, along with our website, scecdsa.ucsc.edu/cvvw

Garlock fault: what is your deal?, Alexandra E. Hatem and James F. Dolan (Poster 233)

Three previously proposed models attempt to explain the kinematics of the Garlock fault (GF) by invoking: (1) conjugate faulting, with respect to the San Andreas fault; (2) intracontinental transform faulting, with respect to Basin and Range (BR) mid-continent extension; and (3) bookshelf slip/rotation, with respect to the Eastern California Shear Zone (ECSZ). We find that none of these processes completely explains the mechanics of the entire fault; instead, we propose that all three models act in concert with laterally variable relative importance along strike. To quantify ECSZ fault-rotation induced sinistral-slip, we use a simple, analytic solution, considering the GF fault as a flexing cantilever beam (e.g., Turcotte and Schubert, 2002). We use step-wise distributions of the proposed ~10 mm/yr of NNW-oriented dextral slip accommodated within the ECSZ at 1 mm/year to understand the effects of non-uniform slip-loading on oroclinal bending and sinistral slip-rate distribution along the GF. We judge goodness of fit by comparing each time step of warping to the present day fault geometry. We infer that the contribution of conjugate slip is greatest closest to the San Andreas fault, decreasing eastward. As originally proposed by Davis and Burchfiel (1973), the slip contribution from BR extension increases from the east end of the fault and reaches a maximum at the Sierra Nevada frontal fault. Conversely, slip contributions from orocinal bending of the GF in response to ECSZ slip increases eastward from the Sierra Nevada frontal fault. We provide percentage estimates of slip contributed by previously proposed models, in addition to our own analytic solution results.


The 2015 Fillmore earthquake swarm started on 5th of July at 2:21 UTC with a ~M1.03 event. It was located about 5 km west of Fillmore in Ventura. The swarm activity peaked on 9th and 10th of July with the largest event of M2.8, continued with several smaller spurs of activity, and tapered off in late July to early August. A total of 210 events in the magnitude range M1.0 to M2.8 were detected and located by the Caltech-USGS Southern California Seismic Network (SCSN). Template based processing of continuous SCSN waveforms added more than 1200 events to the dataset ranging in magnitude from 0.0 to 1.5. Using a magnitude of completeness of M0.6, the b-value for the swarm was 0.85, or only slightly lower than the average b-value for southern California.
The hypocenters have been relocated using waveform cross-correlation and double-difference methods. The swarm is densely clustered, covering an area of approximately 1 km by 2 km, in the depth range of 13 to 14 km. It defines a remarkably planar zone, less than 50 m thick and dipping 26° to N12°W. This plane is parallel to the Simi-Santa Rosa fault (SSRF), and centered about 600 m above the CMT v5.0 fault representation, well within the uncertainty of the fault location.

The focal mechanisms, which are poorly constrained and often have nodal planes inconsistent with the geometrical plane of the swarm, suggest strain-slip partitioning between high angle strike-slip faults and moderately dipping thrust faults. The heterogeneity in the mechanisms suggests that the microseismicity may have occurred just adjacent to the SSRF slip plane or a fault splay in its hanging wall, about 1.7 km below the sediment-basement contact.

The unique spatial and temporal migration of the swarm from east to west suggests fluid diffusion ranging from 0.2 to 0.25 m²/s, but individual seismicity bursts suggest much higher localized diffusion. The migration suggests that the swarm may have been related to a metamorphic dehydration event that occurred at depth below the north edge of the Ventura basin. Such an event could have caused both the microseismicity as well as the fluid-driven slip. However, because the events are small, it is not possible to detect non-double couple components of the moment tensors, which could have confirmed a dilational component of crustal deformation. Similarly, a small and deep aseismic slip event may not be detectable with available geodetic methods.

Statistical Properties of Earthquakes at The Geysers, California, Angela K. Hawkins, Donald L. Turcotte, and Louise H. Kellogg (Poster 138)

This study considers the statistics of induced and triggered seismicity at The Geysers geothermal field, California. Data is considered from the regional Northern California Seismic Network (NCSN) and local Lawrence Berkeley National Laboratory Network (LBNLN). Both data sets give good GR data fits for 2009-2014 but NCSN data have b=1.15 and LBNLN data have b=1.36. Comparing 18,000 individual earthquakes we find on average M(LBNLN) = M(NCSN)+0.5. Thus care must be taken when both data sets are used. We present studies of aftershock statistics of a M 4.53 earthquake. We find both GR and Omori Law statistics to be typical of tectonic earthquakes. We suggest that the earthquake released accumulated tectonic stresses but injected fluids reduce the stress required for rupture initiation. We also consider triggered seismicity caused by two remote earthquakes. We obtain excellent data for the 2010 M=7.2 El Mayor-Cucapah and the M=6.0 South Napa earthquakes. In the first case a M=3.37 event was triggered and in the second case a M=4.48 event was triggered. We conclude that the observed seismicity may have occurred just adjacent to the SSRF slip plane or a fault splay in its hanging wall, about 1.7 km below the sediment-basement contact.

Evidence for trans-San Gorgonio Pass earthquakes based on Holocene slip rates along the San Andreas Fault System at Millard Canyon, Richard V. Heemance, Doug Yule, and Ian Desjarlais (Poster 076)

Since the late 17th century the San Andreas Fault (SAF) in southern California has produced three large (M7.3-7.8) earthquakes that did not break through San Gorgonio Pass (SGP). This pass-as-a-barrier behavior can be explained by the complexity of the SAF system in the SGP, where the fault splays and rotates into a series of en-echelon, oblique-dextral thrusts. These faults, however, form well-preserved fault scarps up to 15 m high suggesting syn-tectonic uplift during large, through-going earthquakes in the pass. This study focuses on the center of the SGP where two sub-parallel thrusts (the northern (NF) and southern (SF)) are 1.5 km apart and cut across at least 3 terraces formed on the Millard Canyon fan. New, 10Be cosmogenic depth profiles and boulder exposure ages constrain the ages of the two oldest Holocene fan surfaces (Q4, Q3) to 8900 (range: 7300-11600) and 8300 (range: 6800-10300) y.b.p.. Radiocarbon ages constrain the younger surfaces (Q2, Q1) at ~15000 y.b.p. and ~600 y.b.p.. Q4 contains a 10.5-15.1 m high scarp along the SAF and has an uplift rate of 0.9-2.2 mm/yr. Q3 is inset 1.5 m within Q4, and contains a 3.6-6.2 m high scarp on the NF with a 0.9-2.4 mm/yr uplift rate. Measured fault dips of 45 (NF) and 20-30 (SF) degrees combined with a slip vector inferred from regional GPS data and 2.1 lateral to thrust offset markers, we calculate the net oblique slip rate on these faults at Millard Canyon at 2.1-4.8 mm/yr for Q4 and 1.0-2.7 mm/yr for Q3 (SF), and 0.8-2.2 mm/yr for Q3 and 1.9-6.8 mm/yr for Q2 (NF). The cumulative slip rate across Millard Canyon (NF+SF) is therefore 1.8-11.6 mm/yr, or more narrowly constrained at 4.0-5.9 mm/yr by using only the overlapping rates along each fault strand. An average slip rate of ~5 mm/yr is 30-70% of the slip rates along the SAF outside of SGP. This ‘slip deficit’ may reflect some combination of slip carried by faults to the north, transferred onto the ECSZ or San Jacinto Fault, or accommodated by off-fault deformation within the SGP. Nonetheless, the slip at Millard Canyon, combined with evidence for at least 3 earthquakes between ~600 and 2500 y.b.p. (see Wolfe et al., 2014 SCEC abstract), suggests that displacement on these faults occurs synchronously with some, but not all, outside-of-the-pass SAF earthquakes.

Profile of Shallow Crustal Structure across the San Andreas Fault Zone, Coachella Valley based on Controlled-Source Data from the Salton Seismic Imaging Project (SSIP), Amanda Hernandez, Patricia Persaud, Klaus Bauer, Joann M. Stock, Gary S. Fuis, John A. Hole, Mark R. Goldman (Poster 178)

The Coachella Valley is predicted to be at the center of the worst ground shaking in the event of the “Big One,” a M7.8 earthquake on the southern San Andreas Fault (SAF). Structural constraints on existing models of the shallow subsurface are essential in this region of rapidly growing population, since they give an improved understanding of the seismic hazard. In order to validate the structural interpretation of our 200 m grid-spacing 2D tomographic results, we analyzed and interpreted first arrivals from nine explosive shots recorded along Line 5 of the SSIP. This structure-based approach confirms the major features in the 2D tomography, and gives details on basement depths, fault zones and basin geometry. Line 5 comprises 281 receivers and is oriented SW-NE across the Coachella Valley, where it extends 37 km from the Santa Rosa Mountains in the Peninsular Ranges to the Little San Bernardino Mountains crossing the strands of the SAF. Using forward modeling ray tracing, we fit traveltime curves to our first-arrival picks and determined the best fitting 1D P-wave velocity models for receivers east and west of each shot, and a 2D velocity model for the profile. In general, 1D models for receivers east of the shots have deeper basement contacts and lower apparent velocities, ~5 km/s at 4 km depth, while models for receivers to the west of shots have shallower basement contacts and velocities up to 6 km/s at ~2 km depth. Based on mismatches in basement contact depths (assuming 5-6 km/s) between the east and west branches of the 1D models, there is a strong possibility of an east-dipping interface along the profile. This is confirmed in our 2D model, which has a shallowly NE dipping basement that deepens eastward towards the Banning Fault at ~2 km depth and shoals abruptly near the eastern end of the line. Based on high velocity zones (~6.1 km/s) derived from traveltimes at ~9.2 km from the western end of the line, we included an offset from ~2 km to 4 km depth near the middle of the line. The 2D model fit is greatly improved when this high-velocity zone is included. If fault-related, this offset could have occurred on the Garnet Hill Fault if it extends southward in the subsurface. Additional information on the geometry of near-vertical faults was obtained from the pre-stack line migration method of Bauer et al. (2013). These findings are compared to our 2D tomographic results to produce a comprehensive picture of the structural complexity near the profile.

Regularly reoccurring seismic swarms at Volcán Guagua Pichincha, Ecuador, Stephen Hernandez, Mario Ruiz, Marco Yepes, and Patricia Mathes (Poster 137)

Volcán Guagua Pichincha is an active dacitic stratovolcano located 12 km west of nearly 2 million urban inhabitants. Guagua Pichincha is currently monitored by seismic, geodetic, and infrasound sensors. Since March 2014, and possibly earlier, seismic activity at Pichincha has been characterized by short duration (< 1 day) seismic swarms with recurrence intervals that vary over time. Over the past 2 months, these swarms have increased in frequency and now occur approximately every 3 - 5 days. At times, these swarms coincide with small transients (<10 microradians) in a
single tilt meter located ~600 m from the crater domes. During any single swarm, the seismic waveforms are highly repeatable and show a progressive rise and subsequent fall in their seismic amplitudes. For events large enough to register at multiple stations, hypocentral locations delineate a vertically elongated column of events directly beneath the volcano summit. Historically, Guagua Pichincha has experienced 5 Plinian episodes of activity in the last 2000 years, with the latest episode occurring in 1660. In 1999, a series of intense dome growth/collapse episodes and large Vulcanian eruptions draped nearby Quito with significant amounts of ash. This significant historical activity and large nearby population reinforces the need for intense monitoring and detailed analysis of seismic and geodetic trends.

Seismogenesis of a Complex Multifault Network, Sierra Cucapah, Northern Baja California, Mexico, Ana P. Hernández Flores, John M. Fletcher, Thomas K. Rockwell, Madhav K. Murari, Lewis Owen, Warren Sharp, Orlando Teran, Kate Scharer, Sinan Akciz, Ronald Spelz, Elias Meneses, Karl Mueller (Poster 240)

This study combines structural, geomorphologic and paleoseismic analysis to characterize the seismogenic behavior of the complex network of faults that ruptured in the Mw 7.2 2010 El Mayor-Cucapah (EMC) earthquake. Detailed mapping of alluvial fan surfaces revealed the existence of seven distinct alluvial fan surfaces. Based on differences in surface weathering and soil development five of the fan surfaces likely have only experienced hyperarid conditions of the Holocene, whereas the other two should have experienced more humid conditions associated with the last glacial maximum in the late Pleistocene. Using cross cutting relationships between the scarps and the alluvial fan surfaces, we identify and map surface ruptures associated with three distinct seismic events including the EMC of 2010. The oldest and the youngest events activated the same portion of the Borrego fault but the intermediate age event occurred along strike on a distinctly different segment. The rupturing of adjacent segments of the Borrego fault in alternating seismic events likely reflects coseismic stress transfer such that one event increases the elastic loading strain on the adjacent segment causing it to rupture in the next event.

Based on structural and stratigraphic relations exposed in trenches, six seismic events were documented on the Laguna Salada fault and four on a single section of the Borrego fault. The events were dated using different techniques that include C14, OSL, y U-series, depending the material available in the stratigraphy. The recurrence intervals of large seismic events that produce surface rupture were found to be an order of magnitude faster along the Laguna Salada fault (1.3 kys), which last ruptured in 1892, compared to the Borrego fault (12 kys), which ruptured in the El Mayor-Cucapah earthquake in 2010. The Borrego fault is part of a complex network where slip is distributed among multiple faults that have down-to-the-east tectonic transport, which lowers the Cucapah range crest and is antithetic to topography. In contrast, slip is concentrated on a complex fault system represented by the Laguna Salada fault, which has west-side down tectonic transport and controls both the uplift of the Sierra Cucapah and subsidence of the Laguna Salada basin. Both fault systems must combine to accommodate geologically measured tectonic loading strains that indicate slip rates much greater than that observed on either one by itself.

Exploring Characteristics of Potential Foreshocks on Highly Compressed Patches in a Rate-and-State Fault Model, Natalie Higgins and Nadia Lapusta (Poster 245)

On both natural and laboratory faults, some mainshocks are preceded by foreshocks. Such foreshocks may be triggered by asseismic processes of the mainshock nucleation at fault heterogeneities such as bumps, as inferred in some laboratory experiments. We explore a rate-and-state fault model in which potential foreshocks occur on patches of elevated normal compression (by a factor of 5 to 10) within a larger velocity-weakening (VW) region, using 3D numerical simulations of long-term earthquake sequences and asseismic slip.

To create the setting where isolated foreshocks can occur during the mainshock nucleation, the patch nucleation size h*patch and the nucleation size of the larger-scale VW region h*main need to be substantially different (by a factor of 10 or more). This separation of scales can be achieved by assigning high levels of compression on the patches. However, one would expect unrealistically large stress drops for events on such patches.

Remarkably, in this model, we find that the stress drops of the patch-hosted events are reasonable and roughly constant, despite a wide variation in the patch compression, due in part to patch ruptures extending into the surrounding VW region. Furthermore, for patch diameter D close to h*patch, a substantial part of the stress change on the patch occurs asseismically. In addition, we observe long-range triggering of one foreshock by another via postseismic slip. Our current work is directed towards quantifying and explaining these findings, as well as exploring whether the microseismicity occurring on highly compressed patches due to nucleation-induced creep has any observable differences from other events.

Dynamic Fault Weakening and Strengthening by Gouge Compaction and Dilatancy in a Fluid-Saturated Fault Zone, Evan T. Hirakawa and Shuo Ma (Poster 264)

Fault gouge deformation likely plays an important role in controlling the strength of mature, large-displacement faults. Experiments show that intact gouge deforms in an overall ductile and stable manner, readily compacting by comminution and structural collapse, but it dilates and experiences brittle failure under large strain rate. We model gouge compaction and dilatancy using a combined Mohr-Coulomb and end-cap yield criterion in a dynamic rupture model of a strike-slip fault with strongly velocity-weakening friction (in a rate-and-state framework). We show that large shear stress concentration associated with the rupture front causes the gouge layer to compact ahead of the rupture, leading to rapidly elevated pore pressure in the undrained gouge layer and significant weakening of the principal fault surface. Weakening ahead of the slipping region lowers static friction and strength drop on the fault. Shortly after the rupture front passes, strong dilatancy during strength drop and rapid sliding reduces pore pressure and strengthens the fault, promoting slip pulses. Large strain localization occurs as a result of rapid gouge dilatancy and strain softening, and strongly limits the stress concentration outside the gouge layer. This leads to negligible inelastic shear strain in the damage zone which is consistent with geological observations and high-speed frictional experiments, and suggests that current dynamic rupture models incorporating inelastic off-fault response may overestimate the effect of off-fault damage. With the presence of well-developed fault gouge the strength of mature faults may be controlled by end-cap, rather than Mohr-Coulomb failure, thus their frictional strengths are significantly smaller than Byerlee friction.

FARockM Perspectives on Earthquake Processes from the Lab to the Field, Greg H. Hirth (Invited Talk Tue 08:30)

Laboratory rock mechanics and complimentary analyses of fault zone microstructures provide numerous constraints on processes that promote earthquake nucleation and rupture. I will provide my perspective on how SCEC has fostered important directions in rock mechanics, where we stand currently and the role that rock mechanics and structural studies can play in future SCEC initiatives. (1) Preceding the Annual Meeting, we will be holding a workshop on the Community Rheology Model (Convened by Hearn, Becker, Fialko, Fuis, Hirth and Thatcher) to discuss, among several topics, how to integrate our understanding of rheology and physical properties into a practical model of lithospheric deformation in Southern California. Here, I will provide a brief summary of the efficacy of (and limitations) of using laboratory based flow laws in such models, and how to integrate observations of microstructures from exhumed fault rocks and xenoliths into a systems-based analysis of deformation in the lithosphere. (2) Perhaps the biggest role that SCEC has played in the rock mechanics community is through its impact on focusing effort towards understanding (and applying) the processes that promote dynamic fault weakening. I will provide an update on where this field stands and highlight areas where a combination of laboratory and theoretical studies need to advance, drawing from our own work and that of the community. One issue that stands out as particularly important is constraining the processes that lead to strain localization during both interseismic/quasi-static and dynamic fault slip. (3) A common link between these topics is identifying the deformation conditions at the “brittle-ductile transition”. Here I will discuss recent experimental work from our lab, in which we
analyze how grain-scale plasticity influences the “effectiveness” of the effective pressure law, and how these processes may control the depth of the seismogenic zone and how it evolves with changing temperature, strain rate and lithology. In addition, I will illustrate why higher temperature/higher pressure experiments may be a key for not only constraining these processes, but also understanding the apparent discrepancy between interpretations regarding the strength/effective viscosity of major faults in California.

Submarine Paleoseismic Slip Rate Constraints of Hosgri and Shoreline Fault Zones from High-Resolution 3D Seismic-Reflection Data, Offshore San Luis Obispo Bay, Central Coastal California, Phillip J. Hogan, Stuart Nishenko, H. Gary Greene, and Bryan Bergkamp (Poster 103)

As part of the Central Coastal California Seismic Imaging Project, marine seismic-reflection profile data were acquired across the Hosgri Fault Zone (HFZ) and Shoreline fault Zone (SFZ) 2011 and 2012 offshore San Luis Obispo Bay using a state-of-the art 12-14 streamer high-resolution 3D P-Cable low-energy seismic survey system. Seismic-reflection profiles, 3D volumes and time slices were used to map the detailed structural geometry of these 2 fault zones. High-resolution 3D seismic imaging of buried marine paleochannels and paleostrandedlines allowed identification of piercing points for estimating Quaternary slip rates.

Broadband ground motion modelling of a major Alpine Fault Earthquake (New Zealand), Caroline Holden and Anna Kaiser (Poster 019)

The large September 2010 and the tragic February 2011 Canterbury earthquakes caused widespread damage by ground shaking and sand liquefaction in the Canterbury region. Both earthquakes were less than 50 km from the Christchurch central business area and had a magnitude that is much smaller than that expected from the Alpine Fault (Mw=8.2). Recent advances in earthquake mechanics allow us to compute seisograms for realistic earthquake scenarios, at specific locations, and with specific site conditions. Such simulations can provide very useful alternative estimates of ground motion from large faults for major population centres in the South Island (NZ).

Synthetic broadband strong-motion records are produced for a possible large Alpine Fault earthquake (Mw=8.2) at selected population centres that may be strongly affected. We compute seisograms using a hybrid approach combining a simple discrete wavenumber approach and a stochastic method. To define the earthquake sources, we apply the validated recipe based on a characterised source model for large crustal earthquakes developed by Irikura and Miyake (2011). The synthetic rock site motions are then used as the input motion for a frequency-dependant site amplification function.

The synthetic records show that near-source ground motion accelerations in main West-Coast towns of the South Island are expected to exceed 20%g during an Alpine fault earthquake, while ground motions in Christchurch are expected to be moderate, with peak ground accelerations (PGA) of 8%g. This high near-source PGA will need further modelling as it is likely due not only to non-linear soil response nor accounted for in this study but also to the presence of a modelled asperity nearby and to strong directivity effects.

Tracking Stress Changes on Faults Through Time using cGPS Observations, William E. Holt, Meredith Krane, Gina Scherbenko, and Adrian Borsa (Poster 225)

We use a geodetic network-processing tool (Holt and Scherbenko, 2013) to analyze cGPS crustal displacements, provides further improvement of the match to observed seismicity rates following El Mayor.

We have also analyzed the Northern California region that contains the 2014 South Napa earthquake. We perform a pre-seismic analysis were we have not removed the seasonal signal. In the region surrounding the South Napa event we have found a large positive dilatational signal and positive Coulomb stress change that peaked just prior to the South Napa event. Furthermore, we have analyzed the strain evolution from 2007 – 2014 and found that the 500 km2 area around Napa shows an average seasonal dilatational strain anomaly of 78 ± 30 x 10^-9 and an average coulomb stress change anomaly acting on right lateral faults of 0.34 ± .013 bars. Observations of crustal displacement from a larger set of cGPS stations were used for the purpose of estimating the longer-range hydrological loading contribution to stress changes on faults in the South Napa region [e.g., Borsa et al., 2014]. The large-scale hydrologic loading model predicts a seasonal strain and stress pattern that is similar to the observed, with predicted stress changes about 20-30% of the observed signal. We also investigated thermoelastic effects [Ben-Zion and Allam, 2013], where large seasonal temperature gradients are observed during spring-summer period between San Francisco Bay and the Sacramento Valley. Thermoelastic strains contribute 20-40% of the magnitude of observed seasonal dilatational anomaly. A comparison of seismicity rates over an 8-year period confirms an increased level of seismicity within areas of peak summer positive coulomb stress change within Northern California.

A Synthetic Study into the Nature and Solution of the Non-Uniqueness in the Surface Wave Inverse Problems, Mehrdad Hosseini (Poster 181)

The solution of a Rayleigh-wave inverse problem may potentially deviate from the realistic shear-wave velocity structure due to the non-uniqueness. To overcome such deviation, it is necessary to understand the source of non-uniqueness and situations which may give rise to the non-uniqueness. In this study, the existence and formation of the non-unique solutions in an inverse problem is demonstrated by modeling the solution space of a synthetic surface wave inverse problem and investigating the major causes that might engender the non-uniqueness, namely (1) the inversion convergence threshold, (2) ambient noise, (3) corner frequency of the recordings, and (4) the water level. Regarding the severity of the non-uniqueness in the phase velocity inverse problems, a technique is proposed to improve the inversion which exploits the match between the synthetic and observed time series used as a posteriori information for constraining the realistic velocity structure. Through a synthetic example, the effectiveness of such method is tested and proven effective.

Macroseismic Intensity Distributions: Robust Indicators of Stress Drop?, Susan Hough (Poster 162)

Seismologists have adopted moment magnitude as the best estimate of earthquake size. Moment magnitude, which depends on shear modulus, rupture area and average slip, does not provide a direct measure of radiated energy, which depends on rupture details. While ruptures are complicated, dynamic stress drop provides a simple parameter that, together with scalar moment, describes to first order the level of radiated
energy. Dynamic stress drop has been notoriously difficult to estimate, conventionally derived from estimates of corner frequency or pulse width, which are then cubed. Studies commonly reveal variability of over three orders of magnitude, from roughly 0.1-100 MPa; uncertainties are rarely estimated. As initially suggested by Boore (1983) and Hanks and Johnston (1992), macroseismic intensities, which generally reflect shaking between roughly 1 and 8 Hz, depend relatively weakly on moment and relatively strongly on stress drop. The U.S. Geological Survey “Did You Feel It?” (DYFI) system now collects and systematically interprets reports from felt earthquakes, using an algorithm to estimate intensity values. I analyze DYFI data for 70 recent 3.9 ≤ Mw ≤ 7.1 earthquakes in California, and suggest that stress drop variability is captured robustly by variability in effective intensity magnitude, MI E, defined to be the magnitude that best fits observed CDE data given a regional intensity-prediction equation. I further define an intensity stress drop parameter, which, for the set of events analyzed, varies by a factor of ~5 (natural-log-based sigma 0.35) assuming intensities are controlled by acceleration. This suggests that the variability of conventionally determined dynamic stress drop values is indeed over-estimated, and that intensity stress drop might provide a more robust estimate. Alternatively, as suggested by a number of past studies, conventional energy magnitude estimates might also be useful for efforts to improve characterization of ground motions.

Extending the BKT Memory-Efficient Displacement-Based Internal Friction Model for Representing Attenuation in Wave Propagation Simulations, Md Monsurul Huda and Ricardo Taborda (Poster 036)

Energy losses in the form of anelastic attenuation due to material internal friction plays a major role in wave propagation problems and earthquake ground motion simulation. These attenuation effects are typically represented through the characterization of the quality factor, Q. There have been several studies in which Q is modeled using viscoelastic devices, where the effects of internal friction are represented by springs and dashpots. A recently introduced model, called the BKT model (after authors Bielak, Karaoglu and Taborda), proposed the use of two Maxwell elements (each made of a spring and a dashpot connected in series) in combination with a Voigt element (consisting of a spring and a dashpot connected in parallel). The BKT model showed very good adherence to intended values of constant Q = Qo. The BKT model, however, depended on a set of parameters that needed to be computed a priori for a fixed set of Qo values. The model, as well, was limited to problems under the assumption of frequency independent attenuation. In this work we show that the internal parameters used in the BKT model can be determined using exact expressions formulated based on a numerical optimization of the model’s fit with Qo. This formulation holds for any value of Qo > 5, with errors less than 5 percent. In addition, we show that using three Maxwell elements substantially improves the accuracy of the model and increases its flexibility, allowing one to model problems with frequency-dependent Q = Q(ω). This further extension of the BKT model is of critical significance for deterministic physics-based earthquake simulations done at frequencies of engineering interest (f > 1 Hz).

Structure and geomorphology of Whitewater Hill and slip transfer from the Banning and Garnet Hill strands of the San Andreas Fault, Brittany Huerta, Doug Yule, and Richard Heermann (Poster 074)

Fault strands that comprise the San Andreas Fault (SAF) system in the northern Coachella Valley region are characterized by slip-rate gradients and slip transfer from one strand to another. The Banning strand SAF has a slip rate of ~5mm/yr in the northern Coachella Valley, but that rate drops to zero when it reaches Cottonwood Canyon in the San Gorgonio Pass. In comparison, the San Gorgonio Pass Fault zone (SGFPZ) has a slip rate of ~5mm/yr in San Gorgonio Pass and, though not well constrained, appears to slow down considerably as it enters the northern Coachella Valley where the fault is referred to as the Garnet Hill Fault (GHF). The fact that the slip rates on the sub-parallel Banning and SGFPZ-GHF strands counteract one another suggests that slip transfer between them. Whitewater Hill is located between the two faults where the slip transfer must occur and contains an actively growing anticline cut by a set of secondary active faults. These structures kinematically link the Banning and SGFPZ-GHF strands of the SAF.

The top of Whitewater Hill is capped by a distinct orange-red soil developed in mid to late Quaternary fan gravels. This horizon serves as a strain marker that helps to define the structural relief between the two faults. In addition, there are at least two buried paleosols at depths beneath the top surface of ~60 and ~150 m. These buried paleosols also provide datums to help define the structure at Whitewater Hill. The relative uplift of the Orange-Rod region and Whitewater Hill gradually diminishes to the east and west, defining a doubly plunging, northwest trending anticline. The north limb of the fold is cut by the moderately north-dipping Banning strand, which steepens and becomes a sub-vertical structure east of Whitewater Canyon and shallows to a sub-horizontal fault west of Cottonwood Canyon. The south limb is cut by two strands of the Garnet Hill fault, a northern strand that is a steeply north-dipping reverse fault with >50 m right-lateral offsets of late Pleistocene and Holocene fans, and a southern strand that is a north-dipping thrust with a 1-2 meter scarp in late Holocene alluvium. The structure and geomorphology of Whitewater Hill therefore defines a fold and a fault system that transfers slip from the Banning strand to the Garnet Hill strand and helps to explain how slip on the San Andreas Fault is carried through the San Gorgonio Pass in complex but understandable ways.

An In-Depth Analysis of Tremor Signals near the Anza Gap: June, 2011, Alexandria A. Hutchinson and Abhijit Ghosh (Poster 158)

The Anza Gap is a 20 km aseismic segment of the San Jacinto Fault (SJF) that is thought to pose a major seismic hazard because there is no record of a large earthquake occurring there in the last 150+ years, while the rest of the SJF has ruptured in ~Mw 6.0+ events [Sanders & Kanamooi, 1984]. Preliminary seismic studies reveal promising indications that distinctive long duration, low frequency signals, detected through multiple automated techniques, may be the result of tectonic tremor in the SJF [Hutchison & Ghosh, SSA, 2015]. Validation of tectonic tremor in this region may provide useful information for seismic hazard assessment near the Anza Gap by elucidating stress transfer dynamics and mechanisms, and helping to determine locking depth. We perform a robust manual analysis on 70+ events in June, 2011, identified through our automated detection methods. The events are also cross-referenced with the Advanced National Seismic System composite earthquake catalog. Here, we study those events using multiple mini-seismic arrays and local surface and borehole seismic network stations. A precise location for tremor events are provided using the multi beam-backprojection method (MBBP) [Ghosh et al., 2009; 2012], employing arrays from the MAOTECRA network. The resulting location is directly compared to a location derived from an envelope cross correlation (ECC) algorithm [Wech & Creager, 2007] over a time window in which both analyses are manually selected from the same waveforms, using the same frequency band (6-8 Hz), which is thought to exclude many anthropogenic sources of noise. The methodologies share consistent source locations suggesting that the tremor-like signals repeatedly occur on either side of the Anza Gap. A clear correlation exists between the locations of suspected ambient tremor detected to the northwest of the Anza Gap and the locations of triggered tremor following the 2002 Denali earthquake [Wang et al., 2013], aiding in our confirmation of tremor. We also perform a frequency analysis of these events, comparing the spectra to local earthquakes. The results demonstrate that high frequencies deplete more rapidly for the signal detected as tremor than for ordinary earthquakes, as is expected for tectonic tremor [Shelley et al., 2007]. Ultimately, we aim to characterize the tremor-like signal sufficiently such that our automated detection methods work satisfactorily to establish an accurate long-term catalog of confirmed tectonic tremor.

Depth-depending earthquake properties beneath Long-Beach, CA: Implications for the rheology at the brittle-ductile transition zone, Asaf Inbal, Rob W. Clayton, and Jean-Paul Ampuero (Poster 165)

Except for a few localities, seismicity along faults in southern California is generally confined to depths shallower than 15 km. Among faults hosting deep seismicity, the Newport-Inglewood Fault (NIF), which traverses the Los-Angeles basin, has an exceptionally mild surface expression and low deformation rates. Moreover, the NIF structure is not as well resolved as other, less well instrumented faults because of poor signal-to-noise ratio. Here we use data from three temporary dense seismic arrays, which were deployed for exploration purposes and contain up to several thousands of
vertical geophones, to investigate the properties of deep seismicity beneath Long-Beach (LB), Compton and Santa-Fe Springs (SFS). The latter is located 15 km northeast of the NIF, presumably above a major detachment fault underthrusting the basin.

Event detection is carried out using a new approach for microseismic multi-channel picking, in which downward-continued data are back-projected onto the volume beneath the arrays, and locations are derived from statistical analysis of back-projection images. Our technique reveals numerous events occurring below the Moho along the NIF, and confirms the presence of an active shallow structure gently dipping to the north beneath SFS. Seismicity characteristics vary along the NIF strike and dip. While LB seismicity is uncorrelated with the mapped trace of the NIF, Compton seismicity illuminates a sub-vertical fault that extends down to about 20 km. This result, along with the reported high flux of mantle Helium along the NIF (Boles et al., 2015), suggests that the NIF is deeply rooted and acts as a major conduit for mantle fluids. We find that the LB size distribution obeys the typical power-law at shallow depths, but falls off exponentially for events occurring below 20 km. Because deep seismicity occurs uniformly beneath LB, this transition is attributed to a reduction in seismic asperity density with increasing depth, consistent with a transition to a diffuse deformation regime.

Recurrence Implications of California Paleo-event Hiatus, David D. Jackson and Keith Richards-Dinger (Poster 081)

Estimated rates and recurrence properties of pre-historic earthquakes depend strongly on recorded dates of paleo-events. California paleo-event data, published in the UCERF-3 reports in 2014 and 2015, reveal a curious property: The paleo-event rate for the whole collection of 32 sites exceeds about 4 per century, yet no events at any of the sites has been recorded in about 100 years. Possible explanations include extreme chance (probability about 1% or less), large-scale clustering with ensemble cv greater than one, or overestimation of paleo-event rates in chance (probability about 1% or less), large-scale clustering with

Connecting depths of seismicity, fault locking, and coseismic slip using long-term fault models, Junle Jiang and Nadia Lapusta (Poster 277)


We excavated new trenches across the Imperial fault 1.4 km north of the U.S.-Mexico international border to test earthquake recurrence models. Two trenches were excavated across a sag pond created by a 30 m-wide releasing step. The stratigraphy at the site exhibits distinct pulses of lacustrine and deltaic deposition with localized zones and layers of liquefied sand deposits. There is evidence for five events in the past 400–500 years. Four of these events appear to be large based on production of accommodation space and associated growth strata, upward fault terminations and fissures, massive liquefaction, and significant vertical offset in the step-over area. Six meters of strike slip passed through the sag in the 1940 Imperial Valley earthquake. If each previous large event exhibited similar displacement as in 1940, this implies a slip rate of 48 mm/yr, nearly twice the best-fit geodetic rate for the Imperial fault and similar to the entire plate boundary rate. As this inferred rate is unlikely to be correct, this in turn suggests that the 1940 rupture experienced a anomalously high amount of displacement in the border region. Further, the “smaller” event, for which evidence is limited to upward terminations and associated folding, has no match at the Dogwood site to the north suggesting that it may represent a southern-ranging rupture along the Imperial fault. Together, these observations do not support a “characteristic” earthquake rupture model for this simple plate-boundary fault.

Character and Implications of a Newly Identified Creeping Strand of the San Andreas fault NE of Salton Sea, Southern California, Susanne U. Janecke and Daniel Markowski (Poster 072)

Detailed mapping and structural analysis at the southern SAF tip provide insight into the Coachella section of the San Andreas fault (SAF), the site of the model earthquake used in the ShakeOut exercise in southern California, and the conflict between cross-fault and pull-apart models involving the Extra fault array and shortening in Durmid Hill. Geologic mapping, U.S.GS seismic reflection, magnetic, gravity datasets, and NIR aerial photography reveal the presence of an additional, previously unknown East Shoreline strand (ESS) of the SAF, that is ~0.5 to ~2.5 km southwest of the main trace. Groups of strike-slip cross-faults connect these two master dextral faults of the SAF. There is no evidence of the sinistral-normal faults of the Extra fault array near the main strand of the SAF. The ESS cuts and folds upper Holocene beds and appears to creep, based on discovery of ~150 m long NW-striking cracks in modern beach deposits. We mapped ~15 km of the ESS in a band on the northeast side of the Salton Sea, between Bombay Beach and Salt Creek. Other data indicate that the ESS continues N to the latitude of the Mecca Hills, and is >35 km long. The 1-km wide ESS contains short, discontinuous traces of NW-striking dextral-oblique faults. These en-echelon faults bound steeply dipping Pleistocene beds, cut out section, parallel NW-trending folds, and produced growth strata. Beds dip toward the ESS on both sides and reflect the component of NE-SW shortening across the ESS. The dispersed fault-fold style of the ESS is due to decollements in mud-rich sediment and ramps and flats o the strike-slip faults. A sheared ladder-like geometric model of the two master dextral strands of the SAF and their intervening cross-faults best explains all the datasets. Contraction across >40 km2 of the southernmost SAF zone in Durmid Hill suggest that contractual interactions among active structures in the SAF zone may inhibit the nucleation of large earthquakes in this region. This conclusion conflicts with the cross-fault and pull-apart geometric models. The ESS may cross Coachella Valley to join the blind Palm Spring dextral fault. The ESS may also continue north along the northeast margin of the Salton Trough or have both a NW and NE branch. The risk of a future large earthquake directly beneath the greater Palm Springs metropolitan area may be larger if the ESS and the Palm Spring fault are a single active structure. Further work will explore this possibility.

Our current work is directed towards (a) establishing whether Dgeod could constrain the maximum depth extent of Drupt, as suggested by our simulations so far, and (b) exploring how the presence of the realistic LC transition affects interpretation of the inferred Dgeod and Dseis based on the physical relations between these observables rising in fault microseismicity. The seismicity cut-off depth (Dseis) and (interseismic) fault locking depth estimated geodetically (Dgeod) give independent constraints on the locked-creeping (LC) transition on faults. The physical relation between the two and whether/how they constrain the depth extent (Drupt) of large earthquake ruptures is poorly understood, thus limiting direct comparisons and quantitative interpretations.

We explore the physical relations between these observables rising in fault models governed by rate-and-state friction and enhanced dynamic weakening, with microseismicity resulting in our models due to fault heterogeneity favoring nucleation. We find that: (i) transition from locked zones (e.g., creeping rates < 0.1 Vpl) to zones creeping with near-platonic rates (> 0.9 Vpl) occurs over a certain depth range, which can be significant; (ii) Dseis is predominantly affected by the location and amplitude of the stress concentration front (SCF) near the top of the LC transition, while Dgeod depends on the spatial distribution of fault slip rates; (iii) microseismicity and the inferred Dseis either stays near the bottom of the seismogenic zone or becomes shallower due to the up-dip migration of SCF, while Dgeod tends to deepen as the stress shadowing region expands throughout the interseismic period; and (iv) Drupt and Dseis can differ due to deep seismic slip below the seismogenic zone, while the discrepancy between Dgeod and Drupt depends on the extent and amplitude of postseismic slip. Therefore, Dseis and Dgeod reflect different aspects of fault behavior and could diverge, especially in cases of deeper penetration of earthquakes and/or significant afterslip. Assuming Dgeod equal to Dseis could lead to an underestimation of fault slip rates and a discrepancy with geological estimates.
simplified models, e.g., for the southern San Andreas and San Jacinto Faults.

Seasonal Water Storage, the Resulting Deformation and Stress, and Occurrence of Earthquakes in California, Christopher W. Johnson, Roland Burgmann, Yuning Fu, and Pierre Dutilleul (Poster 236)

Continuous GPS time series document crustal deformation in California associated with hydroscopic surface loads that change in response to winter snow accumulation, reservoir and groundwater storage, and the persistent drought across western North America. Snow accumulation in the Sierra Nevada and groundwater storage exhibit seasonal periodicity and is observed in GPS time series with vertical displacements on the order of 1-5 mm. The recent drought has produced uplift rates in the areas surrounding the Central Valley of ~5 mm/yr where ground water extraction is primarily controlled by the agricultural industry. The Central Valley is a young sedimentary basin that rises and falls with the groundwater level in the aquifer in response to the poroelastic response to changes in head level. We develop loading models using GPS derived hydrologic mass changes associated with ground water storage and calculate stress cycles of 1-5 kPa throughout California. Though modest, small stress perturbations have been previously associated with changes in earthquake activity and we could expect events to occur more rapidly at times of increased loading. Our modeling efforts are extended to include specific fault geometry associated with California tectonics in order to resolve the Coulomb stress at seismogenic depths on these structures in response to the annual hydrologic cycle. Our current work focuses on evaluating the degree of correlation between stress models, periodically found, in seismicity catalogs, and the orientation of the maximum transient stress when considering the geometry of active faults obtained from regional focal mechanism catalogs. Here, we present preliminary results for the annual hydrologic loading models and associated changes in seismicity.

Growth of fault-propagation folds by flexural slip folding: implications for earthquakes, Kaj M. Johnson (Poster 226)

Blind faults underlying actively growing anticlines are a significant seismic hazard in the western Transverse Ranges. But quantifying the hazard associated with blind reverse faults is not straightforward because the fault is often not well-imaged in seismic data and it is often not entirely clear how the shallow geometry of fault-cored anticlines relates to the underlying seismogenic fault. In practice, blind fault geometry and estimates of slip rates on the blind faults need to be inferred indirectly through fault-related fold models. It is commonly assumed that crustal-scale anticlines grow primarily by slip on underlying faults and the geometry of the fold reflects somehow the geometry of the causative fault. However, in principle, folds can grow amplitude without being cored by a slipping fault; the theory of folding of initial perturbations in isolated layers or multilayers without faulting is quite mature. The purpose of this study is to examine the growth of fault-cored anticlines through the coupled processes of fault slip and flexural-slip folding. We develop a boundary element model of the growth of an anticline over a fault embedded in a medium with viscoelastic layers that slip at frictional contacts. We show that not only does the fault geometry influence fold shape, but the thickness of folded layers and the frictional strength at layer contacts has a first-order impact on the shape of fault-related folds. We further show that fault-cored anticlines may not grow strictly by the mechanism of fault slip, but that folds in a mechanically layered medium can be significantly amplified by buckling under horizontal compression. Some important findings from this work related to earthquake hazard includes: (1) in the early stages of folding the off-fault moment (due to slip at layer contacts) nearly equals the on-fault moment but may greatly exceed the on-fault moment (by a factor of 3-4) at later stages of folding, and (2) distributed deformation off-the-fault contributes significantly to surface uplift over many earthquake cycles and the pattern and rate of surface uplift may be significantly different from the surface deformation predicted by slip on an fault in an elastic half space.

The western terminus of the San Gorgonio Pass fault zone: Structural expression and possible linkage and slip transfer with neighboring faults, Kaitlyn L. Jones and Doug Yule (Poster 077)

The San Gorgonio Pass fault zone (SGPFZ) and its eastern extension, the Garnet Hill Fault, can be traced for 75 km from Calimesa to the Indio Hills. The eastern end of the fault system merges with the Banning strand of the San Andreas Fault via a compressive left stepover in the fault system. However, the western terminus of the SGPFZ and its possible connection with nearby faults is poorly understood. This study presents the results of a large-scale mapping project and detailed evaluation of B4 LIDAR data at the western terminus near Calimesa, CA. Mapping shows that the fault terminates in an asymmetric, open fold that verges to the south above a north-dipping blind thrust. Secondary, up-on-the-north high-angle faults reside in the hanging wall of the blind thrust. The blind thrust emerges 5 km to the east in Cherry Valley where distinct fault scarps displace old alluvium across 3-20 m scarps. The fold at Calimesa is defined two ways. Bedding in the Plio-Pleistocene San Timoteo Formation defines a gently west-plunging anticline with a slightly steeper south limb. In this unit, clast-counts conducted at five locations on the fold consist of igneous clasts, mainly felsic granites, diorites and volcanic porphyries consistent with a Peninsular Ranges source. quartzary alluvium angularly unconformably overlies the San Timoteo strata and is also asymmetrically folded, defining a gently west-plunging, south-vergent anticline. The core of the fold is readily visible in color satellite images where it is bounded by the oval-shaped limit of a distinct, poorly consolidated, oxidized, orange-red soil, commonly developed atop the Quaternary alluvium. Slope maps of the B4 data also help define the fold showing relatively high-relief areas in the core of the fold and low-relief surfaces associated with the Quaternary alluvium at the fold's margins. The SGPFZ thus appears to terminate as an asymmetric fold above a blind thrust. It is interesting to note that the ‘Calimesa fold’ lies <3 km from the down-to-the-southeast Crafton Hills and Beaumont Plain fault zones. We envision that these faults are linked via stepovers to the SGPFZ and help transfer slip from the San Gorgonio Pass region to the San Bernardino strand San Andreas and San Jacinto faults, to the northeast and southwest, respectively. If accurate, this can explain slip gradients and transfer from one fault to another, and provide a connection that can carry San Andreas slip through San Gorgonio Pass.


Ground motion prediction equations (GMPEs) in common use predict the logarithmic intensity of ground shaking as a deterministic value conditioned on a set of explanatory variables plus a normally distributed random variable with a standard deviation sigma_T. The latter accounts for the unexplained variability in the ground motion data used to calibrate the GMPE and is typically 0.5-0.7 in natural log units. Reducing this residual or “aleatory” variability is a high priority for seismic hazard analysis, because the probabilities of exceedance at high hazard values go up rapidly with sigma_T, adding costs to the seismic design of critical facilities to account for the prediction uncertainty. However, attempts to decrease sigma_T by incorporating more explanatory variables to the GMPEs have been largely unsuccessful. An alternative is to employ physics-based earthquake simulations that properly account for source directivity, basin effects, directivity-basin coupling, and other 3D complexities. We have explored the theoretical limits of this approach through an analysis of large ensembles of simulations generated for the Los Angeles region by SCEC’s CyberShake project using the new tool of averaging-based factorization (ABF, Wang & Jordan, BSSA, 2014). The residual variance obtained by applying GMPEs to the CyberShake dataset matches the frequency-dependence of sigma_T obtained for the GMPE calibration dataset. The ABF analysis allows us to partition this variance into uncorrelated components representing source, path, and site effects. We show that simulations can potentially reduce sigma_T by about one-third, which would lower the exceedance probabilities at higher hazard levels by orders of magnitude. Realizing this gain in forecasting probability would have a broad impact on risk-reduction strategies, especially for critical facilities such as large dams, nuclear power plants, lifelines, and energy transportation networks.
GEAR1 forecast: Distribution of largest earthquakes, Yan Y. Kagan and David D. Jackson (Poster 045)

We have created a global seismicity forecast based on past earthquakes and geodetic strain rates (GEAR1, see Bird et al., 2015). The present forecast estimates future earthquake rate density everywhere on earth at 0.1 by 0.1 degree resolution, 6.48 million cells in all. We consider foreshocks, main shocks, and aftershocks without distinction, and we consider only shallow events less than 70 km below sea level. The seismic component of the present model is based on a smoothed version of the GCMT catalog from 1977 through 2013. The tectonic component is based on the Global Strain Rate Map (GSRM2.1) of Kremer et al. (2014), a GEM product. The seismic and tectonic components were prepared and optimized separately, then combined in various linear, log-linear, and other combinations, optimized using pseudo-prospective testing. We found that a log-linear mixture of 60% seismicity with 40% tectonics provided the best forecast of events from 2005 to 2012 based on earlier events. The model also fits well the earthquake locations from 1918 to 1976 reported in the GEM global catalog of instrumental and pre-instrumental magnitude determinations. We are presently formulating it for CSEP testing at magnitude 5.8 and larger. We improve it by optimizing the treatment of larger magnitudes. We include longer duration ISC-GEM catalog of large earthquakes in estimating smooth seismicity. An accumulation of seismic moment data gathered during the last decade justifies a new attempt at a comprehensive statistical analysis of these data. We discuss the new results on earthquake magnitude/moment distribution, especially the determination of maximum/corner moment magnitude. The new statistical analysis of earthquake catalogs suggests that the corner magnitude values used in the GEAR1 paper are the same, only for the Trench zones m_c increases to 9.0.

Numerical simulation of nucleating rupture explains the onset of laboratory earthquakes, Yoshihiro Kaneko, Stefan Nielsen, and Brett Carpenter (Poster 260)

Slow aseismic slip, lasting days to months prior to the initiation of large earthquakes has been inferred from seismological observations, which has useful implications for short-term earthquake predictability. Similar slow-slip phenomena have also been observed in laboratory experiments of shear rupture nucleation on frictional interfaces. However, the mechanisms governing nucleation of shear ruptures have been widely debated. It is also not clear how to properly scale up laboratory results to crustal conditions. Here we use numerical simulation to examine the mechanical process of rupture nucleation observed in modern laboratory experiments. We find that laboratory observations of rupture nucleation under a range of confining pressures are in excellent agreement with models of frictional slip that incorporate dynamic elasticity and rate-and-state friction laws. We show that both in laboratory experiments and simulations, the rupture front motion scales with the elastic energy flow, in agreement with the classical Griffith crack energy balance. We discuss implications of the results for the nucleation of crustal earthquakes.

Vital Signs of the Planet: Southern California Educators Contribute to Crustal Deformation Studies Within San Bernardino and Riverside Counties, Daniel Keck, Sally McGill, Robert de Groot, Erika Durst, Anna Foutz, Jennifer French, Luis Gomez, Scott Kirkwood, Kimberly Kocaya, Dana Ladefoged, Heman Lopez, Alina Padilla, Yolanda Seebert, Laura Secord, Bernadette Vargas, Seth Wallace (Poster 311)

In conjunction with California State University, San Bernardino, Inland Empire middle school and high school teachers have used GPS to monitor movement along the San Andreas and San Jacinto faults within the Inland Empire, San Bernardino Mountains, and high desert regions of Southern California since 2002. Stations observed in 2015 were selected from those that previously had relatively poorly constrained time series, so as to contribute useful new velocity constraints for use by the SCEC community and others. Procedures for the study included setting up a tripod (or spike mount), and an antenna and receiver over existing survey monuments for a 10 hour period each day for 3 days. GPS data were processed at the University of Arizona using GAMIT-GLOBK and benchmark positions were compared to those in previous years. Time series graphs were used to estimate the north, east and vertical velocities of each site.

Velocities for our sites were combined with velocities from SCEC’s Crustal Motion Model version 4 (Shen et al., 2011) and with velocities from continuous GPS stations archived at the Plate Boundary Observatory. One-dimensional elastic modeling of the combined data set was used to infer fault slip rates within a transect across the plate boundary through the San Bernardino Mountains.

Results indicate that the combined slip rate of the 15 faults within our transect is 45.5–46.15 mm/yr. The San Andreas (SAF) and San Jacinto (SJF) faults have the highest rate of movement with a combined slip rate of 17-18.25 mm/yr. This is substantially less than the published 35 mm/yr slip rate of the SAF alone in central California. Nonetheless our inferred slip rates for the SAF and SJF are consistent with previously published slip rates for these faults in southern California over late Quaternary time scales. The two faults are so close together within our transect that their slip rates are strongly inversely related. Our best-fitting model apportions the SJF slipping 9.75 mm/yr and the SAF slipping 8.5 mm/yr, but models with SJF slipping 15 mm/yr and SAF slipping 2 mm/yr, or SJF slipping 3.25 mm/yr and the SAF slipping 14.5 mm/yr also fit the observed site velocities relatively well.

Identification and Estimation of Postseismic Deformation: Implications for Plate Motion Models, Models of the Earthquake Cycle, Sharon Kedar, Yehuda Bock, Donald Argus, Peng Fang, Jennifer Haase, Zhen Liu, Angelyn Moore, Susan Owen, Melinda Squibb (Poster 205)

The presence of postseismic deformation indicates that there is a viscoelastic response of the lithosphere. It is critical then to identify and estimate the extent of postseismic deformation in both space and time, not only for its inherent information on crustal rheology and earthquake physics, but also since it must be considered for plate motion models that are derived geodetically from the “steady-state” interseismic velocities, models of the earthquake cycle that provide interseismic strain accumulation and earthquake probability forecasts, as well as terrestrial reference frame definition that is the basis for space geodetic positioning. As part of the SEES project under a NASA MEAsURES grant, JPL and SIO estimate a combined daily position time series for over 3000 GNSS stations, both globally and at plate boundaries, based on independent solutions using the GAMIT and GIPSY software packages, but with a consistent set of a priori epoch-date coordinates and metadata. The longest time series began in 1992, and many of them contain postseismic signals. For example, about 90 of the global GNSS stations out of more than 400 that define the ITRF have experienced one or more major earthquakes and 36 have had multiple earthquakes, as have most plate boundary stations. We report on a study to quantify the spatial (distance from rupture) and temporal (decay time) extent of postseismic deformation. We examine parametric models (log, exponential) and a physical model (rate- and state-dependent friction) to fit the time series. Using a PCA analysis, we determine whether or not a particular earthquake can be uniformly fit by a single underlying postseismic process – otherwise we fit individual stations. Then we investigate whether the estimated time series velocities can be directly used as input to plate motion models, rather than arbitrarily removing the apparent postseismic portion of a time series and/or eliminating stations closest to earthquake epicenters.

Granitic boulder erosion caused by chaparral wildfire; Implications for cosmogenic radionuclide dating of bedrock surfaces, Katherine J. Kendrick, Camille A. Partin, and Robert C. Graham (Poster 090)

Rock surface erosion by wildfire is significant and widespread but has not been quantified in southern California, or for chaparral ecosystems. Quantifying rates and processes of surface erosion of bedrock outcrops and boulders is critical for interpreting age relations using cosmogenic radionuclide techniques, as even modest surface erosion removes the accumulation of the cosmogenic radionuclides leading to significant underestimating of age. This study documents the effects on three large granitic boulders following the Esperanza fire of 2006 in southern California. The volume of spilled rock fragments was quantified by measuring the removed rock volume from each measured boulder. The dark-colored char, ubiquitously deposited on the rock surfaces, made the spilled volumes easy to discern and measure. Between 8 - 46% of the total surface area of the boulders spilled in this single fire. The volume of
spalled material, when normalized across the entire surface area, represents a mean surface lowering of 0.9 – 10 mm. Spalled material was thicker on the flanks of the boulders, and the height of the fire effects significantly exceeded the height of the vegetation prior to the wildfire. In this study area, the height of the fire effect was approximately 4 m, and the height of the vegetation was approximately 2 m. Surface erosion of boulders was not observed as a result of wildfire activity. The resulting effects in fresh surfaces that appear essentially unaffected by chemical weathering. Such surfaces may be preferentially selected by researchers for cosmogenic surface dating because of their fresh appearance, leading to an underestimation of age. Researchers should be mindful of wildfire spalling effects when selecting dating sites.

**Time-dependent model of aseismic slip on the Central San Andreas Fault from InSAR time series and repeating earthquakes**, Mostafa Khoshamanesh, Manoochehr Shirzaei, and Robert Nadeau (Poster 196)

The Central segment of San Andreas Fault (CSAF) is characterized by a nearly continuous right-lateral aseismic slip. However, observations of the creep rate obtained using small Characteristically Repeating Earthquakes (CRES) show pulses of creep along the CSAF, which may indicate spatially and temporally variable seismic hazard along the CSAF. Therefore, the goal of this study is to obtain a high resolution time-dependent model of creep along the CSAF to examine this hypothesis. To this end, we apply a time-dependent creep modeling approach, which combines InSAR surface deformation time series and observations of fault creep obtained from CRES. The SAR dataset includes C-band scenes acquired by the ERS-2 and Envisat satellites between 2003 and 2011. The resulting creep rate distribution implies a peak rate up to 32 mm/yr along the central part of the CSAF. Afterslip due to the 2004 Parkfield earthquake on the southeastern segment of the CSAF is also manifested in the model and there is clear evidence of creep pulsing along strike and depth of the CSAF. Estimated annual rate of slip deficit accumulation is equivalent to a magnitude 5.6-5.7 earthquake. Taking advantage of the time-dependence of our model, we also rene the scaling relationship, which associates the released seismic moment due to a CRES event with the amount of creep on the fault, surrounding the CRES patches. This study provides the first kinematic model of creep pulsing, constrained using geodetic and seismic data, which can enhance time-dependent seismic hazard maps and improve earthquake operational forecast models.

**Surface process response to blind thrusting at Wheeler Ridge, CA**, Emily J. Kleber, Ramon Arrowsmith, Duane DeVecchio, Samuel Johnstone, and Tammy M. Rittenour (Poster 117)

Wheeler Ridge is an asymmetric east-propagating anticline (10km axis length, 330m topographic relief) above a north-vergent blind thrust fault at the northern front of the Transverse Ranges, San Joaquin Valley, CA. This area was a research focus in the 1990’s when the soils, u-series soil carbonate dating, and deformed strata identified from oil wells were used to create a kinematic model of deformation, and estimates of fault slip, uplift, and lateral propagation rates. Recently collected light detection and ranging (lidar) topographic data allow us to complete meter scale topographic analyses to assess the geomorphic response to variations in uplift rate along the fold axis and show asymmetry of surface response on the forelimb and backlimb. Detailed morphological mapping reveals transitions in geomorphic processes at the hillslope and catchment scale. The largest forelimb drainages (mean area: 0.8 km²) have incised deeply into the landslide-prone marine San Joaquin Formation in the fold core. The variation of ridgelines and drainage patterns of smaller, less incised drainages (mean area: 0.07 km²) in the overlying Plio-Pleistocene alluvial fans preserve evidence of drainage reorganization. On the forelimb, the normalized channels steepness indices (ksn) show a wide range (5-52 m0.9) especially in landslide dominated drainages. In addition to the impact of landslides, variations in bedrock and the dip of underlying layers suggest a residual signal detectable by ksn might be overprinted by erodibility differences. Lidar and field mapping reveal that uplifted backlimb surfaces preserve the relict fan morphology and, similar to the forelimb, the degree of incision increases westward. Backlimb drainages are either long and linear with wide ridgelines draining from the fold crest (mean area: 0.3 km²) or initiate mid-slope (mean area: 0.06 km²). Backlimb drainages show less variation in ksn (12-32 m0.9) than the forelimb, and increase away from the fold tip. Laminar stage IV Bk carbonate horizons at the base of the backlimb and crest indicate a similar relative age. We identify previously unrecognized tectonically deformed alluvial fan units on the backlimb as indicators of surface response to fold uplift and lateral propagation. Pending OSL results will provide numerical ages of previously and newly defined geomorphic units thus improving understanding of the spatial and temporal growth of Wheeler Ridge.

**Continental shelf morphology and stratigraphy offshore San Onofre, california: the interplay between rates of eustatic change and sediment supply**, Shannon A. Klotsko, Neal Driscoll, Graham Kent, and Daniel Brothers (Poster 099)

New high-resolution CHIRP seismic data acquired offshore San Onofre, southern California reveal that shelf sediment distribution and thickness are primarily controlled by eustatic sea level rise and sediment supply. Throughout the majority of the study area, a prominent abrasion platform and associated shoreline cutoff are observed in the subsurface from ~ 72 to 53 m below present sea level. These erosional features appear to have formed between Melt Water Pulse 1A and Melt Water Pulse 1B, when the rate of sea-level rise was lower. There are three distinct sedimentary units mapped above a regional angular unconformity interpreted to be the Holocene transgressive surface in the seismic data. Unit I, the deepest unit, is interpreted as a lag deposit that infills a topographic low associated with an abrasion platform. Unit II thins seaward by downlap and pinches out landward against the shoreline cutoff. Unit II is a mid-shelf lag deposit formed from shallower eroded material and thins seaward by downlap and landward by onlap. The youngest, Unit III, is interpreted to represent modern sediment deposition. Faults in the study area do not appear to offset the transgressive surface. The Newport Inglewood/Rose Canyon fault system is active in other regions to the south (e.g., La Jolla) where it offsets the transgressive surface and creates seafloor relief. Several shoals observed along the transgressive surface could record minor deformation due to fault activity in the study area. Nevertheless, our preferred interpretation is that the shoals are regions more resistant to erosion during marine transgression. The Cristianitos fault zone also causes a shoaling of the transgressive surface. This may be from resistant antecedent topography due to an early phase of compression on the fault. The Cristianitos fault zone was previously defined as a down-to-the-north normal fault, but the folding and faulting architecture imaged in the CHIRP data are more consistent with a strike-slip fault with a down-to-the-northwest dip-slip component. A third area of shoaling is observed off of San Mateo and San Onofre creeks. This shoaling has a constructional component and could be a relict delta or beach structure.

**Community Seismic Network (CSN)**, Monica Kohler, Robert Clayton, Thomas Heaton, Richard Guy, Julian Bunn, Mani Chandy, Anthony Massari (Poster 129)

The Community Seismic Network (CSN) involves participants from communities at large to install low-cost accelerometers in houses, schools, and office buildings for assessment of shaking intensity due to earthquakes. CSN now has approximately 600 stations in the northern Los Angeles region. The sensors are class-C MEMs accelerometers that are packaged with backup power and data memory, and are connected to a cloud-based processing system through the Internet. Most of the sensors are located in ground level locations with an average minimum station spacing of 800 m. This density allows the lateral variations in ground shaking to be determined, which will lead to detection and characterization of earthquake hazards and site response. Over 100 sensors are located on the JPL campus which is serving as a mini-city prototype for characterization of earthquake hazards and site response. Over 170 sensors are located in high-rise buildings with one or two 3-component sensors per floor. With these data we can identify traveling waves in the building as well as determine the resonant frequencies, mode shapes, and inter-story drifts. In dynamic computer simulations, dynamic scenarios are introduced into finite-element building models in order to determine the minimum damage-related sensitivity level CSN sensors may be capable of handling in the presence of environmental and electronic noise, and other sources of building vibrations. By monitoring these quantities before,
during, and after a major shaking event, we hope to identify small-scale damage events within a building as well as the overall state of health of the structure.

**GPU-enabled rupture dynamics simulations**, Jeremy E. Kozdon, Lucas C. Wilcox, and Timothy C. Warburton (Poster 246)

Over the past few years we have been developing a high-order accurate, adaptive, discontinuous Galerkin finite element method for earthquake rupture dynamics based on quadrilateral and hexahedral elements. Our approach is capable of handling both adaptivity in order (known as p-adaptivity) and well as adaptivity in element size (known as h-adaptivity). Previously, we have presented validation results for our CPU+MPI implementation on statically adapted meshes (i.e., meshes that have h- and p-adaptivity that does not change over the course of the simulation). Our numerical method is provably stable, even with adaptivity, curved elements, and intra-element material heterogeneity.

Here we present the extension of the numerical approach to multi-GPUs systems through the use of the OCCA library (http://http://libocca.org/). OCCA is an abstraction of several offloading paradigms for fine-grained, on-node parallelism (e.g., CUDA, OpenCL, OpenMP). Our CPU+GPU+MPI implementation currently includes elastodynamics with slip weakening friction and has shown almost-ideal weak-scaling across 32 NVIDIA Titan Black GPUs. Three out of the four elastodynamics kernels (core computational routines) perform at close to memory bandwidth, that is their performance is limited by memory access and not floating point operations. We are in the process of validating the implementation of rupture dynamics as well including dynamic mesh adaptivity.

**Static Stress Transfers Causes Delayed Seismicity Shutdown**, Kayla A. Kroll, Keith B. Richards-Dinger, James H. Dieterich, and Elizabeth S. Cochran (Poster 155)

It has been long debated what role static stress changes play in the enhancement and suppression of seismicity in the near-field region of large earthquakes. While numerous observations have correlated earthquake triggering and elevated seismicity rates with regions of increased Coulomb failure stress (CFS), observations of seismic quiescence in stress shadow regions are more controversial. When observed, seismicity shutdowns are often delayed by days to months following a negative stress perturbation. Some studies propose that the delay in the seismic shutdown can be caused by rupture promoting failure on one fault type while suppressing activity on another; thus the observed seismicity reflects the weighted contribution of the two faulting populations. For example, it was noted that in the 75 years following the 1906 San Francisco earthquake, strike-slip faulting earthquakes were inhibited, while thrust faulting events were promoted. However, definitive observations supporting this delayed shutdown mechanism are rare. In this study, we report seismicity rate increases and decreases that correlate with regions of Coulomb stress transfer, and show observations of a delayed shutdown in the Yuha Desert, California. We use a Coulomb stress change model coupled with a rate-and state- earthquake model to show that the delay in the shutdown is due to the combined changes in the rates of normal and strike-slip faulting events following the 2010 M5.72 Ocotillo aftershock of the 2010 El Mayor-Cucapah earthquake.

**A non-ergodic Ground-Motion Prediction Equation for California with Spatially Correlated Coefficients**, Nicolas M. Kuehn and Niels Landwehr (Poster 020)

Traditional probabilistic seismic hazard analysis (PSHA) is based on the ergodic assumption, which means that the distribution of ground motions over time at given site is the same as their spatial distribution over all sites for the same magnitude, distance, and site condition. With a large increase in the number of recorded ground-motion data, there are now repeated observations at given sites and from multiple earthquakes in small regions, and this assumption can be relaxed. We use a novel approach to develop a non-ergodic ground-motion prediction equation (GMPE), which is cast as a varying coefficients model (VCM). In this model, the coefficients are allowed to vary by geographical location, which makes it possible to incorporate effects of varying source, path and site conditions. Therefore, a separate set of coefficients is estimated for each source and site coordinate in the data set. The coefficients are constrained to be similar for spatially nearby locations. This is achieved by placing a Gaussian process prior on the coefficients, which ensures that they are spatially correlated. The amount of correlation is determined by the data. The spatial correlation structure of the model allows one to extrapolate the varying coefficients to a new location and trace the corresponding uncertainties. The approach is illustrated using data from the NGA West2 dataset, using only California records. The VCM outperforms a traditionally estimated GMPE in terms of generalization error, and leads to a reduction in the standard deviation by about 40%, which has important implications on seismic hazard. The scaling of the model is physically plausible, and its effect on hazard is demonstrated for two simple cases.


The M7.2 2010 El Mayor Cucapah earthquake (EMC) is a complex and unusual multi-segment event offering the opportunity to shed light on the mechanical behavior of faults as either individual segments or part of a more complex system. Although the dynamic behavior of individual faults is well studied, the cascade of smaller events into larger multi-segment events remains a matter of much discussion, including how faults interact with each other, and most importantly, what it takes to have them break in sequence. Reproducing the complex rupture of the 2010 EMC earthquake using dynamic models is not an easy task. Indeed, geologic observations, in contrast with what was originally suggested from combined seismological and geodetic models, revealed much more complexity (e.g., surface dip angles and discontinuous segments). The surface expression of the earthquake showed a complex pattern including minor ruptures. Here we present an effort to model as much possible of the complexity of this event. We have put together a Finite Element (FE) mesh that allows us to represent the complexity of the domain that hosted the rupture. The geometry of our fault is characterized by multiple stepovers and changes in dip and strike. In order to reproduce the slip pattern and complexity of the rupture we performed a full 3D dynamic analysis including and excluding the topographic relief of Sierra Cucapah and surroundings. Our simulations of the 2010 EMC event are part of a larger project that aims to combine dynamic models with observations from various sources (e.g. inverted slip distribution based on SAR interferometry) into a single model of slip.

**Evidence for fast seismic lid structure beneath the California margin from regional waveforms**, Voon Hui Lai, Robert W. Graves, Shengli Wei, and Don V. Helmberger (Poster 230)

The lithospheric structure of the Pacific and North American plates play an important role in modulating plate deformation along the California margin. Earthquakes such as the 2014 March 10 Mw 6.8 Mendocino and 2014 August 25 Mw 6.0 Napa events recorded at regional distances across California provide an opportunity to study horizontal paths and track the lateral variation in the lower crust–uppermost mantle structure under the California margin. Observations from both Napa and Mendocino events show direct SH-wave arrivals at Southern California Seismic Network (SCSN) stations are systematically earlier (up to 10 s) for coastal and island stations relative to inland sites. The shift in SH arrival times may be due to features such as varying crustal thickness, varying upper mantle velocity and the presence of a fast seismic lid. To test the different hypotheses, we perform extensive forward modeling using both 1-D frequency-wavenumber and 3-D finite-difference approaches. The model that best fits the SH arrival times has a fast lid (Vs = 4.7 km/s) underlying the whole California margin, with the lid increasing in thickness from east to west to a maximum thickness about 70 km in the western offshore region. The model agrees largely with the result from previous study by Melbourne and Helmberger (2001), which used S-SS differential travel times. We note that the crustal variation across the two plates has influence on the SH arrival times as well. The fast, thick seismic lid lends strength and rigidity to the Pacific plate lithosphere in contrast with the weaker North American continental plate, which influences the overall plate deformation along the Californian margin and is in agreement with GPS measurements.
Insights into the geometry and volume of Quaternary volcanic rocks in the Brawley Seismic Zone, Salton Sea area, California, from aeromagnetic data, Victoria E. Langenheim and Heather Wright (Poster 224)

We use aeromagnetic data to examine the depth, lateral extent, and volume of young volcanic rocks in the Brawley Seismic Zone of the southern Salton Sea, CA. This region is within an extensional stepover between the southernmost San Andreas Fault and the Imperial Fault. The Salton Buttes include five Holocene rhyolite domes aligned in a NE-SW direction, roughly perpendicular to extension. In addition to surface volcanism, evidence for shallow noneruptive intrusive material comes from basalt and rhyolite encountered in drillholes and the presence of a gravity and magnetic anomaly in the same area. Determining the amount and location of these igneous bodies would aid volcanic hazard assessment, geothermal resource assessment, and modeling deformation. Here, we focus on use of magnetic techniques to resolve dimensions and location of igneous rocks due to elevated magnetic properties of igneous rocks relative to surrounding basin sediments.

Aeromagnetic data reveal a NE-trending magnetic high that encompasses the Salton Buttes superposed on a NW-trending high that extends about 30 km from the town of Calipatria. We use matched filter analysis to separate the aeromagnetic data into different wavelength components by modeling the observed anomalies as a sum of anomalies from distinct equivalent source layers at increasing depths. Our preliminary results indicate dipole-equivalent source layers at depths of 1.4, 4.1, and 22.6 km. Note that the actual source depth for the layers may be shallower, given that broader-wavelength anomalies can be fit by both deep and shallow sources. The depth of the deepest layer is likely overestimated because the high heat flow in this area indicates that the Curie isotherm (the temperatures at which rocks are no longer magnetic) is considerably shallower than 22.6 km.

We estimate the volume of magnetic material in this area by transforming the aeromagnetic data into the equivalent gravity field that would be observed assuming a density distribution proportional to the magnetization distribution. We then calculate the anomalous excess mass using Gauss’ theorem, which yields a preliminary volume estimate of 40 km$^3$ of magnetic material throughout the crust above the Curie isotherm. This value may be too high, given that crystalline basement rock or metamorphosed sediments may also be magnetic. Incorporating constraints from seismic, gravity, and physical property measurements would help refine our results.

Preliminary investigations into the Fish Lake Valley Fault Zone (FLVFZ) and its interactions with normal faulting within Eureka and Deep Springs Valley, Michael J. Lawson, An Yin, and Edward Rhodes (Poster 115)

Fish Lake Valley Fault Zone (FLVFZ) is the northern continuation of the Furnace Creek Fault Zone (FCFZ), and is an important transfer structure within the Walker Lane Shear Zone, which has been interpreted to accommodate up to 15-25 percent of the Pacific-North American plate motion (Faulds et al., 2005). The history of slip on the FLVFZ shows that it is highly variable (up to 11 mm/yr in the middle Pleistocene), with a long term rate (since 10 Ma) of 5 mm/yr (Rehens and Sawyer, 1997). Frankel et al. (2007b) utilized offset alluvial fans and 10Be cosmogenic dating along the northern section of the FLVFZ, and found it has accommodated late Pleistocene slip rates of ~2.5 to 3 mm/yr. In another paper that same year, Frankel et al. (2007a) found greater rates within the northern section of the Death Valley Fault Zone, which is interpreted to be contiguous with the FLVFZ. Utilizing 10Be and 36Cl geochronology, offset alluvial fan channels resulted in a minimum rate of 4.2 ±1.9/1.1 mm/yr (Frankel et al., 2007a). This variation in slip rate has been proposed by previous workers to be due to strain transience, an increase in the overall strain rate, or due to other unknown structures (Lee et al., 2009). Currently, we are investigating the cause of this variation, and the possibility of the transfer of slip to faults south of the FLVFZ. Preliminary data will be shown from work done within Eureka Valley, and Deep Springs Valley, California utilizing scarp transects, geomorphic scarp modeling, and Optically Stimulated Luminescence (OSL) dating techniques. Fish Lake, Eureka, and Deep Springs Valleys offer a unique window into the evolution of bookcase faulting, and the transition to strike slip and normal faulting.

Robust Hazard and Risk Assessment Through Robust Simulation, Yajie Lee, Zhenghui Hu, William P. Graf, Charles K. Huyck, and Michael T. Eguchi (Poster 032)

Catastrophe modeling of natural disaster events is essential for hazard reduction, risk mitigation and insurance pricing. The typical approach utilizes multiple models with a logic tree to represent the scientific uncertainty in assessing future hazard or risk. The assessed outcome, however, is conventionally represented as a single solution (such as a mean hazard curve or single ‘EP’ curve), with a high level of precision. Although a single representation certainly desired, hazard or risk may be misunderstood and underestimated without a proper understanding and characterization of the uncertainty embedded in the modeling approach. Presented with the illusion of precision, decision makers may be left with a false sense of security facing future catastrophe losses. In this study, we present the work by the authors (Lee et. al., 2014; Taylor, et. al., 2013) in which we utilize the USGS 2014 National Seismic Hazard Mapping (NSHM) models for robust seismic hazard analysis and loss assessment of spatially distributed building portfolios with the Robust Simulation technology. A more complete picture of the uncertainty is revealed through multiple scientifically credible models and characterized in hazard or risk outcome.

Hidden Earthquakes Detection before and after the 2015 Mw 7.8 Gorkha Earthquake in Nepal Using Multiple Global Seismic Arrays, Bo Li and Abhijit Ghosh (Poster 135)

A complete picture of the spatiotemporal distribution of foreshocks and aftershocks of large earthquakes helps us to better study earthquake dynamics, stress evolution, and seismicity forecasting [Cocco et al., 2010]. However, many events remain undetected by the current global seismic network due to the limitations in density and distribution of seismic instruments worldwide. In this study, we apply the back-projection method [Ishii et al., 2007] using multiple global seismic arrays to detect hidden earthquakes (events that are not listed by the current standard global earthquake catalog) before and after the 2015 Mw 7.8 Gorkha earthquake in Nepal. According to the Advanced National Seismic System (ANSS) comprehensive earthquake catalog, there are 226 aftershocks in the global catalog in 19 days since the mainshock. Using the array methods, we are able to detect not only most of the globally recorded events, but also many hidden aftershocks missing in the ANSS catalog. We even detect early aftershocks that occur before the first aftershock recorded in the global catalog. These aftershocks usually remain undetected because of the arrival of various seismic phases immediately following a large earthquake [Lengline et al., 2012]. Our improved aftershock catalog contains twice the number of events compared to the global catalog and shows east-west spatial distribution of seismicity similar to the ANSS catalog. Majority of the detected events are clustered within the coseismic rupture area, and the rest are located to the north and south of the rupture area. In addition, we detect foreshocks within 10 days before the mainshock, while no foreshocks are recorded in the ANSS catalog. Detection of these hidden events greatly improves the completeness of the global standard foreshock and aftershock catalog, and enables us to better study the spatiotemporal distribution of foreshocks and aftershocks.

Observations and Implications of Fault-Zone Trapped Waves from the Rupture Zone of the 2014 M6 South Napa Earthquake, California, Yong-Gang Li, Rufus D. Catchings, and Mark R. Goldman (Poster 278)

Prominent fault-zone trapped waves (FZTWs) were recorded at the USGS’s two 1.9-km-long seismic arrays (Line 1 and Line 2) of 40 short-period seismographs deployed across the northernmost projection and the southern part of surface breaks of West Napa fault Zone (WNFZ) that ruptured in the 24 August 2014 Mw 6.0 South Napa earthquake. We also observed FZTWs at another 900-m-long 10-station seismic array (Line 3) deployed south of the Carquinez Straits across the intersection of the Franklin and Southampton faults, which appear to be southward continuations of the WNFZ. We analyzed waveforms from 55 aftershocks in both time and frequency to characterize the subsurface structure of fault damage zone associated with the M6 South Napa earthquake. Measured post-S durations of the FZTWs increase with epicentral distances and focal depths from the recording arrays, suggesting a low-
velocity waveguide along the WNFZ at depth in excess of 5-6 km. Locations of the aftershocks that generated the FZTWs and 3-D finite-difference simulations demonstrate that the subsurface rupture zone has a remarkable velocity reduction of ~40-50% between Line 1 and Line 2, coincident with the ~14-km-long mapped surface rupture zone and a ~500-m-wide anomalous zone. The low-velocity waveguide associated with the WNFZ extends farther south; it first leads to a ~1400-m-wide area with a more moderate velocity reduction of 30-35%. Based on preliminary results from FZTWs, we interpret that rocks along the WNFZ were severely damaged in the 2014 M6 South Napa earthquake while the moderate rock damage extends along the south-bound pre-existing faults. The waveguide effect appears to have localized and amplified ground shaking along the WNFZ and along faults farther to the south, consistent with the strong ground motion observations of Baltay and Boatwright (2015). Thus, we suggest that during future major earthquakes, the waveguide effect may result in localized amplification, extend ground shaking, and increase damage along the WNFZ and its extensions further to the south, even if the surface rupture is limited to only a portion of the WNFZ. The fault-zone waveguide effect on large amplitudes and long duration of ground shaking along the San Andreas fault system in Imperial-Coachella Valley is also in study for a better valuation of earthquake hazard in Southern California.

Full-Wave Anisotropy Tomography in Southern California, Yu-Pin Lin, Li Zhao, and Shu-Huei Hung (Poster 183)

Shear-wave splitting has always been a key observable in the investigation of upper-mantle anisotropy. However, the interpretation of shear-wave splitting in terms of anisotropy has been largely based on the ray-theoretical modelling of a single vertically incident plane SKS or SKKS wave. In our study, we use sensitivity kernels of shear-wave splitting to anisotropic parameters calculated by the normal-mode theory, which automatically accounts for the full-wave effects including the interference of SKS with other phases of similar arrival times, the near-field effect, and multiple reflections in the crust. These full-wave effects can lead to significant variations of SKS splitting with epicentral distance and are neglected in ray theory. We image the upper-mantle anisotropy in Southern California using nearly 6000 SKS splitting data and their 3D full-wave sensitivity kernels in a multiscale inversion enabled by a wavelet-based model parameterization. We also appraise our inversion by estimating the spatial resolution lengths using a statistical resolution matrix approach, which shows the finest resolution length of ~25 km in regions with better path coverage. The anisotropic model we obtain displays the structural fabrics in relation to surface geologic features such as the Salton Trough, the Transverse Ranges and the San Andreas Fault. The depth variation of anisotropy does not suggest a strong decoupling between the lithosphere and asthenosphere. At long-wavelengths, the orientations of the fast axis of anisotropy are consistent with the absolute plate motion in the interiors of the Pacific and North American plates.

Geodetic constraints on frictional properties of the Imperial fault, Southern California, Eric O. Lindsey and Yuri Falko (Poster 209)

We analyze a suite of geodetic observations across the Imperial fault in Southern California that span the complete earthquake cycle. We record interseismic deformation using four separate ENVISAT InSAR viewing geometries and continuous and survey-mode GPS, resulting in a dense set of observations of both shallow creep and regional strain accumulation due to secular loading. These data are combined with observations of coseismic and postseismic surface slip due to the 1979 Mw 6.6 Imperial earthquake. We compare the geodetic data to two-dimensional models of the earthquake cycle on a strike-slip fault obeying rate- and state-dependent friction. We find that data from all parts of the earthquake cycle are required to constrain key fault properties such as the rate-dependence parameter (a-b) as a function of depth; the extent of shallow creep; and the recurrence interval of large events. The data are inconsistent with a deep (30 mm/yr) slip rate on the Imperial fault; and we propose that an extension of the San Jacinto - Superstition Hills fault system through the town of El Centro may accommodate a significant portion of the slip previously attributed to the Imperial fault. Models including this additional sub-parallel fault are in better agreement with the available observations, implying that the long-term slip rate of the Imperial fault is lower than previously suggested, and that there may be a significant unmapped hazard in the western Imperial Valley.

Seismic Evidence for a Four-Year Episode of Deep Transient Creep Preceding the 2004 Parkfield Earthquake, Rachel Lippoldt, Marshall Rogers-Martinez, and Charles G. Sammis (Poster 269)

The 2004 M6 Parkfield CA earthquake was preceded by a four-year period of anomalously high seismicity adjacent to, but not on, the San Andreas Fault. The rate of small events (Mw<3) at distances between 1.5 and 20 km from the fault plane and at depths greater than 8 km increased from 6 events/yr prior to 2000 to 20 events/yr between 2000 and the 2004 earthquake. This increase in seismicity coincided with an increase in the duration of non-volcanic tremor, which, if tremor is indicative of creep on the fault plane, suggests that creep may have driven the enhanced seismicity. A causal relation between creep at the base of the fault zone and off-fault seismicity is supported by Coulomb stress transfer calculations that predict the observed spatial pattern of the seismicity. In particular, an observed SE striking lineation of enhanced seismicity is shown to be a direct consequence of a deepening brittle-ductile transition SE of Parkfield, as evidenced by a deepening of the tremor and low-frequency earthquakes. Other evidence for a causal link between deep creep and off-fault seismicity is the observation that off-fault seismicity before and after the 2004 earthquake occurred in the same location. This is expected if the foreshocks are driven by an episode of deep creep and the aftershocks are driven by afterslip, both occurring on the same deep extension of the fault plane. Finally, a transient increase in off-fault seismicity at Parkfield was observed to follow the 2010 Maule and the 2011 Tohoku earthquakes. Since the seismic waves from these events were observed to trigger tremor at Parkfield, this observation can be taken as further evidence for a causal link between deep creep and off-fault seismicity, particularly since the increase in off-fault seismicity was limited to deep events having the same spatial pattern as those that preceded the 2004 earthquakes. A similar anomaly in on-fault seismicity between 1990 and 1994 did not show any evidence of anomalous off-fault seismicity, and did not culminate in a M6 earthquake.

Extracting Seismic Attenuation Coefficients from Cross-Correlations of Ambient Noise at Linear Triples of Stations, Xin Liu, Yehuda Ben-Zion, and Dimitri Zigor (Poster 176)

We develop and apply an algorithm for deriving inter-station seismic attenuation from cross-correlations of ambient noise recorded by linear arrays. Theoretical results on amplitude decay due to attenuation are used to form a linear least-square inversion for inter-station Q values of Rayleigh surface waves propagating along linear arrays having three or more stations. The noise wave field is assumed stationary within each day and the inter-station distances should be greater than the employed wavelength. The inversion uses differences of logarithmic amplitude decay curves measured at different stations from cross-correlation functions within a given frequency band. The background attenuation between noise sources and receivers is effectively canceled with this method. The site amplification factors are assumed constant (or following similar patterns) in the frequency band of interest. The inversion scheme is validated with synthetic tests using ambient noise generated by ray-theory-based calculations with heterogeneous attenuation and homogenous velocity structure. The inter-station attenuation and phase velocity dispersion curves are inverted from cross-correlations of the synthetic data. The method is then applied to triplets of stations from the regional southern California seismic network crossing the Mojave section of the San Andreas fault, and a dense linear array crossing the southern San Jacinto Fault zone. Bootstrap technique is used to derive empirical mean and confidence interval for the obtained inverse Q values. The results for the regional stations yield Q values around 25 for a frequency band 0.2-0.36 Hz. The results for the San Jacinto fault zone array give Q values of about 6-30 for frequencies in the range 15-25 Hz.

Recent Achievements of the Collaboratory for the Study of Earthquake Predictability, Maria Liukis, Maximilian Werner, Daniël Schorlemmer, John Yu, Philip Maechling, Jeremy Zechar, Thomas H. Jordan, the CSEP Working Group (Poster 044)

The Collaboratory for the Study of Earthquake Predictability (CSEP) supports a global program to conduct prospective earthquake forecasting experiments. CSEP testing centers are now operational in California, New Zealand, Japan, China, and Europe with 435 models under evaluation.
In this project, we compare empirical approaches for correcting the atmospheric signal in synthetic coseismic SAR imagery. We generate synthetic data where the statistics of the stratified atmospheric contribution reflect the delay inferred from pressure, temperature and water vapor data from the North America Regional Reanalysis (NARR) Model. We estimate the atmospheric turbulence statistics from Moderate Resolution Imaging Spectroradiometer (MODIS) data. The simulated earthquake occurs along a basin-bounding normal fault in the Basin and Range Province. We find improved estimates of earthquake magnitude, depth and stress drop after applying the correction accounting for the spatially heterogeneous atmosphere relative to cases where the correction is based on constant atmospheric properties or where no correction is applied.

A Case for Historic Joint Rupture of the San Andreas and San Jacinto Faults, Julian C. Lozos (Poster 251)

The southern California earthquake of 8 December 1982 ruptured the San Andreas Fault from Cajon Pass to at least as far north as Pallet Creek (Bisai et al., 2002). The 1982 rupture has also been identified in trenches at Burro Flats to the south (Yule and Howland, 2001). However, the lack of a record of 1982 at Plunge Creek, between Cajon Pass and Burro Flats (McGill et al, 2002), complicates the interpretation of this event as a straightforward San Andreas rupture. Paleoseismic records of a large early 19th century rupture on the northern San Jacinto Fault (Onderdonk et al., 2013; Kendrick and Fumal, 2005) allow for alternate interpretations of the 1982 earthquake.

I use dynamic rupture modeling on the San Andreas-San Jacinto junction to determine which rupture behaviors produce slip patterns consistent with observations of the 1812 event. My models implement realistic fault geometry, a realistic velocity structure, and stress orientations based on seismicity literature. Under these simple assumptions, joint rupture of the two faults is the most common behavior. My modeling rules out a San Andreas-only rupture that is consistent with the data from the 1812 earthquake, and also shows that single fault events are unable to match the average slip per event for either fault. The choice of nucleation point affects the details of rupture directivity and slip distribution, but not the first order result that multi-fault rupture is the preferred behavior.

While it cannot be definitively said that joint San Andreas-San Jacinto rupture occurred in 1812, these results are consistent with paleoseismic and historic data. This has implications for the possibility of future multi-fault rupture within the San Andreas system, as well as for interpretation of other paleoseismic events in regions of complex fault interactions.

Modeling large stress drops and interaction of LA and SF repeaters at Parkfield, Semechah K. Y. Lui and Nadia Lapusta (Poster 282)

Studies of small repeating earthquakes enable better understanding of earthquake source physics. We aim to infer the fault properties in the area of well-studied SF and LA repeating sequences on the creeping section of the San Andreas Fault by numerical modeling, focusing on two intriguing observations: (1) the stress drops of these repeaters are inferred to be much higher, ~50 MPa, than the typical 1-10 MPa range and (2) these sequences appeared to interact irregularly before the 2004 M 6.0 Parkfield event but not after.

Our rate-and-state fault model of the repeaters features two velocity-weakening (VW) patches embedded into a large velocity-strengthening (VS) region. One of our major findings is that interaction between patches is dominated by the effect of accelerated postseismic slip around them, and not by direct static stress changes due to coseismic slip. We are able to numerically reproduce similar seismic events as the SF and LA sequences, with comparable moment magnitude, recurrence time, triggering time, and high stress drop, by incorporating enhanced dynamic weakening of the VW patches due to thermal pressurization. We find that the stress drop of the simulated repeaters depends on the properties of the surrounding creeping VW segment, since those properties partially control the rupture size. Our current work is directed towards determining the degree of heterogeneity in the model required for the observed irregular interaction.

Interpreting Crustal Stress Orientation Along the San Andreas and San Jacinto Faults: A Forward Modeling Study With Constraints From
Seismology, Geodesy, Topography, and Gravity, Karen M. Luttrell, Bridget R. Smith-Konter, David T. Sandwell, and Joel Spansel (Poster 229)

The active tectonics of the southern San Andreas transform plate boundary system respond to and contribute to the 4 D stress field throughout the region. We investigate the nature of this stress field in Southern California, with particular focus near the major strain-accumulating San Andreas and San Jacinto faults, by creating a forward model that incorporates observations from seismology, geodesy, gravity, topography, and earthquake rupture history, as well as investigating the relationship to downhole observations of stress azimuth.

The forward model consists of three independent crustal stress field components: (1) a plate driving force of undetermined magnitude and orientation; (2) a heterogeneous fault loading stress accumulation along locked fault segments; and (3) spatial variations in crustal stress due to differences in topography. The forward model is then compared to the in situ stress field orientation inferred from earthquake focal mechanisms.

We estimate the magnitude of the in situ stress field as that required to maintain its orientation in the presence of topography, which tends to resist the motion of strike-slip faults. Our results indicate that differential stress at seismogenic depth must exceed 62 MPa. To assess the orientation of the plate driving stress, we consider twelve independent segments of the San Andreas Fault System from Imperial Valley through Parkfield. We determine that along much of the central San Andreas fault, the maximum horizontal stress (SHmax) is oriented north-south (~0°EoF), but that from Coachella to Imperial SHmax is rotated clockwise, oriented ~14°EoF. Furthermore, SHmax along the San Jacinto and Superstition Hills segments gradually rotates clockwise from ~6°WofN in the south to ~8°EoF in the north.

With these results, we are able to match the in situ stress orientation of ~60% of the near-fault strike-slip areas to within 15° and >90% of the near-fault strike-slip areas to within ±30°, comparable to the errors associated with focal mechanism determination. Creating a forward model consistent with so many different types of observations corroborates the credibility of the individual model components and reinforces the robustness of the inferred stress rotations. The underlying physical cause of these rotations may be related to differences in segment locking depth, earthquake cycle maturity, fault friction and strength, or the nature of the connecting segments.

Earthquake Nucleation and Propagation on Rate and State Faults: Single vs Two State Variables Formulation and Evolution by composite aging-slip law, Xiao Ma and Ahmed Elbanna (Poster 153)

Earthquake nucleation and propagation has been studied extensively within the framework of single rate and state formulation with either the aging or the slip evolution laws. In this presentation we report on our ongoing work on simulating earthquake cycles on faults described by the two state variables formulation of the rate and state law. Beside the slip and aging evolution law we also consider the composite state law proposed by Kato and Tullis [2001].

The two state formulation has been found to provide a closer description of observed relaxations following jumps over a wide range of sliding speeds. Gu and Rice [1984] has also shown through a quasi-static stability analysis that the two state formulation may lead to chaotic vibrations for a range of wavenumbers and slip rates. Meanwhile, compared to the slip and aging laws, the composite law matches better the observations in both the slip-0lode-slip experiments and the velocity stepping tests.

We conduct a stability analysis for sliding with one and two state variables using different state evolution laws. We show that chaotic behavior in a single block is possible for the two-state variables formulation using the slip law but not the aging law. We also use the Spectral Boundary Integral Equation method [Lapusta et al., 2000] to simulate ruptures on 2D anti-plane faults embedded in an elastic full space. We show that nucleation using the composite law is very similar to nucleation using slip law. There are differences in the cycle simulation results between the two laws, however. The two state variables formulation, compared to the single state one, is found to lead to a richer dynamic response with more complex instability patterns. Our investigation will enable us to quantitatively determine the influence of using different friction and evolution laws on the details of the different phases of the seismic cycle.

Structure of the Los Angeles Basin – Results from LASSIE seismic experiment, Yiran Ma, Robert W. Clayton, and Elizabeth Cochran (Poster 222)

LASSIE (Los Angeles Syncline Seismic Interferometry Experiment) consists of a dense (1-km spacing) linear array of broadband stations deployed across the LA basin for approximately two months (September – November 2014). We show the results from two common methods – ambient noise and receiver function (RF), which revealed a detailed shallow velocity model (< 5 km deep), as well as the shape of the basement of the basin.

The basin RFs are complicated, however, the dense array enhances the lateral coherency of the signals and allows the structure to be imaged. The basement shape is clearly shown in the migrated image of the PpPs phase. The Ps conversion at the basement is the largest signal (including the direct wave) in the first 3 s. However, the Ps phase does not form as clear an image compared with the PpPs phase, possibly due to a requirement of more accurate velocity model (particularly Vp/Vs ratio) for migration, as well as the interference of other phases generated in the internal interfaces of the basin.

The surface wave signals from the ambient noise cross-correlations between LASSIE and surrounding SCSN stations are used for velocity inversion. In addition to the fundamental mode Love and Rayleigh wave, we also observed higher mode Rayleigh wave in short-period cross-correlations. The 1-10 s period Rayleigh and Love wave dispersion curves provide excellent constraints on top 5 km SV and top 3 km SH velocity structures respectively. Strong anisotropy (SV > SH) is observed for the top 1 km, which may provide information on the fractures of the sedimentary rocks and needs further investigation.

SCEC Open-Source Ground Motion Simulation Software, Philip J. Maechling, Scott Callaghan, Kevin Milner, Maria Lukis, Fabio Silva, and David Gill (Poster 043)

Southern California Earthquake Center (SCEC) researchers have developed an ecosystem of open-source scientific software that implements physics-based earthquake ground motion simulations. The software in SCECs ground motion modeling ecosystem offers a spectrum of capabilities ranging from attenuation relationship-based ground motion prediction equations to 3D physics-based probabilistic seismic hazard models. With funding support from NSFs Software Infrastructure for Sustained Innovation (SII) Program and PG and E, SCEC releases these software programs to the broader scientific community as open-source scientific software. SCECs open-source scientific software distributions include OpenSHA, which implements Calibrations most recent Earthquake Rupture Forecast (UCERF3), Unified Community Velocity Model (UCVM), which implements 3D velocity models, the SCEC Broadband Platform (BBP), which implements multiple 1D ground motion simulation methods, Hercules, 2nd order finite element wave propagation code, AWP, a 10th order finite difference wave propagation code, CyberShake, which implements a physics-based PSA model, and the SCEC Collaboratory for the Study of Earthquake Predictability (CSEP) forecast testing framework. Here, we review how SCEC software projects use coding standards, development tools, version control systems, and software testing approaches including use of automated testing tools, unit tests, acceptance tests, and regression tests, and use of continuous integration and nightly testing. We also review the contents of each SCEC software distribution including source code, installation documentation, make files, scripts, manifests, licenses, test inputs and results, example problems data sets, example results, and we discuss distribution of complex software stacks integrated as KVM and Virtual Box virtual images. Based on these reviews, we describe the current best open-source software practices in use by the SCEC software development group. Our goal is to standardize all our software development on these best practices, preserving useful scientific software, establishing scientific value with appropriate verification and validation testing, exchanging inputs and results between codes, providing a software ecosystem that can be examined, and extending powerful research capabilities to the broad SCEC scientific and engineering community.

The adage “no dates, no rates” is particularly applicable to projects assessing hazards related to active faults and folds in Southern California. Luminescence dating provides an age estimate for the last time sediment was exposed to sunlight and can be used to refine earthquake histories and accumulation of slip on faults and folds by dating associated and cross-cut sediment packages, units, and landforms. Luminescence dating is particularly useful for the typically coarse grained (sand) and charcoal poor sediments associated with alluvial fans and fluvial deposits commonly studied and trenchd for SCEC projects. Moreover, advances in single-grain luminescence dating have improved precision and accuracy of the technique. The development of the most robust and precise age models combine multiple dating methods; taking advantage of the benefits of luminescence with other techniques in diverse settings and deposits.

We recommend that future studies focus the application of luminescence dating to (1) high-value sites; (2) carefully chosen deposits with a good chance of solar resetting and a clear relation to the fault/fold of interest; and (3) where existing geochronologic databases from the region can be incorporated. In addition, we encourage the application of other dating methods, including C-14, U-series, and cosmogenic nuclides, to help assess and validate OSL ages. Reassessing past results is particularly important in understanding of geomorphic processes leading to improved field planning, sampling strategies, and laboratory techniques.

The recent SoSAFE Geochronology Workshop highlighted SCEC-funded luminescence chronologies and made fundamental recommendations for archiving meta-data (Scharer_14169_report). A key request was that all luminescence data be documented following reporting standards and be made available to the SCEC community. Reports in this data base will provide, at a minimum, the GPS location and depth of samples, type of sample (lithology and likely environment of deposition), the analyzing laboratory, analysis type, pretreatment methods, and a table of the full analytical results. This poster is an answer to that request and will provide a map of all known luminescence dating sites for studies between AD 2000 and 2015, a compilation of all related reports or papers, and a report that includes a detailed worksheet outlining the above parameters for each study.

Neotectonics in the San Diego Bay pull-apart basin, Rose Canyon-Descanso fault system, Jillian M. Maloney, Neal W. Driscoll, and Jeffrey M. Babcock (Poster 101)

The Rose Canyon fault zone is a Holocene active fault zone that trends through the city of San Diego, CA, the 8th largest city in the U.S. As such, it poses a seismic hazard to over 3.2 million people in the county, plus adjacent areas including the city of Tijuana, Mexico (population 1.3 million). Near downtown San Diego, the Rose Canyon fault zone steps offshore and several faults splay into San Diego Bay. These faults accommodate transension across the San Diego Bay pull-apart basin created by a right step between the onshore Rose Canyon fault and offshore Descanso fault. The slip rate on the Rose Canyon fault is 1-2 mm/yr and parts have been dated north of San Diego Bay in the early and late Holocene, but questions remain about the Rose Canyon-Descanso fault system that are important for understanding seismic hazard in the region. In particular, little is known about the rupture history and patterns of the faults within the step-over. We examined high resolution sub-bottom Chirp data within San Diego Bay to constrain fault geometry and relative recency of slip on the major faults within the basin, including a newly identified fault that trends beneath Harbor Island. These data reveal detailed fault geometry, which is important for assessing the role of slip between these segments play in rupture propagation across the step-over and their contribution to seismic hazard. Additionally, some fault strands offset the transgressive surface and the seafloor indicating that they are active in the Holocene. These new constraints on offshore faults can be compared onshore faults for a better understanding of fault rupture patterns along the Rose Canyon-Descanso fault system.
At many places along the San Andreas Fault, geodetic and seismic studies have suggested the presence of near-field compliant fault zones (CFZ’s). These zones of damaged rock display reduced elastic moduli compared to intact rock, resulting in both higher geodetic strain rates and lower seismic velocities within the fault zones. In this study, we investigate the CFZ surrounding the San Andreas Fault in the San Francisco Peninsula by examining interseismic deformation over the past several decades. We use new and existing survey GPS measurements, as well as older electronic distance measurements, to characterize the deformation of the CFZ. The data come from networks at Black Mountain and Lake San Andreas, both small-aperture geodetic networks on the San Francisco Peninsula with survey GPS occupations spanning at least 15 years. We compare the inferred fault zone properties between the two networks, which are separated by less than 40 kilometers but which represent different geologic boundaries and show different fault ages. We also compare patterns in seismicity between the two regions. The differences in inferred fault parameters between these two regions may be related to differences in fault age, and may give clues as to how CFZ’s develop over time.

Constraining Moment Deficit Rate on Crustal Faults from Geodetic Data with Application to Southern California, Jeremy L. Maurer, Kai Johnson, Paul Segall, and Andrew Bradley (Poster 212)

Constraining moment deficit rates (MDR) on crustal faults using geodetic data is an under-utilized but powerful method for constraining seismic hazard. In contrast to traditional slip inversions that depend on regularization assumptions, placing bounds on the MDR is well-posed. There are few methods for estimating bounds on the MDR: we use synthetic tests to show that one approach, constrained optimization bounding (COB), places conservative bounds on the MDR given sufficient knowledge of both data and prediction errors. The COB method is a modification of the constrained optimization approach for estimating the MDR (e.g., Murray & Segall, 2002; Maurer & Johnson, 2014). We use COB to estimate the current MDR in Southern California. Inferring the MDR from GPS velocities requires a model that relates fault slip to surface velocity. We use the elastic plate-block model of Johnson (2013). This approach relates the MDR indirectly to the GPS velocities through a specific set of kinematic assumptions about the velocity field, while MDR is more directly related to strain rate in the rock. We also use a method to map GPS-derived strain rates to the MDR on faults independent of assumptions about the long-term kinematics of deformation. In this approach we use GPS baseline elongation rates to infer the rate of moment deficit on all UCERF3 faults in southern California. The plate-block model gives a 1.67-2.05 x1019 Nm/yr for the entire Southern California fault system, equivalent to a magnitude 8.2-8.3 event every 150 years. The baseline inversions give a total moment accumulation rate on faults of 1.75-2.25 x 1018 Nm/yr, consistent with the plate-block model results. However, the inversion give large systematic residual baseline rates. The residual strain rate field, when converted to moment rate using a Kostrov-like summation, gives moment rates 0.7-1.75 x 1019 Nm/yr of moment accumulation, yielding a total moment accumulation rate in southern California of 2.25-4 x 1019 Nm/yr for the baseline method or 2.6-3.0 x 1019 Nm/yr for the plate-block model. Examples of the MDR estimates on individual fault segments range from low on the creeping section (0-1 x 1016 Nm/yr) to high on the Carrizo plain (2.4-3.4 x 1018 Nm/yr). Understanding the MDR with its uncertainty thus provides valuable information for understanding earthquake hazards in this geologically complex region.

Repeating Earthquakes Confirm and Constrain Long-Term Acceleration of Aseismic Slip Preceding the M9 Tohoku Earthquake, Andreas P. Mavrommatis, Paul Segall, Naoki Uchida, and Kai M. Johnson (Poster 172)

We find that changes in the recurrence intervals of repeating earthquakes offshore northern Japan in the period 1996 to 2011 imply long-term acceleration of aseismic creep preceding the M9 Tohoku-oki earthquake, confirming a previous inference from completely independent GPS data (Mavrommatis et al., 2014, GRL).

We test whether sequences of repeating earthquakes exhibit a statistically significant monotonic trend in recurrence interval by applying the nonparametric Mann-Kendall test. Offshore northern Tohoku, all sequences that pass the test exhibit decelerating recurrence, consistent with decaying afterslip following the 1994 M7.7 Sanriku earthquake. On the other hand, offshore south-central Tohoku, all sequences that pass the test exhibit accelerating recurrence, consistent with long-term accelerating creep prior to the 2011 M9 earthquake.

Using a physical model of repeating-earthquake recurrence, we produce time histories of cumulative slip on the plate interface. After correcting for afterslip following several M~7 earthquakes in the period 2003-2011, we find that all but one sequence exhibit statistically significant slip accelerations. Offshore south-central Tohoku, the estimated slip acceleration is on average 2.9 mm/yr^2, consistent with the range of 2.6-4.0 mm/yr^2 estimated from independent GPS data (Mavrommatis et al., 2014).

From a joint inversion of GPS and seismicity data, we infer that a substantial portion of the plate interface experienced accelerating creep in the 15 years prior to the M9 Tohoku-oki earthquake. The large slip area of the Tohoku-oki earthquake appears to be partly bounded by accelerating creep, suggesting that most of the rupture area of the Tohoku-oki earthquake was either locked or creeping at a constant rate during this time period. Accelerating creep would result in increasing stressing rate on locked parts of the interface, thereby promoting nucleation of moderate to large earthquakes.

Time-dependent deformation of California from inversion of GPS time series, Robert McCaffrey (Poster 197)

The GPS displacement time series from the Plate Boundary Observatory (PBO), Crustal Motion Model 4 (Shen et al., JGR, 2011) and the Pacific Northwest (McCaffrey et al., JGR, 2013) are used to estimate time-dependent deformation of California from 1992 to the present (2015.6). The data are initially fit by estimating the parameters of transient sources and a steady slope (site velocity). The sources include all large earthquakes since 1992 plus after-slip for many of them and several volcanic sources. The parameters are estimated by least-squares fit to the time series. (Also estimated are seasonal terms and offsets due to equipment changes and other non-tectonic causes.) Compared to other methods where earthquake offsets are estimated independently at each site and component, this approach requires the offsets to be derived from just a few source parameters and hence imposes a spatial correlation on the offsets (and therefore on the velocities). This helps improve the velocities of sites with few observations, like campaign or short-duration continuous sites. Combined with a block model to represent the steady motion (based on the estimated time series slopes) a full history of the deformation can be estimated. This deformation model can be used to calculate strain rates and Coulomb stress changes anywhere and at any time in the model domain. This work is funded by SCEC and supports its Community Geodetic Model effort.

Applying Bayes` theory to assess statistical significance of potentially induced seismicity due to wastewater injection in Oklahoma and California, Mark McClure, Riley Gibson, Kittawan Chiu, and Rajesh Ranganath (Poster 064)

Several decades of seismicity and wastewater disposal data in California and Oklahoma are analyzed to seek evidence of induced seismicity and assess statistical confidence. The data is analyzed with a method designed to account for several difficulties: nonrandom locations of injection wells and seismicity, spatial and temporal clustering, and fat-tailed distributions of seismicity observations. Seismicity observations are described with a nonlinear and flexible statistical distribution. In each gridblock, a Gibbs sampler is used to infer the joint probability distribution of model parameters describing natural and induced seismicity. The model accounts for spatial and temporal correlation using parameters estimated within the Gibbs sampler. Likelihood ratio tests are used to assess statistical significance in each gridblock and across each state. The results shows strong significance in Oklahoma, but not in California. The algorithm identifies one instance of potentially induced seismicity in California (due to wastewater disposal), the earthquake sequences in the vicinity of Coalinga in the 1980s. This analysis technique could be applied.
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to other regions and extended to seek associations between induced seismicity and geological and operational parameters.

Database of SCEC Geochronology Results and Associated Metadata, Griffin S. McMullen (Poster 307)

Geochronology results along with associated metadata from projects funded by the Southern California Earthquake Center during the SCEC3 (1 Feb 2007 to 31 Jan 2012) and SCEC4 (1 Feb 2012 to 31 Jan 2017) phases were compiled into a series of organized data tables. This database will be made available to the SCEC community once a system is in place to embargo recent, unpublished analyses for a set time period. Data sets compiled include radiocarbon (Carbon-14) and cosmogenic nuclides (Beryllium-10 and Aluminium-26). Radiocarbon samples were analyzed at the KECK AMS Facility, Earth System Science Department, University of California Irvine, and at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. The lab notebooks and lab conducted all cosmogenic isotope analyses. In addition to lab-provided data and standards, sample metadata was collected from publications, project reports, and personal communication with investigators. This metadata includes the associated SCEC project report number, year sample was acquired, purpose of the sample, fault studied, study site name, longitude, latitude and surface elevation of sample site location, and sample material. Metadata for cosmogenic nuclide samples also includes information on sample mass, carrier mass, sample density, shielding factor, and carrier concentration that are needed to calculate an effective surface exposure age using the CRONUS Earth Age Calculator Version 2.2. Carbon 14 dates are currently in uncalibrated form. The database illustrates the breadth of SCEC geology research over the preceding decade, and will serve as a resource for future investigations.

Popcorn in an Oven: How Does a Tremor Source Burst into Low-Frequency Earthquakes?, Deepa Mele Veedu and Sylvain Barbot (Poster 261)

A number of tremor sources burst into low-frequency earthquakes (LFEs) in the deep extension of the San Andreas Fault in the last decade. Among the tremor sources, a particular LFE family near Parkfield exhibited doubling recurrence intervals alternating between about three and six days. A simple physical model producing successive slow and fast ruptures can explain the doubling recurrence intervals, but the source characteristics of the LFEs may not be fully explained by this simple model. The source characteristics show that tremor bursts containing more LFEs and lasting longer are associated with lower-amplitude ground motion. Here, we investigate the physics of the micro-asperities under rapid loading to model the tremor duration and the number of LFEs in a burst. We find that the number of LFEs per burst is controlled by peak velocity of the modeled slip event. However, the duration of the tremor burst is not directly controlled by the duration of the underlying slip. The findings imply the triggering and the occurrence of LFEs shortly after the slip events, in a manner similar to mainshock/aftershocks interactions. The results from our numerical model enable us to better understand the pops of triggered tectonic tremors associated with underlying slip events.

Remotely Triggered Small Earthquakes in the Himalayas by the 2007 Mw 8.5 Sumatra Event and Preliminary Assessments of associated Dynamic Stresses, Manuel M. Mendoza, Abhijit Ghosh, and Shyam S. Rai (Poster 159)

Due to sparse seismic networks in central Himalaya, knowledge of the fault geometry, earthquake distribution and stress dynamics at this convergent plate boundary is limited and inadequate to assess seismic hazard with reasonable confidence. Previous studies have shown that dynamic triggering can be a catalyst for additional brittle failures (Gomberg and Johnson, 2005), providing valuable information on the fault properties during periods of local inter-seismic slip. Therefore, it is necessary to investigate dynamic triggering and its controlling mechanism in the Himalayas to better understand the effects of fault-stress loading. Analyzing seismic data from a dense local seismic network that operated between 2005 and 2012 (Mahesh et al., 2013) in Kumaon-Garhwal Himalaya, we find micro-earthquakes dynamically triggered by the 2007 Mw 8.5 Sumatra teleseismic (4,700 km) event. We generated a 30-day catalog surrounding the teleseismic event and show a dramatic increase in earthquake activity with respect to the background seismicity rate immediately after the arrival of the teleseismic waves. The elevated activity (500% increase) of small local earthquakes persist several days after the passage of the teleseismic wave train suggesting that a secondary, non-dynamic mechanism is at work. Absolute and relative hypocentral locations show earthquake clusters, illustrating the areas that are particularly susceptible to small stress perturbation from dynamic stress. Furthermore, for the initially triggered micro-earthquakes, we calculate dynamic stresses impacted by the low-frequency teleseismic Rayleigh wave train to be ~0.019 MPa. These results are consistent with previously calculated dynamic stresses associated with remote triggering, which range between ~0.01 - 1 MPa (Prejean et al., 2004). Other instances of teleseismic events triggering local earthquakes are observed in our dataset and will be investigated to constrain the threshold of dynamic stresses impacted on critically stressed faults in this region. Improved understanding of remote triggering in the Himalayas will help to outline its current state in the earthquake cycle and estimate future destructive earthquakes.

Estimating directivity and related source properties of moderate San Jacinto fault zone earthquakes with second seismic moments, Haoran Meng, Jeff McGuire, and Yehuda Ben-Zion (Poster 267)

We use second seismic moments to estimate directivity, source time function and centroid velocity of several M=4 earthquakes on the San Jacinto fault zone (SJFZ). The analysis utilizes Empirical Green’s Function deconvolution to calculate the second moment and related properties of the events with a well constrained inverse problem that has far less (only 6) parameters than finite source inversions. Excellent station coverage and high quality records provide potential for deriving robust results for rupture properties and correlating the results with contrasts of seismic velocities and other fault zone and earthquake properties. Initial analysis of the March, 2013, M5.1 earthquake on the SJFZ indicates clear directivity to the North West as expected from the local velocity contrast and rock damage asymmetry. We find that the Peak Spectral Accelerations in the frequency band around the corner-frequency are highly correlated with the expected directivity signal from our second moment estimates. We are currently extending the study to additional earthquakes. Updated results will be presented in the meeting.

Mitigating Spatial Bias of Back-Projection Imaging Through Physics-Based Aftershock Corrections: Application to the 2015 M7.8 Nepal Earthquake, Lingsen Meng, Alin Zhang, and Yuji Yagi (Poster 171)

The 2015 Mw 7.8 Nepal-Gorkha earthquake with casualties of over 9,000 people is the most devastating disaster to strike Nepal since the 1934 Nepal–Bihar earthquake. Its rupture process is well imaged by the teleseismic MUSIC back-projections (BP). Here, we perform independent back-projections of high-frequency recordings (0.5-2 Hz) from the Australian seismic network (AU), the North America network (NA) and the European seismic network (EU), located in complementary orientations. Our results of all three arrays show unilateral linear rupture path to the east of the hypocenter. But the propagating directions and the inferred rupture speeds differ significantly among different arrays. To understand the spatial uncertainties of the BP analysis, we image four moderate-size (M5–6) aftershocks based on the timing correction derived from the alignment of the initial P-wave of the mainshock. We find that the apparent source locations inferred from BP are systematically biased along the source-array orientation, which can be explained by the small amount of 3D velocity structure deviated from the reference model (e.g. IASP91). We introduced a SLOWNESS error term in travel time as a first-order calibration that successfully mitigates the source location discrepancies of different arrays. The calibrated BP results of three arrays are mutually consistent and reveal a unilateral rupture propagating eastward at a speed of 2.7 km/s along the down-dip edge of the locked Himalaya thrust zone over ~150km, in agreement with a narrow slip distribution inferred from finite source inversions.

Simulating ground motions from large mega-thrust earthquakes in the North Island of New Zealand, Marina Merlin, Yoshihiro Kaneko, and Carolina Holden (Poster 025)

In the North Island of New Zealand where the Hikurangi subduction interface appears to be fully locked at 23 km beneath Wellington, the
absence of recorded mega-thrust earthquakes necessitates the use of simulation-based approaches for ground motion prediction. In this study, we simulate long-period (>2 seconds) ground motions of plausible magnitude-8 mega-thrust earthquakes in the North Island of New Zealand using a spectral element code (SPECFEM3D). Our approach accounts for (i) the 3D velocity model of New Zealand derived from body-wave tomography (Eberhart-Phillips and Reyners, 2012) and (ii) the 3D plate interface geometry derived from seismicity and seismic-reflection data (Williams et al., 2013). We consider a range of kinematic source parameters, including various slip distributions and rupture propagation directions, and for each source scenario, we calculate site-specific ground motion parameters, such as long-period response spectra, peak ground displacements, and peak ground velocities. Our result suggests that rupture nucleating from the up-dip end of the locked zone and propagating into the down-dip direction causes the largest ground motion in the Wellington city among a range of scenarios considered so far. We will report on our current efforts on identifying key source parameters that would affect the long-period (>2 seconds) ground motions in major cities in the North Island of New Zealand.

Paleoearthquake displacement and age data from the 1995 Middle Ranch Trench site, Sierra Madre Fault, CA, Nikolaos Midttnou, Tim Dawson, Kate Scharer, and Shannon Mahan (Poster 119)
The Sierra Madre fault zone (SMFZ) is a ~135-km-long, north-dipping reverse fault system that stretches along the foot of the San Gabriel Mountains 20 km north of Los Angeles, California. There are limited data on the recurrence interval, typical offsets, and slip rate of this fault. This study aims to revive unpublished trench data from the Middle Ranch trench site, located at the intersection between two segments of the SMFZ, the San Fernando fault and the Central Sierra Madre fault, to better constrain the timing and magnitude of earthquakes on the SMFZ. In 1995, T. Fumal, T. Dawson, and W. Frost excavated a 4.5-m-deep, 9-m-long trench near Little Tujunga Canyon across one of two scarps produced during the Mw=5.7, 1971 San Fernando earthquake. The trench exposed a thick upper soil with abundant charcoal, several meters of bedded loose fluvial gravel and sand layers, and interbedded indurated sand and silt deposits. Fumal interpreted three distinct earthquake episodes, each with ~70 cm of dip-slip displacement, along a north-dipping, 60-cm-thick fault zone. Conflicting results from radiocarbon, thermoluminescence (TL), and infrared stimulated luminescence (IRSL) dating prevented Fumal from drawing strong conclusions about the recurrence interval or slip rate, but nonetheless provide a maximum average recurrence interval for this strand of about 5000 years. Our goal is to revisit the earthquake evidence and dating from this important site so that it can be published. We scanned the original photographic negatives in order to produce a high-resolution photomosaic of the trench wall. The poster presents the original logs, re-interpretations of the fault zone deformation, a detailed discussion of the dating that was completed, and plans for additional dating. Comparison of the Middle Ranch trench results to other trenches along the SMFZ will provide better insight into the fault’s recurrence interval, as well as improve understanding of earthquake behavior at the segment boundary and the relationship of the SMFZ with the broader plate boundary setting.

A new model to characterize slip profiles, comparing observed slip variations between the 1992 Mw=7.3 Landers and 1999 Mw=7.1 Hector surface ruptures, Christopher W. Milliner, James Dolan, Amir Allam, Charlie Sammis, James Hollingsworth, Sebastien Leprince, Francois Ayoub (Poster 111)
Co-seismic, along-strike slip heterogeneity is widely observed for many surfacerupturing earthquakes, as revealed by field and high-resolution geodetic methods. This co-seismic slip variability, however, is currently poorly understood. We cross-correlate optical, pre- and post-event air photos using the program COSI-Corr to measure the near-field, surface deformation pattern of the 1992 Mw=7.3 Landers and 1999 Mw=7.1 Hector Mine earthquakes in high-resolution. From a spectral analysis of the slip distributions of both events (produced from over 1500 measurements) we find slip variation is far from random, and is scale invariant and self-affine fractal. We find a fractal dimension of 1.72 ± 0.20 and 1.62 ± 0.30 for the Landers and Hector Mine earthquakes, respectively, indicating slip is more variable for the former. We show deterministically that the wavelength and amplitude of slip fluctuations of both earthquakes can be directly correlated to geometrical fault complexities of similar size (such as stepovers, kinks or bends). We find that the spatial correlation between slip fluctuations and geometrical fault structure can explain why the complex surface rupture of the Landers earthquake has a rougher slip distribution than the geometrically simpler surface rupture of the Hector Mine event. We provide observational evidence and statistical models to explain why fractal slip has not been observed in traditional low-resolution geodetic and field surveys. From our results we show that fractals provide a more accurate representation of slip profiles than semi-elliptical or triangular distributions, which can only capture the first-order spatial variation of slip. Moreover we discuss comparisons of slip variation observed from our individual events to that also found in the geomorphic record from other studies, and the implications this has for long-term strain release along fault systems. This yields a simple framework and a physical explanation for understanding coseismic slip variation that can synthesize recent results of slip variation found from numerical simulations, field surveys, and geodetic studies. Our results have implications for the fundamental relationship between fault geometrical structure and earthquake rupture behavior, and allow for simple modeling of realistic slip profiles for use in seismic hazard assessment, numerical rupture simulations and paleoseismology studies.

Joint Seismic-Geodetic Real-Time Finite Fault Models for Earthquake Early Warning, Sarah E. Minson, Maren Bøse, Thomas H. Heaton, Egill Hauksson, Claude Felizardo, and Deborah E. Smith (Poster 067)
Because seismic and geodetic data observe complementary parts of the earthquake rupture process, we combine real-time seismic and GPS data streams to constrain the earthquake centroid, fault orientation, spatial extent of rupture, and determine a distributed slip model. With this source information we obtain magnitude estimates that do not saturate for large earthquakes and produce improved shaking forecasts relative to other algorithms used for earthquake early warning (EEW) that instead rely on a point-source approximation of the fault orientation, and spatial distribution of slip are determined in real-time as the earthquake rupture evolves by combining an analysis of the spatial distribution of ground acceleration from the Finite Fault Rupture Detector (FinDer) algorithm (Bøse et al., 2012) with a geodetic distributed slip model based on the Bayesian Evidence-based Fault Orientation and Real-time Earthquake Slip (BEFORES) algorithm (Minson et al., 2014). By using the
FinDer output as the prior probability density for BEFOREs, we obtain the joint Bayesian posterior probability distribution. This probability distribution describes the relative probability of all fault geometries and slip models given the available seismic and geodetic observations. Note that in obtaining this joint source model there is no additional computational cost above that of the component seismic and geodetic analyses. Further, the Bayesian framework that we use to combine seismic and geodetic EEW algorithms could be arbitrarily extended to include any other desired analyses of independent data without extra computational expense.

PRISM Scholars: Measuring the Slip Rates of the Faults within a Transect across the Pacific-North America Plate Boundary in the Imperial Valley, Southern California and Mexico, Michelle Miranda, Jennifer Juarez-Ayalz, Alicia Ortiz-Simon, and Sally McGill (Poster 304)

Undergraduate scholars in the NSF-funded PRISM program (Proactive Recruitment in Introductory Science and Mathematics) used GPS site velocities to infer fault slip rates in southern California. GPS data collection can help measure the increasing strain around the faults that make up the boundary between the North American and Pacific Plates. This strain can be used to infer increasing stress on the faults, leading to future earthquakes. We used an elastic half-space model to estimate the possible slip rates of each fault within a transect across the plate boundary passing through the Imperial Valley, constrained by the GPS velocities within the transect from the Plate Boundary Observatory and other published sources. An arc tangent formula was used to find the benchmark velocities that would be expected for various possible fault slip rates. These calculated velocities are compared to the velocities observed using the GPS system. Over 10,000 combinations of slip rates and locking depths for seven faults were tested using a spreadsheet. The best-fitting model found for the Imperial transect had a reduced chi-squared value of 130. This value was much higher than expected, and indicates that further trials are needed to find a better fitting model, perhaps using different locking depths. The locking depths were initially set based on depth of seismicity, but a better fit was achieved when locking depths were allowed to be more shallow. The best-fitting model obtained so far for the faults within the transect gave the following right-lateral slip rates: Agua Blanca, ≥ 3 mm/yr; San Miguel, 1 mm/yr; Laguna Salada, 2 mm/yr; Weinfert fault, 0 mm/yr; Imperial fault, 30 mm/yr; Brawley fault ≥ 5 mm/yr; and an unnamed fault farther east, ≥ 2 mm/yr. Thus, within these latitudes, the Imperial Fault is accommodating the majority of the plate boundary slip.

Documenting displacements of the 24 August 2014 South Napa earthquake using high-resolution photogrammetry, Alexander E. Morelan, Charles C. Trexler, and Michael E. Oskin (Poster 121)

Following the 24 August 2014 Napa earthquake, we used structure from motion (SfM) to produce extremely high-resolution three-dimensional point clouds with mm-scale resolution of surface rupture through anthropogenic features. We show that this method is useful for rapid and inexpensive recording of fault displacement. The SfM technique represents a significant advance over traditional post-earthquake field measurements, which are irreproducible because displacement may change over time due to afterslip, and because the detailed features of a surface rupture quickly degrade either due to weathering or repair. Using SfM, we documented ten sites with tectonic slip along the surface rupture of the South Napa earthquake. Using repeat surveys, we documented two sites with appreciable afterslip over the days, weeks, and months after the earthquake. We illustrate a simple workflow that allows other workers to conduct surveys with enough reference information to easily scale and orient fine scale features of surface rupture captured with SfM.

Ground motions from scenario earthquakes in the Wasatch fault zone, Utah, and implications for seismic hazard in the Wasatch Front, Morgan P. Moscetti, Stephen Hartzell, Leonardo Ramirez-Guzman, Arthur Frankel, and Peter Powers (Poster 93)

We compare synthetic ground motions from long-period (T > 1 s) 3-D simulations of M7 earthquakes on the Salt Lake City segment of the Wasatch fault. Utah, to ground motions from empirical ground motion prediction equations (GMPEs) to evaluate the seismic hazard implications of the use of these simulations. The set of scenario earthquakes comprises 96 earthquake rupture models, which vary kinematic rupture parameters controlling slip distribution, hypocenter, average rupture velocity and rise time. We compare the 5-percent-damped response spectral accelerations (1.5, 2, 3, 4, 5, 7.5, 10 s) to the predictions from the four NGA-West2 GMPEs that include the effects of deep sedimentary basins. In general, we find that the range of long-period ground motions predicted from the simulations falls within two standard deviations of the median GMPE ground motions. This general observation holds for both near-field and far-field ground motions. However, several regions of the Wasatch Front, which overlie deep sedimentary basins and are located more than 10 km from the fault, exhibit anomalously large simulated ground motions. The peak ground motions from these regions are from short-period (< 10 s) surface waves, which are amplified and scattered within the local sedimentary basins. Channeling of seismic energy into the sedimentary basins to the north and south of the Salt Lake City segment—Weber and Utah basins, respectively—produces significant ground motion amplifications, relative to the GMPEs, with simulated ground motions more than two standard deviations above the median GMPE ground motions. Although the ground motions from short-period surface waves generated from our simulated scenarios on the Salt Lake City segment of the Wasatch fault zone are poorly predicted by the GMPEs and represent an important contribution to the seismic hazard in the Wasatch Front.


The Mecca Hills, Southern California, consists of a 30 km-long, 8 km-wide north-plunging anticlinorium related to transpression and dextral/dextral normal faults along the southern San Andreas Fault (SAF). Although an iconic area for studying transpressional deformation and the Late Cenozoic sedimentary record, the long-term history of faulting, significance and kinematics of the subsidiary faults in the crystalline rocks, and relationship between these faults and the main trace of the SAF remain unclear. We examine the petrologic, kinematic, and timing relationships between 4 subsidiary faults and related damage zones parallel to the SAF to evaluate relationships with the SAF and the Eastern California Shear Zone.

At least 6 major faults cut the Mesozoic to Late Tertiary crystalline and sedimentary rocks in the Mecca Hills, including the SAF. Hematite- and clay-coated fracture and slip surfaces are common in damage zones of the subsidiary faults. Slip surface orientation data of hematite-coated surfaces in the Painted Canyon Fault damage zone cluster at 110°, 65° SW and at 196°, 90° W. Similar surfaces in the Platform Fault damage zone cluster at 049°, 69 SE° and 003°, 83° E. Clay-coated slip surfaces in the Hidden Springs Fault damage zone cluster at 195°, 53° W and 198°, 11° W. Multiple slip vector orientations are observed on a single fault surface, consistent with oblique and dip-slip motion on faults in the Mecca Hills. Damage zones of faults in the Mecca Hills are meters-wide clay gouge zones, with multiple clay gouge zones present in some damage zones. Clay gouge associated with crystalline rock is often vibrantly colored while sedimentary rocks in damage zones are gougued or brecciated in a “mixed zone” adjacent to the fault. Iridescent hematite and smooth clay surfaces suggest frictional heating on these surfaces, possibly from seismic slip. Scanning electron microscopy data reveal 10s-100s of µm thick, brecciated hematite slip surfaces. The specular hematite appears originally syn-tectonic and subsequently reworked with host rock and comminuted in multiple slip events. We apply hematite andapatite (U-Th)/He dating from the fault surface and host rock, respectively, to constrain fault thermal evolution and evaluate hematite (U-Th)/He dates as recording hematite formation, fault slip, or erosional cooling in the Mecca Hills. Collectively, these data will provide insight into the geochemical, structural, and temporal evolution of these structures.

The Community Geodetic Model, Jessica R. Murray, Rowena Lohman, and David Sandwell (Invited Talk Mon 14:00)
The SCEC Crustal Motion Map (CMM) provided average geodetic velocities from southern California data collected through 2004. Core SCEC4 science targets require input that captures spatiotemporal variations at high resolution. The Community Geodetic Model (CGM) aims to provide this by leveraging the complementary features of Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) data. Advances since the completion of the CMM, including a larger continuous GPS network, the launch of new SAR satellites, and development of InSAR time series analysis techniques, provide essential CGM building blocks. Raw GPS and InSAR data are being analyzed and combined via appropriate models to generate GPS station time series, spatially gridded InSAR time series, and a self-consistent integration of the two.

Creating the CGM requires synthesis of existing analyses and development of new methodologies. In a series of in-person and virtual workshops, geodesy experts and potential users have defined the target CGM product, identified important decision points in CGM development, evaluated candidate methodologies, and adjusted the plan accordingly.

By comparison of continuous GPS time series from several processing centers we have uncovered and addressed discrepancies. We are finalizing a methodology for merging these time series, incorporating campaign data. GPS-derived secular velocities are needed to constrain some InSAR analyses and have intrinsic value to the broader SCEC community for interseismic deformation studies. Calculating these rates is complicated by factors such as long term postseismic signals, particularly in regions with little pre-earthquake GPS data, and the potential for bias introduced by the scale term applied during GPS reference frame alignment. These are topics of ongoing evaluation and decision-making by CGM contributors.

An important finding is that some InSAR time series derived without GPS constraints show good agreement with GPS even at long spatial scales and thus might provide deformation time series in regions with sparse GPS coverage. The new Sentinel-1a and ALOS-2 satellites now supply ascending and descending data for southern California with short baselines and frequent repeats, opening exciting new avenues for improved InSAR time series analysis and atmospheric corrections. Through the CGM effort thus far we have laid the groundwork to capitalize on these unique observations in the coming years.

Stochastic characterization of 3D mesoscale seismic velocity heterogeneity in Long Beach, California, Nori Nakata and Gregory C. Beroza (Poster 014)

Earth’s seismic velocity structure is heterogeneous at all scales, and mapping that heterogeneity provides insight into the processes that create it. At large scale lengths, seismic tomography is used to map Earth structure deterministically. At small scale lengths, structure can be imaged deterministically, but because it is impractical to image short-wavelength heterogeneity everywhere, we often resort to statistical methods to depict its variability. In this study, we develop random-field model representations of a 3D P-wave velocity model under Long Beach, California, estimated from dense-array recordings of the ambient seismic waveform. We focus on heterogeneity at the mesoscale, which is smaller than synoptic 10+ km scale of regional tomography but larger than the micro scale of borehole measurement. We explore four ellipsiodally anisotropic models, including von Karman, Gaussian, self-affine and Kummer models, based on their autocorrelation functions. We find that the von Karman model fits the imaged velocity model best among these options with a correlation length in the horizontal direction about five times greater than in the vertical direction, and with strong small-scale length variations (fractal dimension of 3.96). We validate our results by showing that our model reasonably predicts the observed decay of scattered waves in the coda of a nearby earthquake. This suggests that quantitative measures of velocity variability will be useful for predicting high frequency ground motion in earthquakes.

Investigating Ground Motion Variability at a Precariously Balanced Rock (PBR) site near the San Jacinto Fault in Riverside, CA, Corrie Neighbors, Elizabeth S. Cochran, and Jim Brune (Poster 174)

We investigate the seismic wave coherence, or the spatial correlation of ground motion, at small spatial scales (<100 m) near a precariously balanced rock (PBR) site. PBRs are thought to act as low-resolution seismoscopes that operate over long periods of geologic time thereby yielding a direct indication of past ground shaking in regions of high seismicity. However, the acceptance of PBRs by the seismologic community remains in question due to the uncertainty concerning ground motion variability in the near field of a PBR. To investigate this question, the Pitas Point-Ventura fault (PPVF) has been monitored using 28 rings of 25, 50, and 100 meters of a sensor at a PBR site. Over a 15-month period, we recorded over 100 local earthquakes, predominantly associated with the San Jacinto fault, of magnitude 2.0 and greater. While the PBR and surrounding sites are located on Cretaceous age granites, due to the nature of PBR site morphology, it is likely that the near-surface geology is spatially heterogeneous due to the presence of weathered granite of variable thickness in the near surface and unexposed corestones at depth. Thus, we will attempt to characterize the waveform coherency at various azimuths and distances and characterize the subsurface site properties using the horizontal to vertical spectral ratio (H/VSR) method, which yields the dominant period(s) of the material. Determining the variability of ground motion across PBR sites will provide insight into wave propagation across a rock landscape and will reveal how reliably PBRs can be used to constrain the maximum unexceeded ground motions from historic earthquakes.

Anomalous Uplift at Pitas Point, California: Whose fault is it anyway?, Craig Nicholson, Christopher C. Sorlien, Thomas E. Hops, and Arthur G. Sylvester (Poster 221)

Recently, several investigators have proposed that damaging earthquakes of magnitude near M8 may have occurred in the western Transverse Ranges based on repeated ~8-m uplift events of coastal marine terraces located around Pitas Point near Ventura [e.g., Rockwell et al., 2014]. Many believe the principal focus for these proposed events is the north-dipping Pitas Point-Ventura fault [Hubbard et al., 2014], part of the larger, primarily offshore North Channel-Pitas Point-Red Mountain fault system [Kamerling et al., 2003]. However, this model of multiple, large Holocene events on the Pitas Point-Ventura fault (PPVF) has accrued fundamental inconsistencies, not the least of which are: the appropriateness of the 2D fold model used to infer oblique subsurface 3D fault geometry, the implied Holocene slip rate for the blind PPVF, and the lack of seafloor offset or widespread tsunami deposits from such expected, shallow M8 uplift events that extend offshore. The reason for these discrepancies may be that uplift at Pitas Point is primarily driven by slip on the south-dipping, listric Padre Juan fault (PJF) [Grigsby, 1988], not the PPVF. The PJF juxtaposes the N-verging, asymmetric San Miguelito anticline in its hanging wall above the more symmetric Ventura Avenue-Rincon anticline in its footwall. Fault and fold geometry is well determined by industry wells that produce from the distinctly different and vertically separated San Miguelito and Rincon oilfields, and by imaging offshore with seismic reflection data. In places, the PJF exhibits up to 2.6 km of vertical separation, with much of this slip likely occurring in the last ~200 kyr. This fault soles into the weak Rincon Shale at a depth of ~7 km and thus represents a classic out-of-syncline thrust. Such faults are known to generate anomalously large slip for their size and may explain why the uplift rate at Pitas Point is so much higher than elsewhere along the coast. The presence of the shallow, listric PJF and localized shortening across its footwall strongly suggest that the uplift events at Pitas Point are anomalous, and not necessarily indicative of the expected slip at depth farther along strike of the PPVF, or even the average slip expected during large earthquakes. Rather, these uplift events at Pitas Point are probably localized to where slip on the PJF predominates, or where the PJF and PPVF strongly interact, and thus are confined to a limited length and depth of the active fault(s) involved.

A 50 km jump in seismic slip during the Mw 7.1 Harrai (Pakistan) earthquake: consequences for earthquake triggering and rupture forecasting, Edwin Nissen, John R. Elliott, R. Alastair Sloan, Tim J. Craig, Gareth J. Funning, Alex Hutko, Barry E. Parsons, Tim J. Wright (Poster 058)

The size and potential impact of an earthquake scale with the length of seismic rupture, and thus depend strongly on whether or not slip is arrested at fault segment boundaries. Here, we use geodetic and seismic waveform data to reveal that rupture of a Mw 7.1 earthquake in Pakistan
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jumped ~50 km between two shallow, blind reverse faults, a gap that is unprecedented amongst well-studied earthquakes. Slip on the second fault increased the total seismic moment by half and doubled the event duration and area of maximum ground shaking. Initiation of slip on the second fault coincides with the passage of emergent surface waves from the first event and occurs where Coulomb stress changes are small and probably negative, suggesting instead a dynamic triggering mechanism. Contemporary earthquake rupture forecasts such as California’s UCERF3, which limit earthquake jumps to a maximum of a few kilometers, may therefore underestimate the probability of large magnitude events in areas of significant fault complexity.

Nucleation process of the Mj 6.7 northern Nagano prefecture, Japan, earthquake of November 22, 2014, Shunta Noda and William L. Ellsworth (Poster 173)

On November 22, at 10:08:18PM (JST) part of the Kamishiro fault in northern Nagano prefecture, Japan, ruptured in a reverse faulting earthquake of Mj 6.7 and Mw 6.2. A brief, but intense foreshock sequence, which included six earthquakes between Mj 2.0 and 2.8, began 4 days before the mainshock. The foreshocks concentrated in the immediate vicinity of the mainshock hypocenter. In this study we model the initiation process of the mainshock using seisograms recorded on the nearby stations of NIED Hi-net at frequencies up to 10 Hz. The initial rupture process is inferred by solving a linear system defined by the representation theorem for seismic sources. Instead of imposing a rupture velocity, the allowable slipping area on the fault is confined to lie within the radius 0.95*Vs*t. Once a node has been activated, it remains part of the solution at all later times. Thus, activated nodes may start, stop, restart, or never slip as required by the data. The system is regularized using a centered Laplacian operator to spatially smooth the model; there is no temporal smoothing. The system is solved using non-negative least-squares. We compare results obtained using synthetic seisograms for the Green’s functions (SGF) to ones using empirical Green’s functions derived from the foreshocks (Mj 2.7 - 2.8) (EGF). Even for the initial rupture which can be explained by simple models, it is found that solutions that use EGFs are more stable than those that use SGFs because some stations have strong path or site effects that are not captured by the synthetics at high frequency. The rupture initiates with a Mw 3 sub-event in the first 0.15 s, and then propagates away from the foreshock zone as a Mw 4 sub-event at 0.4 s. Our results show that the nucleation process was cascade-like.

Foreshock probability forecasting experiments in Japan, southern California and whole globe; and suggestion of space-time ETAS model with history-dependent magnitude frequency, Yoshikyo Ogata (Poster 059)

I am concerned with discrimination whether currently occurring earthquakes will be followed by a significantly larger earthquake or not. The forecasts are made by checking all combinations of earthquakes and applying a close time intervals and distances [1], and the discrimination is evaluated based on cluster tightness [2]. For example, the probability forecast model was estimated from the JMA hypocenter data of earthquakes of M≥4 in the period 1926-1993 [2]. Then we presented the performance and validation of the forecasts during 1994-2010 [3]. The forecasts perform significantly better than the unconditional (average) foreshock probability throughout Japan (M≥4). Similar performance can be seen in cases of southern California (M≥3.5) and global PDE (M≥4.7) catalogs. The frequency of the actual foreshocks is consistent with the forecasted probabilities. Furthermore, it is worth examining whether forecasting performance can be improved if we apply the space-time ETAS model driven by the history-dependent magnitude distribution that are predicted by the above foreshock discrimination procedure [4]. Namely, if an assumed future earthquake is within a space-time domain connected [1] to any previous earthquake, then its magnitude is forecasted by taking account of the foreshock probability. If the assumed next earthquake is in outside of the above region, then we forecast the magnitude using the original baseline distribution.

Reference:


The damage of the April 25 2015 Gorkha earthquake aroused much concern about seismic risks along the Himalayan front though the rupture occurred only in a deeper part of the megathrust. We still do not have enough information on both inter-plate and intra-plate sources, on crustal structures and attenuation relationships, and on site effects. The knowledge based on individual disciplines increase steadily, but the efforts for integration are still rather slow and not well organized. Our group had conducted an integrated studies on earthquake hazards for 5 years from 2010 to 2014 within a JICA-JST SATREP® project in India. The study consisted of GPS monitoring, paleoseismology, strong motion, and building sensor. 8 permanent GPS stations along 3 transects in NW India are revealing crustal movements across the Himalayan front. Paleoseismological studies were carried out on frontal and upper-plate faults at 7 sites. A few strike-slip faults in the upper plate were newly recognized and one of them, the Kangra Valley fault is supposed to be the source of the 1905 earthquake instead of the frontal fault (Malik et al. 2015 in press). This indicates a possibly near future frontal earthquake in NW India. The last large event from the central seismic gap is still continued, but one big event in 15th century S-1505 is being confirmed. The next earthquake in the gap will be the most serious issue for India and Nepal. 26 strong motion seismometers were deployed in the Ganga plain approximately between Delhi and Varanasi. The network has recorded global M>7 events and local M>5 events and the data were processed to model crustal structures and to develop ground motion forecasts. The building sensor group conducted a case study in Chandigarh, the largest city on the front, and revealed the vulnerability of buildings to assess the damages. The Indian counterparts continue all fields of investigations and seeking for more integration and coordination for hazard studies. In May 2015, a new SATREP project in Nepal is approved. This project aims at earthquake hazard risk mitigation through seismic potential evaluation, ground motion forecast, hazard assessment, hazard information and education. This will help to evaluate the seismic risks from Himalayan front in wider areas. (Science and Technology Research Partnership for Sustainable Development by Japan International Cooperation Agency and Japan Science and Technology Agency)


The High-F project seeks to advance SCEC’s physics-based, deterministic earthquake simulation methods with the long-term objective of improved ground motion estimates and seismic hazard models. As part of SCEC’s High-F research initiatives, a verification and validation exercise targeting deterministic ground motion prediction for the 2014 M5.1 La Habra, CA, earthquake is underway. Three codes currently participate in the comparisons, namely AWP-ODC and AWP-RWG (4th-order finite difference, FD) and Hercules (2nd-order finite elements, FE). We use a point source with mechanism derived from strong-motion data and a slip-time history obtained from a dynamic rough-fault rupture model with frequency content up to 5 Hz. The areal extent of the simulation region is 180 km x 135 km, with a target depth of 62 km. The model covers the entire greater Los Angeles basin and other structural features in its vicinity. The verification has progressed in incremental steps from a simple halfspace model via a smooth 1D crustal model, to ongoing efforts involving 3D crustal variation. The minimum S-wave velocity of the models is 500 m/s. We have compared results generated with lossless and frequency-independent anelastic attenuation, with additional tests exploring the significance of frequency-dependent Q. Our results from the verification exercise at the various complexity levels have allowed us to
Aftershock forecasting by using the Hi-net automatic hypocenter catalog in Japan, Takahiro Omi, Yosihiko Ogata, Katsuhiko Shiomi, Bogdan Enescu, Kaoru Sawazaki, and Kazuyuki Aihara (Poster 061)

Real-time aftershock forecasting is particularly difficult since a significant number of events that occur at short times after large mainshocks are missing in earthquake catalogs. To address this issue, we have recently developed a statistical model of incompletely detected aftershocks [1] and a forecast method by considering estimation uncertainty of forecasting models [2], and have shown the effectiveness of these methods for early aftershock forecasting. Further difficulty comes from the fact that we have to prepare forecasts based on a hypocenter catalog available in real-time, which is more incomplete than a revised catalog containing many manually reviewed events that are not available in real-time. Here we address this issue by analyzing the Hi-net automatic hypocenter catalog by the National Research Institute for Earth Science and Disaster Prevention, Japan. We compare performances of three forecasts respectively using the real-time Hi-net catalog, the revised JMA catalog, and the generic forecast model that represents standard aftershock activity in Japan. The forecasts are evaluated based on the final version of the JMA catalog. We find that the forecast by using the Hi-net catalog is just slightly worse than that by using the JMA catalog, but is significantly better than the generic model forecast. This result indicates that the real-time Hi-net catalog is useful for real-time aftershock forecasting in Japan.

Ref:

Deep-crustal rupture of an intraplate strike-slip fault system recorded by pseudotachylyte networks, Omero F. Orlandini, Kevin H. Mahan, Karl J. Mueller, and Michael L. Williams (Poster 122)

Magnitude-area scaling relations of large strike-slip earthquakes have been a source of uncertainty and contention in the earthquake community. The depth to which fault slip may propagate is as fundamental to this issue as it is difficult to constrain in the modern and paleoseismic record. Pseudotachylytes (PST) are veins of amorphous material generated by dynamic frictional instabilities; these findings provide a challenge to the seismological community to develop tools for measuring propagation of deep seismic ruptures into the lower crust during large magnitude earthquakes.
Observations of SAR coherence change have a demonstrated use for damage assessment for hazards such as earthquakes, tsunamis, hurricanes, and volcanic eruptions. These damage assessment maps can be made from imagery taken day or night and are not affected by clouds, making them valuable complements to optical imagery. The coherence change caused by the damage from hazards (building collapse, flooding, ash fall) is also detectable with intelligent algorithms, allowing for rapid generation of damage assessment maps over large areas at fine resolution, down to the spatial scale of single family homes.

We will present the progress and results we have made on automating the analysis of SAR data for hazard monitoring and response using data from both the Italian Space Agency’s (ASI) COSMO-SkyMed constellation of X-band SAR satellites, Sentinel 1a, and ALOS (1 and 2). Since the beginning of our project, our team has imaged deformation and coherence change caused by many natural hazard events around the world. Most recently, in the days following the April 25, 2015 M7.8 Gorkha earthquake, the JPL/Caltech ARIA project produced coseismic GPS and SAR displacements, fault slip models, and damage assessments from SAR coherence change. We will present progress on our data system technology that enables rapid and reliable production of imagery. We will also present results on demonstration products for LA Office of Emergency Management.

Progress Towards Improved Global Aftershock Forecasts, Morgan T. Page, Jeanne Hardebeck, Karen Felzer, and Andrew Michael (Poster 062)

Following a large earthquake, seismic hazard can be orders of magnitude higher than the long-term average as a result of aftershock triggering. Due to this heightened hazard, there is a demand from emergency managers and the public for rapid, authoritative, and reliable aftershock forecasts.

In the past, USGS aftershock forecasts following large, global earthquakes have been released on an ad-hoc basis with inconsistent methods, and in some cases, aftershock parameters adapted from California. To remedy this, we are currently developing an automated aftershock product that will generate more accurate forecasts based on the Reasenberg and Jones (Science, 1989) method. To better capture spatial variations in aftershock productivity and decay, we estimate regional aftershock parameters for sequences within the Garcia et al. (BSSA, 2012) tectonic regions. We find that regional variations for mean aftershock productivity exceed a factor of 10.

The Reasenberg and Jones method combines modified-Omori aftershock decay, Utsu productivity scaling, and the Gutenberg-Richter magnitude distribution. We additionally account for a time-dependent magnitude of completeness following large events in the catalog. We generalize the Helmstetter et al. (BSSA, 2006) equation for short-term aftershock incompleteness and solve for incompleteness levels in the global NEIC catalog following large mainshocks.

In addition to estimating average sequence parameters within regions, we quantify the inter-sequence parameter variability. This allows for a more complete quantification of the forecast uncertainties and Bayesian updating of the forecast as sequence-specific information becomes available.

A Petascale software framework for pseudospectral algorithms and multiscale phenomena simulations, Dmitry Pekurovsky (Poster 041)

Some of the most challenging simulations of modern computational science involve multiscale phenomena. Due to the difficulty of including and resolving all scales involved in a problem, these kinds of simulations tend to be very compute-intensive, and careful attention must be paid to efficient algorithms. P3DFFT is a software package providing efficient solutions for Fast Fourier Transforms and related algorithms in three dimensions. By using 2D domain decomposition it overcomes the scaling limitation of many other implementations. Its scalability has been demonstrated on up to half a million cores. P3DFFT is an open source software library (https://github.com/sdsc/p3dfft), has an easy to use interface, extensive documentation, and a growing user base. Applications of this library come from a range of scientific fields, including DNS turbulence, astrophysics, oceanography, X-ray crystallography and material science. Ongoing work involves expansion of the capabilities of this library, adapting it to a wider range of use scenarios as well as more diverse algorithms used in multiscale phenomena simulations, while maintaining scalability on post-Petascale platforms.

Comparing tremor migration styles in Cascadia and Guerrero using cross-station cross-correlations, Yajun Peng and Allan Rubin (Poster 156)

Non-volcanic tremor is generally interpreted as the seismic manifestation of slow slip, and tremor locations have been used extensively to infer deformation styles near the seismic-aseismic transition. Taking advantage of S-wave coherence among stations separated by a few km, we obtain high precision tremor locations in Cascadia using cross-station cross correlations, with either 3-station detectors (southern Vancouver), or 3-array detectors (Olympic Peninsula). We find that independent of any anisotropic fault fabric, tremor bursts usually migrated rapidly along the slowly-advancing main rupture front, even when it deviated strongly from the usual (along-dip) direction. We observe that rapid tremor reversals (RTRs) originate from the main front regardless of their size, and many start by propagating along the main front. This could be consistent with RTRs being triggered by a cascading failure of asperities, supporting that tremor, despite its generally low seismic moment release, sometimes affects the underlying slow slip significantly. The large-scale RTRs beneath the Olympic Peninsula repeatedly occupy the same source region, and the early repetitions were not tidally driven, suggesting additional fault weakening processes not accounted for by conventional rate-and-state friction laws.

Preliminary results of tremor locations beneath Guerrero, Mexico indicate that the cross-station method also performs well in this region. Similar to Cascadia, tremor activities in our study region were comprised mostly by short tremor bursts lasting minutes to hours. Many of these bursts show clear migration patterns, with recurrence intervals of a few km/day, comparable to those in Cascadia. However, the propagation of the main front was often not in a simple unilateral fashion. We observe many along-dip migrations with recurrence intervals of about a half day within a region about 10 km along strike and 35 km along dip, after the main front moved beyond this region, suggesting possible tidal modulation. These migrations appear not to originate at the main front, in contrast to tremor migrations from a few km to tens of km across observed in Cascadia (Rubin and Ambruster, 2013; Peng et al., 2015; Peng and Rubin, in preparation), but possibly similar to Shikoku, Japan (Shelly et al., 2007).

Systematic Detections of Missing Earthquakes from the Matched Filter Technique, Zhigang Peng, Lu Li, Zhuo Yang, Sizhuang Deng, Jing Wu, and Dongdong Yang (Poster 133)

Earthquakes occur every day in California and elsewhere around the world, either naturally or induced by human activity. While many have been identified and located by analysts in seismic network centers, a significant fraction of them are still missing, especially during intensive earthquake swarms, or immediately before or after moderate-to-large earthquakes. These missing events could be further identified by a semi-automatic matched filter technique, which uses waveforms of existing events as templates to scan through continuous data for new events with high similarities. Here I report our recent efforts in conducting a systematic detection of missing earthquakes around the world from this technique. These include detecting triggered earthquakes in China following the 2015 Mw7.8 Nepal earthquake, foreshocks of the 2010 Mw7.2 El Mayor-Cucapah earthquake, and early aftershocks of the 2013 Mw6.7 Lushan and Mw8.3 deep Okhotsk Sea earthquakes. We find a significant increase of normal-faulting earthquakes in southern Tibet following the Nepal mainshock, which matches well with the static Coulomb stress increase. On the other hand, transient increases of microseismicity in Chongqing and Beijing during the surface waves are best explained by remote triggering due to dynamic stress changes. We are in the process of analyzing other regions and updated results will be presented at the meeting.

Micromechanics based off-fault permeability evolution during earthquakes, Thibaut Perol and Harsha S. Bhat (Poster 280)

We investigate the role of off-fault damage and damage-enhanced off-fault permeability on earthquake nucleation on faults surrounded by a relatively high pore fluid pressure. This mimics a situation in which
wastewater, injected in a reservoir, diffuses towards a fault. First, we develop a micromechanical model for permeability evolution in brittle materials that are strain rate sensitive. We extend the micromechanical model developed by Bhat et al. (2012) in which the constitutive description of a brittle material is governed by micro-cracks to relate damage and inelastic strains. This allows evaluating the micro-cracks aperture, plugged into Gueguen and Dienes (1989) to find the permeability. Additionally, we present preliminary results on the role of off-fault dynamic permeability changes on earthquake nucleation by solving the coupled dynamic rupture propagation and pore fluid pressure diffusion.

Reproducing Magnitude-Invariant Stress Drops in Fault Models with Thermal Pressurization, Stephen M. Perry and Nadia Lapusta (Poster 281)

Stress drops, observed to be magnitude invariant, are a key characteristic used to describe natural earthquakes. Theoretical studies and lab experiments indicate that dynamic weakening, such as thermal pressurization, may be present on natural faults. At first glance, these two observations seem incompatible, since larger events may experience greater weakening and should thus have lower final stresses. We hypothesize that dynamic weakening can be reconciled with magnitude-invariant stress drops due to larger events having lower average prestress when compared to smaller events. The additional weakening would allow the final stresses to also be lower, but the stress drops may be similar.

To explore this hypothesis, we study long-term earthquake sequences on a rate-and-state fault segment with enhanced dynamic weakening due to thermal pressurization using a fully dynamic simulation approach. Our seismogenic segment has uniform friction properties. Our results show that such models can explain both the stress drop magnitude invariance and observationally inferred breakdown energy increase for a range of event sizes. Smaller events indeed have larger initial stresses than medium-sized events, and we get roughly constant stress drops for events spanning up to five orders of magnitude in moment. These events also have increases in breakdown energy consistent with observations. We are working toward quantifying the robustness of these findings by exploring a range of fault properties, including the efficiency of dynamic weakening. Note, however, that our largest, segment-spanning events spanning up to five orders of magnitude in moment. Significant variations in SH orientation occur at length-scales less than 1 km, with a prominent east of short-length-scale variations in SH orientation also present. In the Wilmington oil field located in the Thums-Huntington Beach Fault and the NIF, data from 11 deviated wells yields a pattern of elongation directions, which differs from the more complex pattern obtained for the Huntington Beach wells located ~12 km to the southeast. The short-length-scale variations in SH direction are attributed to the proximity to faults, fault segmentation, or fault overlap; and indicate the likely complexity that may be found in stress fields near other active faults.

Release & Evaluation of the Statewide Community Fault Model (SCFM) Version 3.0 and Continued Updates to the SCEC CFM 5.0, Andreas Plesch, John H. Shaw, Craig Nicholson, Christopher C. Sortien, and SCFM 2015 workshop participants (Poster 217)

The California Statewide Community Fault Model (SCFM) Version 3.0 is now a comprehensively reviewed and evaluated statewide model that consists of the southern California CFM 4.0 and more than 190 fault representations for northern California. While CFM 4.0 was previously reviewed and formally released (Nicholson et al., 2014), in recent years, the northern California component also underwent substantial updates and improvements including the addition of about 40 new fault representations. To facilitate community review and a thorough evaluation of the updated, complete SCFM, a group of about 30 colleagues were invited to a well attended workshop hosted by the USGS at Mono Lake. For this review, a complete fault documentation spreadsheet of SCFM was prepared with identifying information, such as average strike and dip, and source material on each fault. As SCFM represents faults in 3D, we also developed a SCFM viewer based on SSEC VDO to enhance model visualization and comparison of 3D fault surfaces, imagery, Qfault traces and a catalog of relocated hypocenters. All materials and detailed evaluation instructions including ranking guidance were made available through a public web page. The workshop included members of the USGS, PG&E, Lettis, CGS and SCEC among others. It yielded two main results: often quite critical evaluations in the form of numerical and/or qualitative ranking of alternative fault representations, and strong guidance on future model improvements. Based on these evaluations, a set of 126 fault representations was selected to comprise a primary or preferred fault model within SCFM 3.0.

In southern California, as a result of recent updates, CFM 5.0 now contains 90 distinct fault zones, or separate fault systems, defined by over 300 individually named faults, with over 350 new or updated primary and alternative 3D fault representations added to CFM since Version 3.0. Improvements to CFM since 2014 include completion of an updated and expanded fault set for active faults in the Mojave, additional detailed faults in the offshore Borderland, and initial development of alternative models and an expanded fault set involved in the complex 3D deformation in the Ventura Special Fault Study Area. In addition, within the Gocad CFM environment, updated macros were developed to visualize focal mechanisms as beachballs or as selected nodal planes to better check for internal consistency between modeled CFM surfaces and dominant slip orientations in 3D.

Analytic model for landslide effects on cosmogenic inheritance: Implications for landform ages and fault slip rates, Veronica B. Prush and Michael E. Oskin (Poster 094)

Dating of alluvial fan surfaces using cosmogenic nuclides (CNs, i.e. 10Be, 26Al, 36Cl, etc.) is an important tool for constraining fault slip rates from landform offsets. However, the utility of CNs is hampered by the effects of inheritance, which is the fraction of a CN concentration attributed to cosmic ray exposure prior to deposition. Inheritance results in a long-tailed skew in the distribution of apparent surface sample ages. Inheritance has been quantified using a variety of methods, including sampling catchment source material, modeling the exponential falloff in CN concentration with depth, or by removing outliers that skew the age distribution from an assumed Gaussian distribution. Many studies that utilize the latter method acknowledge that goodness-of-fit statistics
suggest a normal distribution is inappropriate for such datasets. Because inheritance is a function of erosion rate and many areas of interest are located in high erosion-rate settings dominated by landslides, we have developed an analytical model for inheritance that accounts for landside effects. Landslides are power-law distributed events (larger events are less frequent, but accomplish more erosion than smaller events). We model the average return time between landslides at a point in the landscape as a Poisson process. Convolving this with the exponential ingrowth of CNs on an exposed, steadily eroding surface results in a generalized pareto distribution of CN inheritance in the landscape, and thus also in the sediment produced from that landscape. Using this model, we fit the distributions of sample ages, including previously identified outliers, for a number of example studies from southern California. Based on our model, we show that the youngest sample age is closest to the true age for the surfaces, and that the shape of the sample distribution informs the robustness of this result and reveals new information on relative impact of landslides on the landscape. Younger ages, and thus higher fault slip rates, are predicted from offset landforms dated with a population of individual clasts.

Tectonic geomorphology of the Santa Ynez Range: DEM and GIS analysis of geomorphic indices to evaluate Quaternary uplift along the Santa Ynez fault, Santa Barbara County, California, Ani M. Pytlewski and Nate W. Onderdonk (Poster 104)

The east-west trending Santa Ynez fault (SYF) is a major structure (>120 km in length) that marks the northern edge of the Santa Ynez Range in southern California. Clear lineaments, steep topography, and potentially offset terrace deposits of the Santa Ynez River along the northern range front suggest that the fault has had, and continues to have, a significant impact on the tectonic evolution of the Santa Ynez Range. However, Quaternary slip history, amounts, and kinematics are not well understood. This information is crucial to identifying a potentially seismicogenic structure and its mechanistic link in shaping the current topography. Therefore, the faults influence the growth of the Santa Ynez Range and importance for tectonic history, topographic development, and seismic hazard remain unknown. In this study we present DEM-based GIS and morphometric analyses combined with field observations to examine the tectonic geomorphology of the Santa Ynez Range in relation to activity on the SYF. GIS and geomorphic data show over 20 perturbed longitudinal stream profiles with knick points in homogenous rock along both the northern and southern range fronts. However, quantitative geomorphic indices show lower mountain front sinuosity (Smf) values (1.06 – 1.12) and valley floor-to-height ratio (Vf) ratios (0.19 – 1.68) in the northern Santa Ynez Range. Combined with shorter (<6 km), steeper drainage geometries, these measurements suggest a greater degree of tectonic activity along the northern Santa Ynez Range front than the southern, most likely due to dip-slip displacement on the Santa Ynez fault. Multiple levels of fluvial terraces (likely Pleistocene in age) appear to be offset along the Santa Ynez fault consistent with the interpretation of recent uplift along the fault. Ongoing field mapping, correlation, and OSL dating of these terraces will test this hypothesis, and allow us to quantify the long term Quaternary slip rate on the SYF.

Eikonal noise-based tomography of the Southern California plate boundary region, Hongrui Qiu, Dimintzi Zigon, Fan-Chi Lin, and Yehuda Ben-Zion (Poster 182)

Eikonal noise-based tomography can be used in places with good station coverage to determine directionally-dependent surface wave phase velocities. This is done here for the southern CA plate boundary region. We first calculate noise cross-correlation functions for year 2014 between 346 stations in area. Rayleigh wave phase travel times are then derived for each station pair between periods of 5 and 13 sec using frequency-time analysis. For each common station acting as a virtual source, the available travel time measurements with sufficient quality are used to construct a travel time map to all other stations. To solve the 2pi ambiguity associated with cycle skipping, a linear straight ray inversion is conducted as in Zigone et al. (2015) to obtain a reference model. By solving the eikonal equation, we then evaluate both phase velocity and propagation direction at each location for each virtual source. Isotropic phase velocities and 2-psi azimuthal anisotropy are determined statistically with measurements from all the virtual sources. The results agree well with previous observations of Zigone et al. (2015) in the overlapping area. Clear velocity contrasts and low velocity zones are seen near the San Andreas, San Jacinto, Elsinore and Garlock faults. We also find 2-psi azimuthal anisotropy with fast directions parallel to geometrically-simple fault sections. Updated results will be presented in the meeting.

Preferential earthquake-nucleating locations on faults determined by heterogeneous direct- and evolution-effect parameters of rate- and state-dependent friction, Sohohn Ray and Robert C. Viesca (Poster 276)

Rock friction experiments show that low-velocity fault friction may have a direct and subsequent evolutionary response to changes in slip velocity; the magnitude of which are respectively proportional to parameters a and b in constitutive relations of such rate- and state-dependent friction [e.g., Dieterich 1979; Ruina, 1983]. When a and b are uniform on a fault, translational invariance implies any location is a potential nucleation site, the choice determined by pre-instability conditions and external forcing. With heterogeneous parameters, symmetry is broken, which can create preferred nucleation sites. Recent work showed such heterogeneity does create favorable sites (Ray and Viesca, last meeting).

Here we study how the locations of preferred sites are influenced by the distributions of:

(i) relative rate-weakening parameter (0 < a/b < 1) and
(ii) absolute rate-weakening parameter (a-b < 0).

We examine the influence of (i) and (ii) by varying one or varying both (similarly or disparately). The smallest wavelength of variation is comparable to or larger than the size of the developing instability. We consider that elasticity may set either nonlocal (slip between half-spaces) or local (slip below and near a free surface) interactions. We use a dynamical system approach (Viesca, in prep) complemented by solutions for slip rate and state evolution during instability development to determine the preferred sites. When (i) varies and (ii) is fixed or varied, an instability develops where relative rate-weakening is locally or globally strongest (a minimum of i) for both types of elastic interactions. This may or may not coincide with the strongest absolute rate-weakening (a minimum of ii). This indicates that parameter (i) is comparatively dominant in deciding the location of a slip instability. However, fixing (i) and varying (ii), we find that elasticity contributes to determining the preferred site: i.e., nucleation occurs at the local minimum and maximum of (ii) for nonlocal and local interactions, respectively. Additionally, the number of potential nucleation sites increases if the constituent wavelengths of parameter variation are small compared to a characteristic length scale for the developing instability. We find that the finite number of densely spaced preferential sites can complicate the prior determination of the location of instability.

Hybrid broadband ground motion simulation of the 2010-2011 Canterbury earthquakes, Hoby N.T. Razafindrakoto, Brendon A. Bradley, Ethan Thomson, and Robert W. Graves (Poster 018)

This study presents hybrid broadband ground motion simulations of the 2010-2011 Canterbury earthquakes. Simulations are conducted for ten events ranging from Mw4.7-7.1, four of which are represented as finite-fault models and six as point sources. Both 1D and various 3D velocity models for the region are also examined. Using the 1D velocity model, it is observed that simulated peak ground velocities (PGV) are unbiased with respect to observations. The simulated short period (T<1s) spectral accelerations (SA) on the other hand decay faster compared to the observed and the empirical ground motions for source-to-site distances, Rrup>50km, possibly as a result of the approximate Moho-depth or truncation in the summation of multiple ray paths for the high-frequency simulation. Long period SA ordinates are also under-predicted using the 1D velocity model. For certain stations, the analyses of within-event residuals reveal systematic site effects that are consistent with the observations from empirical ground motion modeling. Finally, the use of a 3D crustal structure eliminates systematic biases at long vibration periods and improves the fit with respect to the observed intensity measures.
Long-term fault slip rates typically are assumed to sum to total plate velocity in kinematic models of strike-slip plate boundaries. However, in several locations in southern California, slip rates determined from geodetic data differ from geologic estimates. That sites of geologic investigation are not uniformly distributed along fault systems may compound these discrepancies. For example, releasing steps where sediment accumulates and leaves a continuous record of slip are favored trenching sites, but may not yield representative rates. We investigate the influence of site location on slip rate with: 1) a parametric study of step geometry using 2D mechanical models and 2) case studies of active southern California faults using 3D models. The suite of 2D models reveals how fault length, friction and step geometry (fault overlap and perpendicular separation) affect fault slip and off-fault strain over geologic time scales. We calculate each system’s kinematic efficiency and determine the probability that a site along the fault will reveal a representative rate (i.e. mean ± 1 mm/yr). Faults with longer segments are most efficient, accommodating ~56-86% of plate displacement. Systems with short segments, large overlap and large spacing are the least efficient, accommodating as little as 24% of plate displacement. We find that the probability of sampling a representative slip rate is greater along short faults, due to the low overall slip magnitudes relative to typical errors, and is inversely correlated with the kinematic efficiency of the system. For longer faults the probability of sampling a representative rate is much lower and is most strongly controlled by the shape of the slip distribution rather than the overall efficiency. Geologic slip rates from within the releasing steps along the San Jacinto Fault in southern California show reduced rates relative to other sites. This is consistent with the results of 3D models of the San Jacinto fault undertaken for this study. We find that rates within the step are within mean values for the faults, while those along the segments are not. The results of this study suggest that sites located near steps between long fault segments are most likely to yield representative geologic slip rate estimates.

Earthquake likelihood models derived from multiplicative combinations of earthquake and fault-based variables, David A. Rhodees, Annemarie Christophersen, and Matthew C. Gerstenberger (Poster 054)

We derive a set of multiplicative hybrid earthquake likelihood models which combine earthquake and fault data for the New Zealand CSEP testing region. In these models, the cell rates in a spatially uniform baseline model are scaled using selected subsets of five covariates derived from the magnitudes and locations of past earthquakes, the location of the boundary between the Australian and Pacific plates and the location and slip rate of mapped faults. The hybrid model parameters are optimised for earthquakes of magnitude 5 and greater over the period 1987-2006, and tested on updates from the period 2007-2014. No updating of models is undertaken during the fitting or testing period. In the tests we consider two cases of the earthquake-based covariates: using all data prior to 1987 and 2007, respectively. Hybrids containing the earthquake-based covariates perform better in the latter case. The most informative hybrid models in the fitting and testing period are comprised of three and four covariates, respectively, including both earthquake- and fault-based variables. Proximity to mapped faults is overall the most informative individual covariate. The results can be used to improve earthquake source modelling for probabilistic seismic hazard analysis.

Heating and weakening of faults during earthquake slip, James R. Rice (Invited Talk Sun 18:00)

Field and borehole observations of active fault zones show that earthquake shear is often highly localized to principal slipping zones of order 10s of microns to a few mm wide, lying within a broader gouge layer typically of order of a few cm wide, and with all that being a feature located within a much broader zone of cracked/damaged rock bordering the fault over a scale of 1-10s m width. Fault gouges are often rate strengthening, especially at higher temperatures, and are then resistant to shear localization under typically slow laboratory deformation rates. However, extreme localization due to shear heating and development of highly elevated pore pressure is shown to be a predicted and lab-validated consequence of rapid straining. That pressurization can develop in fluid which pre-exists in the gouge as groundwater, or in the volatile H2O or CO2 phases emerging at high pressure from thermal decomposition reactions in hydrated silicates (clays, serpentines) or carbonates. These processes join the ubiquitous weakening by flash-heating at frictional asperity contacts to make conventional friction properties almost irrelevant at seismic slip rates. Results have implications for the mode of slip-rupture propagation in earthquakes (self-healing vs. crack-like) and shed new light on why statically strong faults like the SAF can produce large ruptures which show negligible localized heat outflow and little evidence of melt formation, at least in the shallow to middle crust. As some have recently advocated, evaluating the susceptibility of major fault zones to extreme thermal weakening, when feasible, should become a component of seismic hazard analysis.

Is the Southern San Andreas Fault Really Overdue or Just Late in the Cycle?, Thomas K. Rockwell (Poster 080)

Compilation of paleoseismic data from several dozen trench sites in the southern San Andreas fault system, along with more precise dating of Lake Cahuilla sediments that cross many of these sites, allows for sequencing of the past 1100 years of large (M7 and larger) earthquakes for the southern 150 km of the main plate boundary system. Major faults capable of larger earthquakes include the San Andreas, San Jacinto, Elsinore, Imperial, Cerro Prieto, Laguna Salada, and possibly the Earthquake Valley faults. Displacement data have been generated for most of these faults for the past one to several events. Using these observations on timing and displacement in past large earthquakes, and assuming reasonable seismogenic thicknesses, estimates of moment release through time can be made. Based on these estimates, at least three generalizations are clear: 1) M7 and larger earthquakes account for most of the moment release in the southern San Andreas fault system over the past 1100 years; 2) large earthquakes on individual faults are quasi-periodic but display a relatively high coefficient of variation in recurrence time, similar to most long California records; and 3) moment release has temporally varied during the past 1100 years but within potentially predictable bounds. Together, the record suggests that the
southern San Andreas fault is late in the cycle but not necessarily “ overdue”, and that a systems level approach may be more accurate in long term earthquake forecasting than data generated from a single element of the fault system.

**Testing the SH1D Assumption for Geotechnical Site and Basin Response Using 3D Finite Difference Modeling, Arthur J. Rodgers and Arben Pitarka (Poster 012)**

Current state-of-practice of geotechnical site response and soil-structure analyses generally assume a vertically propagating horizontally polarized plane wave is incident on a plane-layered (one-dimensional) soil column. Ground motions representing the wavefield incident to the bedrock base of the soil column are developed from observed and sometimes scaled time-histories or synthesized by various methods. The site-specific ground motion at the surface is then computed from the response of the soil column to the bedrock incident wavefield, possibly including non-linear response of the geotechnical near-surface. This is the so-called SH1D assumption. While this approach is widely used, it ignores important complexities of the incident wavefield. Specifically, the standard approach assumes: 1) the incident wavefield is only composed of vertically propagating body waves; 2) ignores oblique incidence; and 3) neglects the three-component nature of the wavefield that includes surface waves and rotational motions. Surface waves often carry much of the seismic energy and can excite all three components of motion. Therefore, it seems most appropriate to include the most representative characterization of the incident wavefield in site-specific analyses. We are performing parametric studies with three-dimensional (3D) elastic finite difference simulations to compare the near-surface response of sedimentary basins to horizontally polarized planes (arbitrary incident) and point source (double couple) earthquakes. Simulations involve simple, parametric representations of basin geometries and layered material properties of the sedimentary basin and surrounding hard rock. We compare the frequency-dependent site response for different excitations and attempt to quantify the differences between the plane-wave and fully 3D basin response.

**Geodesy-based estimates of loading rates on faults beneath the Los Angeles basin with a new, computationally efficient method to model dislocations in 3D heterogeneous media, Christopher Rollins, Walter Landry, Sylvain Barbot, Donald Argus, and Jean-Philippe Avouac (Poster 204)**

North-south compression across the Los Angeles basin is accommodated by slip on thrust faults beneath the basin that may present significant seismic hazard to Los Angeles. Previous geodesy-based efforts to constrain the distributions and rates of elastic strain accumulation on these faults [Argus et al 2005, 2012] have found that the elastic model used has a first-order impact on the inferred distribution of locking and creep, underlining the need to accurately incorporate the laterally heterogeneous structure and complex fault geometries of the Los Angeles basin into this analysis. We are using Gamma [Landry and Barbot, in prep.], a newly developed adaptive-meshing finite-difference solver, to compute elastostatic Green’s functions that incorporate the full 3D regional elastic structure provided by the SCEC Community Velocity Model. Among preliminary results from benchmarks, forward models and inversions, we find that: 1) for a modeled creep source on the edge dislocation geometry from Argus et al [2005], the use of the SCEC CVM material model produces surface velocities in the hanging wall that are up to ~50% faster than those predicted in an elastic halfspace model; 2) in sensitivity-modulated inversions of the Argus et al [2005] GPS velocity field for slip on the same dislocation source, the use of the CVM deepens the inferred locking depth by ~3 km compared to an elastic halfspace model; 3) when using finite-difference or finite-element models with Dirichlet boundary conditions (except for the free surface) for problems of this scale, it is necessary to set the boundaries at least ~100 km away from any slip source or data point to guarantee convergence within 5% of analytical solutions (a result which may be applicable to other static dislocation modeling problems and which may scale with the size of the area of interest). Here we present updated results from inversions of an updated GPS velocity field [Argus et al, AGU 2015] for the inferred distribution of locking and creep on 1) the Argus et al [2005] dislocation source and 2) major fault planes in the SCEC Community Fault Model, using the full 3D SCEC velocity model in addition to vertically stratified and elastic halfspace models.

**Full source tensor inversions of San Jacinto fault zone earthquakes using 3D Green’s functions with the gCAP3D method, Zachary E. Ross, Yehuda Ben-Zion, Lupei Zhu, and Robert W. Graves (Poster 166)**

We perform a full source tensor inversion of several M > 4 earthquakes that occurred in the San Jacinto fault zone in southern California, with an emphasis on resolving signatures of volumetric source changes. A previous study on these events with Green’s functions based on a 1D velocity model identified statistically significant explosive isotropic components (Ross et al. 2015). Here we use the SCEC 3D Community Velocity Model to derive Green’s functions with source-receiver reciprocity and finite-difference calculations based on the code of Graves (1996). About 50 stations are used at epicentral distances of up to 55 km. The inversions are performed using the ‘generalized Cut and Paste’ method, which includes CLVD and isotropic components (Zhu and Ben-Zion 2013). The derived source tensors are compared to the results of the previous study based on the simplified 1D velocity model. The results are analyzed with bootstrap analysis to estimate uncertainties involved. Additional tests are performed using synthetic waveforms to study the effects of neglecting various features on the source inversions.

**Quantification of ground motion reductions by fault zone plasticity, Daniel Roten, Kim B. Olsen, Steven M. Day, and Yifeng Cui (Poster 008)**

We explore the effects of fault zone nonlinearity on peak ground velocities (PGVs) by simulating a suite of surface rupturing earthquakes in a visco-elastic model; 3) when using finite-difference or finite-element models with the AWP-OCD 3D finite difference code, cover magnitudes from 6.5 to 8.0, with several realizations of the stochastic stress drop for a given magnitude. We test three different models of rock strength, with friction angles and cohesion values based on criteria which are frequently applied to fractured rock masses in civil engineering and mining. We use a minimum shear-wave velocity of 500 m/s and a maximum frequency of 1 Hz. In rupture scenarios with average stress drop (~3.5 MPa), plastic yielding reduces near-fault PGVs by 15 to 30% in pre-fractured, low-strength rock, but less than 2% in massive, high quality rock. These reductions are almost insensitive to the scenario earthquake magnitude. In the case of high stress drop (~7 MPa), however, plasticity reduces near-fault PGVs by 35 to 45% in rocks of low strength and by 7 to 15% in rocks of high strength. Because nonlinearity reduces slip rates and static slip near the surface, plasticity acts in addition to, and may partially be emulated by, a shallow velocity-strengthening layer. Fault zone plasticity also limits the occurrence and severity of extreme ground motions. For an M 8.0 earthquake with average stress drop, for example, the largests PGVs are reduced from 4.4 m/s to 4.0 m/s in strong ground to less than 3.2 m/s in average and poor quality rock. These simulation results suggest that nonlinear effects may be relevant even at long periods, especially for earthquakes with high stress drop.

**Dynamic imaging of strain and stress evolution in laboratory earthquakes with the ultra high-speed digital image correlation technique, Vito Rubino, Ares J. Rosakis, and Nadia Lapusta (Poster 266)**

Dynamic imaging of strain and stress during rupture enables unprecedented observations of key rupture features as well as decoding of the nature of friction. We present the dynamic evolution of strains and stress drop in our dynamic rupture experiments. We employ a laboratory earthquake setup to study dynamic ruptures in a highly instrumented setting, where we produce both supershear and sub-Rayleigh events. Earthquakes are mimicked in the laboratory by dynamic rupture propagating along the inclined frictional interface of two quadrilateral Homalite plates prestressed in compression and shear. The diagnostics previously employed in this setup include temporally accurate but spatially sparse laser velocimetry measurements as well as a sequence of full-field photoelastic images. These measurements have been successfully employed to capture important rupture features but they do not give enough information to characterize the full-field strains and stresses. In this study, we obtain the experimental sequences of full-field displacements, velocities, strains and stresses produced under a wide range of slip rates by our newly developed technique of ultra high-speed digital image correlation (DIC). This is the first technique capable of
imaging spatial and temporal variations in strains and stresses during spontaneously developing experimental dynamic rupture. This technique combines pattern-matching algorithms with ultra-high-speed photography and highly tailored analysis to obtain full-field time histories. We have verified the accuracy of the measurements by comparing the velocity time-histories at selected locations with the measurements using the well-developed technique of laser velocimetry. The newly developed ultra-high-speed full-field imaging technique can also be used to obtain unprecedented measurements of evolving dynamic friction during dynamic rupture, and we will report on our initial results on the dynamic friction evolution.

Wastewater Disposal, Hydraulic Fracturing, and Seismicity in Southern Kansas, Justin L. Rubinstein, Fabia Terra, and William L. Ellsworth (Poster 143)

The concurrent appearance of seismicity with the expansion of oil and gas activities in southern Kansas after September 2012 suggests that industrial operations are inducing earthquakes. These earthquakes occur in a portion of the Missippian Lime Play, an oil and gas field stretching from central Oklahoma to northwestern Kansas. As has been seen in other areas of high-rate wastewater injection, the seismicity appears to be driven by the disposal of produced water by injection into deep sedimentary formations. We focus on an 1800 km² region in Harper and Sumner counties where a temporary, 14-station seismic network deployed by the USGS monitors ongoing seismicity. Regional and national networks supplement the temporary network. Earthquake locations and magnitudes are reported by the USGS, and high-rate wastewater injection sites are maintained in the National Wildlife Refuge in northwest Nevada for over 13 months as of Aug. 2015. The Nevada Seismological Laboratory has located over 5700 earthquakes per day in the study area. The earthquake rate in the 87 days following the change in regulations dropped to 1.8 M2 and 0.2 M3 earthquakes per day in the same region over the same amount of time. The two largest earthquakes (M4.1 and M4.0), however, occurred after the new regulation was put in place.

Update on Persistent Seismicity at Sheldon National Wildlife Refuge, Northwest Nevada from July 2014 to Present, Christine J. Ruhl and Kenneth D. Smith (Poster 131)

Unusually long-duration swarms have persisted near the Sheldon National Wildlife Refuge in northwest Nevada for over 13 months as of Aug. 2015. The Nevada Seismological Laboratory has located over 5700 earthquakes since the first ML 3.0 event on 12 Jul. 2014, with many more detections observed since deployment of temporary station COLR about 15 km from the source area on 17 Nov. 2014. The entire sequence to date includes over 217 (21) earthquakes ≥ ML 3.0 (≥ ML 4.0), occurring in distinct bursts of activity with no clear mainshock. Seven earthquakes between MW 4.5 and 4.7 have occurred: four between 5 Nov. and 13 Nov. 2014, one on 22 Jan. 2015, and two on 16 and 27 Jul. 2015. The most energetic periods of Nov. 2014 and Jul. 2015 were preceded by relative quiescence lasting 1 ~ 2 months. We develop a set of double-difference relative periods of Nov. 2014 and Jul. 2015 were preceded by relative quiescence and Ma1.5 earthquakes are included in the rule of wastewater disposal in 5 areas in southern Kansas. Since this regulation has been in place, earthquake activity has decreased by 40-50%. In the 87 days between January 1, 2015 and March 29, when the order was enacted, there were on average three M2 earthquakes and 0.3 M3 earthquakes per day in the study area. The earthquake rate in the 87 days following the change in regulations dropped to 1.8 M2 and 0.2 M3 earthquakes per day in the same region over the same amount of time. The two largest earthquakes (M4.1 and M4.0), however, occurred after the new regulation was put in place.

Experimental Investigation of Dynamic Weakening in Granite by Using a New Biaxial Machine, Ormid Saber, Frederick M. Chester, and Jorge L. Alvarado (Poster 252)

Investigation of the transient friction response during a change from sliding at low slip rates to high rates (~1 m/s) is necessary to model earthquake nucleation, rupture propagation, and the diversity in modes of fault slip. Recent advances in testing friction at seismic slip rates by using rotary- and impact-shear machines have shown dynamic weakening friction at velocities greater than ~0.01 m/s. Several thermally activated weakening mechanisms have been proposed for dynamic weakening such as flash heating, pore fluid pressurization, melt generation, and powder lubrication. Further advances can be achieved in understanding velocity dependence of friction by developing machines that are able to generate step-like velocity jumps from low to seismic slip rates with high acceleration in order to investigate transient constitutive behavior. We have developed a machine that is able to impose velocity-steps between low to high slip rates under accelerations as high as 100g (more than an order of magnitude higher than rotary machines). The machine is able to perform friction experiments in both triaxial and double-direct configurations, and ultimately will be equipped with a pressure vessel to conduct experiments on confined samples at high normal stresses (up to 100 MPa) with independent pore and confining pressures. We present our first results of double-direct shear experiments using the machine on bare surface of granite (Westerly), at normal stresses of 2 to 20 MPa, in which the samples are slid at 1 mm/s for several mm of slip and then velocity is stepped up to a constant slip rate in the range of 10 to 1000 mm/s. These experiment results are consistent with previous work on similar materials in which flash heating and generation of nanopowders are considered the main cause of weakening. Dynamic weakening occurred in all the tests, and the magnitude of the steady-state friction depends primarily on normal stress velocity. The results show small critical slip for weakening (0.5-25 mm) and the change in friction is a function of product of velocity and normal stress (rate of heat generation due to frictional work). The experiments are ended after a total slip of 40 mm by decelerating the sample to stationary condition during which frictional recovery is observed. The friction-velocity curves exhibit a hysteresis loop during weakening and healing phases which may reflect the change in temperature or surface structure during the slip.

Segmentation Along the Newport-Inglewood Rose Canyon Fault Zone: Implications for Rupture Propagation, Valerie J. Sahakian, Jayne Bormann, Neal Driscoll, Alistair Harding, Graham Kent, and Steve Wasnouisky (Poster 098)

The Newport-Inglewood/Rose Canyon fault zone (NIRC) is an active component of the southern California strike-slip fault system in the Pacific-North American plate boundary. Despite its close proximity to densely populated coastal regions of Southern California, the NIRC fault geometry and expected earthquake behavior are poorly constrained. As a result of these uncertainties, current hazard models lack critical information regarding potential earthquake magnitudes and ground shaking caused by rupture on the offshore portion of the fault. Here, we present an improved characterization of the NIRC fault zone’s architecture and segmentation. We employ nested marine seismic reflection data of varying vertical resolutions to map the NIRC location, strike, dip, and stepovers based on subsurface observations. These reflection data were collected in 1979, 2006, 2008, 2009 and 2013. We
identify four main geometrical fault segments separated along strike by three stepovers between 0.5 and 3 km in width, whereby width is measured as the horizontal distance between fault strands or termini. Empirical studies of rupture propagation show that past earthquake ruptures in other regions have propagated across discontinuities of this width. We additionally employ a quantitative approach to constrain the potential earthquake magnitude for the NIRC fault zone by modeling the Coulomb stress changes that result from possible rupture initiation scenarios. Earthquakes initiated on the central fault strand by Carlsbad Canyon favor through-going rupture across the entire length of the NIRC fault zone. Additionally, the modeling results suggest that the southernmost stepover by La Jolla may act as an inhibitor to through-going rupture due to the strike and dip of the adjacent fault despite the stepover’s short width. Finally, our stress modeling results suggest that the maximum potential magnitude of an earthquake rupturing all of the mapped offshore segments of the NIRC fault zone is Mw 7.5.

Sub-surface investigation of geomorphic offsets and implications for recent slip along the Carrizo section of the San Andreas fault, CA, James B. Salisbury, J.R. Arrowsmith, T.K. Rockwell, S.O. Aksiz, A.M. Williams, and L. Grant Ludwig (Poster 087)

We excavated trenches across several active gullies at Van Matre Ranch (VMR) in the Carrizo Plain (35.152798°, -119.697454°) to investigate the interaction of climate-modulated channel incision and aggradation, and earthquake punctuated geomorphic offsets. The active trace of the San Andreas fault (SAF) at VMR is narrow and well-expressed in the landscape and preserves several closely-spaced, similarly-sized offset channels and beheaded gullies, as interpreted from previous studies. We targeted four of the smallest discernible offsets initially investigated in the field by Sieh (1978), three of which were subsequently re-analyzed using the B4 lidar data (Zielke et al., 2010 and 2012) [Sieh/Zielke offsets: 46, 47/ZA8401a, 48/ZA8405a, 49/ZA8410]. Three of the four beheaded gullies have associated sub-surface channel deposits from which we refined existing surface slip measurements and sampled for optically stimulated luminescence (OSL) estimates of initial channel incision/fill. At our Trench 1 (focused on Sieh 1978 offset 46) we found no associated sub-surface channel deposits from the ‘beheaded gully’ and conclude that the swale is actually a fosse (depression) between two small (~10 m radius) offset alluvial fans. At trench 1, however, we discovered a buried channel fill (unrelated to the fosse) a offset total of ~14 m. Along with the ~4 m offset of the youngest alluvial fan (based on the reconstruction of the fan apex), these data suggest that slip in the Mw 7.9 1857 earthquake was ~4 m at the VMR site and the additional 10 m of offset for the buried channel fill occurred in at least one and possibly more prior earthquakes. This also suggests that there have been no major incision events at VMR since the incision and filling of the ~14 m offset channel.

Wide-swath Interferometry of the San Andreas Fault System from Sentinel-1A and ALOS-2, David T. Sandwell, Xiaohua Xu, Eric Lindsey, Xiaopeng Tong, Paul Wessel, and Pablo Gonzalez (Poster 194)

Two new InSAR satellites are providing complete coverage of the San Andreas Fault system with frequent observations and short interferometric baselines. Sentinel-1A is a C-band radar, mostly operated in a new wide-swath mode (TOPS), having a 250 km-wide swath and ascending/descending coverage at a 24-day interval. ALOS-2 is an L-band radar operated in a ScanSAR mode (350 km swath) on descending orbits and standard swath-mode (70 km) on ascending orbits on a 42-day interval. Both satellites have been operational for about 1 year and thus have collected sufficient data to begin wide-area time series analysis. For example for the Los Angeles area there are currently 8 repeats along ascending/descending tracks of ALOS-2 and 13/13 repeats along ascending/descending tracks of Sentinel-1A.

We are enhancing the GMTSAR software package to enable systematic processing of these two new data types. The ALOS-2 ScanSAR processing is performed using mostly standard methods. Interferograms, constructed from each of the 5 subswaths, are combined (no adjustments) in geographic coordinates resulting in a seamless 350 km by 350 km interferogram. The phase of each of the 5 interferograms is unwrapped independently and an N2pi constant is added to each to form a single seamless unwrapped map. Over these large horizontal distances, there are residual trends and waves due to the variations in the ionosphere. The Sentinel-1A TOPS processing requires new tools to solve for the azimuthal shift between the master and slave images to an accuracy of a thousandth of a pixel. This shift is estimated in a two-step process where first a traditional spatial cross-correlation is used to estimate the shift to a tenth of a pixel. Then a more refined estimate is determined from the phase difference in the overlapping region of the of the burst interferograms. One novel aspect of our approach is to avoid the azimuthal deramp/interpolate/deramp process, which is needed for accurate resampling of the slave image using a sinc interpolator. We avoid the deramp/eramp steps by using the more accurate interpolation provided by the shift property of the Fourier transform. The ALOS-2 ScanSAR processing tools are already available in GMTSAR while the Sentinel-1A TOPS tools are still being developed and tested.

Low magnitude limits on seismogeodesy with MEMS accelerometers for events in the Salton Trough and the San Francisco Bay Area, Jessie K. Saunders, Dana E. Goldberg, Jianghui Geng, Jennifer S. Haase, Yehuda Bock, Diego Melgar, D. Glen Offield, Christian Walls, Doerte Mann, Glen Mattioli, David Mencin (Poster 070)

We assess the field performance of seismogeodetic stations equipped with SIO Geodetic Modules and low-cost MEMS accelerometer packages (“GAPs”) using four intermediate-sized (~M4.0) earthquakes, two in the San Francisco Bay Area and two near the southern Salton Sea. The seismogeodetic networks consist of 15 SCIGN and PBO stations in southern California and 10 PBO stations in the Bay Area upgraded in Summer 2013 and Winter 2015, respectively. The seismogeodetic approach optimally combines accelerometer data with collocated high-rate GNSS observations to obtain accurate broadband displacements and seismic velocities in the near field; we employ the method of precise point positioning with ambiguity resolution and accelerometer (PPP-ARA). Previous testing on the NEES/UCSD Large High Performance Outdoor Shake Table demonstrated that for large magnitude earthquakes the GAP seismogeodetic combination with 10 Hz GNSS observations yield displacements and velocities on par with the combination using observatory-grade accelerometers. In this study we show that the field-deployed MEMS accelerometers recorded strong motion from four events: a M4.2 on December 24, 2014 and a M4.1 on May 21, 2015, both near the southern end of the Salton Sea as well as two M4.0 earthquakes in the San Francisco Bay Area that occurred near Fremont on July 21, 2015 and near Piedmont on August 17, 2015, at epicentral distances of 3 to 40 km. The GAP seismogeodetic combinations produced stable displacement and velocity time series with low-amplitude long-period variations, but with increased precision compared to GNSS-only solutions. While the velocities showed significant ground motion and that an event was occurring, the displacements, as would be expected for these intermediate magnitude events, did not exhibit any significant variations. This null result provided definite evidence that the events were not developing into large ruptures with significant displacements, an important datum for whether or not to issue an early warning of an earthquake of consequence. Our results with intermediate magnitude earthquakes, below the detection threshold for GNSS-only networks, demonstrate that the GAP-upgraded stations will be able to provide important complementary confirmation of seismic earthquake early warning products.

Some like it hot: The spectrum of temperature rise during earthquakes, Heather M. Savage, Pratigya J. Polissar, Hannah S. Rabinowitz, and Rachel Sheppard (Poster 275)

Temperature rise during an earthquake depends on shear strength, total slip and active width of the fault zone, all of which are important parameters necessary for more accurate rupture models. Here we describe the use of extractable organic molecules (biomarkers) for measuring earthquake slip in fault zones. By comparing the thermal maturity of biomarkers in fault zones to the thermal maturity in rocks immediately adjacent to the fault, we can determine if the fault has experienced significant frictional heating. We present results from a number of faults from different depths and tectonic environments, including the Japan Trench, the Punchbowl fault, CA, as well as several carbonate-bearing thrust and normal faults. Models that couple newly established thermal maturation kinetics with thermal diffusion in fault
zones allow us to determine the maximum temperature achieved in each fault. Even the absence of a signal allows for a maximum slip event to be estimated, because of the limits placed on heating by the reaction kinetics. We discuss the range of maximum fault temperatures seen with this method to date, and discuss implications for estimates of frictional work and slip localization in fault zones.

**Toward a 3D Kinematic Rupture Generator Based on Rough Fault Spontaneous Rupture Models, William H. Savran and Kim B. Olsen (Poster 011)**

As the frequency limit of deterministic strong-ground motion simulations approach engineering relevant frequencies (>10 Hz), finite-fault source models with realistic small-scale rupture complexity become increasingly important. Spontaneous rupture modeling provides a physical framework to compute realistic broadband rupture models of earthquake faults. However, at this time, it is numerically unfeasible to use spontaneous rupture simulations directly for the large number of strong-ground motion simulations necessary for current seismic hazard projects (e.g., CyberShake, the Broadband Platform). Instead, we aim to capture the statistics of complex spontaneous rupture models in a method allowing for rapid and computationally inexpensive generation of physically realistic broadband kinematic source models. We present our progress toward this method using 3D spontaneous rupture modeling on a vertical strike-slip rough fault geometry in a layered crustal model. The statistics for the method is derived based on ensembles of rupture models that compare favorably to GMPEs.

**A coherence-based Small-Baseline Subset method for InSAR with applications to the Coachella Valley, California, David A. Schmidt, Xiaopeng Tong, Andrew Barbou, and David Sandwell (Poster 195)**

For C-band radar like ERS and ENVISAT, the InSAR coherence is significantly compromised in vegetated and cultivated regions, leaving the active deformation within those areas unmapped. We have improved the conventional small-baseline subset (SBAS) method by introducing coherence of the interferograms into the inverse problem. Instead of discarding those pixels where one or more of the interferograms are incoherent, we keep all the pixels in the processing chain and design a covariance matrix based on the coherence of each interferogram. This coherence-based SBAS method results in a deformation map that is more spatially continuous than the conventional approach, and helps to better constrain the deformation across the plate boundary. To further refine the SBAS-InSAR products, we also apply an elevation-dependent correction to the derived InSAR velocity map to take into account any remaining atmospheric artifacts, which helps to further enhance any deformation signals. In the time series inversion, a damping term is typically included which acts to smooth the InSAR time series; we find the optimal smoothing weights by comparing the InSAR time series to nearby GPS time series.

We applied this improved InSAR time-series method to ERS-1/2 and ENVISAT data near the Coachella Valley, California, where agricultural parcels and golf courses are prevalent. Discontinuities in the high-resolution velocity map reveal the surface trace of the San Andreas Fault system. The InSAR velocity map also reveals deformation that can be attributed to the aquifer’s response to the withdrawal of fluid. The northern part of the Coachella valley region is subsiding at average rates of 5-10 mm/yr from 1992-2000 and the subsidence area is reduced to the west edge of the Coachella valley from 2003-2010. The subsidence near Palm Desert is bounded by a lineament lying parallel to the San Andreas Fault, which could indicate that a buried fault in the Coachella Valley is acting as a permeability boundary.

**Virtual Quake and Tsunami Squares: Scenario Earthquake and Tsunami Simulations for Tsunami Early Warning, Kasey W. Schultz, Michael K. Sachs, Mark R. Yoder, Eric M. Heien, John B. Rundle, Donald L. Turcotte, Andrea Donnellan, J. Q. Norris (Poster 050)**

Plans for the first operational prototype for a Pacific Rim Tsunami Early Warning (TEW) system utilizing real-time data from the Global Navigational Satellite System (GNSS) are now gaining momentum. The proposed Pacific Rim TEW prototype may follow the Japanese Meteorological Society’s early warning algorithms and use earthquake parameters rapidly determined from GPS data to select the most similar earthquake and tsunami scenario from a database of precomputed scenarios to guide alerts and disaster response. To facilitate the development of this Pacific Rim TEW system, we have integrated tsunami modeling capabilities into the earthquake simulator Virtual Quake (formerly Virtual California). We will present the first results from coupling the earthquake simulator output (seafloor displacements) with the tsunami modeling method called Tsunami Squares. Combining Virtual Quake and Tsunami Squares provides a highly scalable and flexible platform for producing catalogs of thousands of tsunami scenarios for a wide range of simulated subduction zone earthquakes.

**Surface Cracking during the 2014 M8.1 Pisagua, Northern Chile Earthquake, Chelsea P. Scott and Richard W. Allmendinger (Poster 123)**

The Mw 8.1 April 1, 2014 Pisagua earthquake provides opportunity to examine how durable coseismic cracks record the upper plate deformation of a single subduction earthquake along the South America-Nazca plate boundary. We document in the brittle saline soils of the hyperarid Atacama Desert a large population of cracks activated in the 2014 event and examine if the crack record serves as a viable strain indicator for the earthquake. Our field observations indicate that the fresh cracks are almost always reactivated pre-existing cracks, were likely re-opened by both the Mw 8.1 mainshock and the Mw 7.7 aftershock, commonly cluster along topographic scars, and degrade quickly by eolian processes and sloughing of the walls. We measured the strike of >3700 cracks spanning the length of the rupture area and calculated the apparent strain magnitude from crack apertures measured along three transects at varying distances from the earthquake centroid. Although the crack record is noisy, the rotation of measured crack orientations across the rupture zone is broadly consistent with the change in strike predicted from the geodetic datasets (SAR data, GPS data) and earthquake slip models. Crack apertures indicate an apparent strain magnitude that exceeds the strain inferred from the geodetic datasets and interpreted from a million year crack record by almost two orders of magnitude. We attribute this high apparent strain to the degradation of the crack walls during and shortly after the earthquake.

**Poroeelastic and Earthquake Nucleation Effects in Injection Induced Seismicity, Paul Segall, Shaoyu Lu, and Jeremy Maurer (Poster 279)**

The standard model of injection-induced seismicity considers changes in Coulomb strength due solely to changes in pore-pressure. We consider two additional effects: full poro-elastic coupling of stress and pore-pressure, and time dependent earthquake nucleation. Stress and pore-pressure due to specified injection rate are modeled in a homogeneous, poroelastic medium following Rudnicki [1986]. Stress and pore-pressure are used to compute seismicity rate through the Dieterich [1994] model. For constant injection rate, the time to reach a critical seismicity rate scales with $t \sim \nu^2/(\nu_c f_c)$, where $\nu$ is distance from the injector, $c$ is hydraulic diffusivity, and $f_c$ is a factor that depends on mechanical properties, and weakly on $\nu$. The seismicity rate decays following a peak, consistent with some observations. During injection poro-elastic coupling may increase or decrease the seismicity rate, depending on the orientation of the faults relative to the injector. If injection induced stresses inhibit slip, abrupt shut-in can lead to locally sharp increases in seismicity rate; tapering the flux mitigates this effect. The maximum magnitude event has been observed to occur post-injection. We suggest the seismicity rate at a given magnitude depends on the nucleation rate, the size distribution of fault segments, and if the background shear stress is low, the time varying volume of perturbed crust. This leads to a roll-over in frequency magnitude distribution for larger events, with a corner magnitude that increases with time. We expand on the analysis of Segall and Lu [2015, JGR] to include the potential rupture of fault segments within the perturbed zone. Larger events are absent at short times, but approach the background frequency with time; larger events occurring post shut-in are thus not unexpected. Theoretical predictions are compared with field observations.

**Continuity of slip rates across the kinematically linked Calico, Blackwater, and Harper Lake faults, Mojave Desert, California, Jacob A. Selander and Michael E. Oskin (Poster 109)**
MEETING ABSTRACTS

Structural connections across a zone of shortening within the Mojave East California Shear Zone (ECSZ) suggest that late Quaternary slip rates along the Calico-Blackwater-Harper Lake-Tin Can Alley fault system are linked. To test the importance of these links for transferring dextral strain across the Mud Hills thrust. A fifth site along the Calico fault within the northwest Calico Mountains shows an abundance of late Quaternary landforms without measurable offsets, indicating that activity of the Calico fault is now completely transferred to other structures before reaching this area. Fault displacements were measured from offset alluvial fan deposits or other Quaternary markers; ages of offset fans were determined using Beryllium-10 exposure-age depth profiles. The rates determined are 1.4 ±0.8/-0.4 mm/yr along the Calico fault within the Rodman Mountains, 1.9 ±0.8/-0.4 mm/yr on the Harper Lake fault north of Barstow, 0.2 ±0.2/-0.1 mm/yr on the Gravel Hills fault near its northwestern termination, and a north-south shortening rate of 0.4 to 0.8 mm/yr along the Mud Hills thrust. These data, when combined with previous work, show that the full displacement rate of the Calico fault is transferred across the Manix Basin, and then diminishes completely as slip is distributed on to the Harper Lake fault, Mud Hills thrust, and Tin Can Alley fault. Overall displacement rate gradients mimic long-term displacement patterns, and support an overall decrease in dextral slip rate to the northwest. Fault-tip displacement rate gradients in the Harper Lake-Gravel Hills fault system, its full displacement is accommodated by distributed deformation within the northwest Mojave Desert, and that it is not kinematically linked to dextral faults north of the Garlock fault. Overall, geologic dextral slip gradients and slip rates across the Mojave ECSZ agree well with boundary element model results that represent the region as a network of shorter, disconnected faults with a significant proportion of deformation occurring via shortening and distributed deformation in the surrounding crustal volume.

Reconciling earthquake source parameters from InSAR and long-period seismic waveform data, Nader Shakibay Senobari, Gareth Funning, Jennifer Weston, and Ana Ferreira (Poster 170)

Comparisons between earthquake source parameters as determined by InSAR and the global centroid moment tensor (GCMT) catalogue show widespread discrepancies between locations derived using these independent methods (Ferreira et al., 2011; Weston et al., 2011, 2012). Earthquake centroid location determination using InSAR data (named the “InSAR Centroidal Moment Tensor,” or “ICMT” location) is more robust, since it is independent of Earth velocity structure errors that impact on long-period surface wave inversions used in the GCMT method. Ferreira et al. (2011) showed that these discrepancies cannot be resolved at present by applying more detailed 3D Earth velocity structures from mantle tomography models. Earthquake location determination is extremely dependent on the assumed velocity structure, not only in the GCMT method, but also in all of the seismic-based earthquake source parameter inversions. Velocity structures are typically produced by seismic tomography, which itself depends on seismic phase travel times. These travel times are a function of source location and origin time, plus the path between the source and receivers (i.e. the Earth’s velocity structure). Errors in source location can therefore be compounded as errors in the velocity structure.

In a preliminary study we analyze long-period seismic data for three shallow continental earthquakes studied with InSAR – Zaranw Mw6.5 (Iran, 2005), Eureka Valley Mw6.1 (California, 1993) and Aiquile Mw6.5 (Bolivia, 1998). We use the spectral elemental wave propagation package, SPECFEM3D GLOBE, and Earth model S4ORTS (Ritsema et al., 2010) to calculate Green’s functions and synthetic seismograms for these events using their ICMT source locations. Using a cross-correlation method we were able to estimate phase shifts for each source-receiver pair between synthetic and observed waveforms. We believe these phase shifts may correspond to unmodeled heterogeneity in the S4ORTS model, and if systematically documented could provide additional constraints on seismic tomographic models. GCMT-style source inversions that account for these phase shifts show much better agreement with the ICMT mechanisms than inversions where they are not accounted for. Several published studies relate GCMT location errors to unknown and/or unmodeled heterogeneities within the Earth’s crust and upper mantle. However, here we show that source mechanism and moment can also be sensitive to these unknown heterogeneities in some cases.

Simulation of seismic-wave propagation during the 1927 ML 6.25 Jericho earthquake, Shahar Shani-Kadmiel, Michael Tsesarsky, and Zohar Gvirtzman (Poster 031)
The Dead Sea Transform (DST) is the major seismic source in Israel and neighboring countries capable of producing up to M 7.5 earthquakes known from geological, archeological and historical records. However, due to the low seismicity rate, strong earthquakes and their ground motions were not recorded in Israel. The last major earthquake on the terrestrial part of the DST was the ML 6.25 July 11, 1927 Jericho earthquake and the most destructive earthquake in the region during the 20th century. Estimations of casualties range between 250–500 deaths and 400–700 injuries. Many buildings were damaged, landslides and rockfalls were observed and the flow of the Jordan River had stopped for 21.5 h.

In absence of recorded ground motions we concentrate our efforts on forward numerical modeling to estimate the ground motions during strong earthquakes. We use the Distributed Slip Model (DSM, Shani-Kadmiel et al., 2014), a kinematic, generic, finite fault source with a smooth “pseudo-Gaussian” slip distribution on an elliptical rupture patch to initiate seismic-wave propagation.

In this study we calculate MSK64/EMS98 (Medvedev et al., 1965; Grünthal, 1998) intensities which are compared with 133 macroseismic intensity records, based on physical evidences and reports compiled by Awi et al., (2002) and re-evaluated by Zohar and Marco (2011) to account for local site-attributes. Preliminary results based on a laterally homogeneous velocity model, suggest that (a) contrary to previous studies, the fault ruptured from south to north, and (b) topographic and directivity effects explain most of the data with more than 90% of the predicted intensities within plus or minus one unit of intensity of the reported intensities.

Eliciting Fault Zone Structures in the South Central Transverse Region of the San Andreas Fault with Double-Difference Tomography, Pieter-Ewald Share, Yehuda Ben-Zion, and Clifford H. Thurber (Poster 185)

We attempt to clarify details of the complex fault zone structures in the South Central Transverse Region of the San Andreas Fault (SAF) using a version of the double-difference tomography technique that accounts for body waves and fault zone head waves (FZHW). The study region comprises a 70 by 160 km rectangle centered on the San Gorgonio Pass; 20 km of the region is located SW and 50 km is located NE of the SAF. The area includes 72 stations that recorded 2666 M>1 events during 2013-2014. Arrival times of P and S body waves and FZHW are provided by an automatic detection algorithm. The automatic detection and subsequent data outlier removal produced 39028 and 27196 high quality P and S picks, respectively, and numerous candidate FZHW at various stations close to the SAF. These are used for simultaneous inversion for P and S velocity models and hypocentral locations. Preliminary results, obtained without incorporating the FZHW data, show much structural complexity, as expected. One key future is an anomalously high Vp/Vs region (at approximately 10 km depth), which correlates well with the Crafton Hills Fault Zone. The anomaly is still present at shallower depths (5-6 km) and also expands NW towards Cajon Pass and includes portions of the Banning Fault in the SE. The candidate FZHW are currently being tested with particle motion analysis to weed out false detections. The remaining valid FZHW will be used to map the existence and continuity of bimaterial interfaces, and will be incorporated in the double-difference tomographic inversions for improved velocity models.

Validating Aftershock Models, Bruce E. Shaw, Keith B. Richards-Dinger, and James H. Dieterich (Poster 250)

While traditional earthquake hazard models have focused on long term probabilities, current efforts aim to develop time dependent probabilities on the full range of timescales, including short term clustering which includes aftershocks. A key part of any model development is validating models against observations. Here, we discuss a set of quite demanding observations which, individually, are challenging for any model to match,
implying a complex correlated structure. Taken together, as a whole series of measurements which models are asked to reproduce, they become a very demanding filter, which we argue provides a substantial and strong validation tool.

The set of measurements associated with foreshocks and aftershocks we propose as a significant validation tool are: 1) Time dependence reflected in Omori’s law for foreshocks and aftershocks for different mainshock magnitudes; 2) Productivity reflected in the dependence of the number of foreshocks and aftershocks as a function of mainshock magnitude; 3) Differential magnitude distributions of clustered events, a measure suggested by Shearer [2012], showing the distribution of sizes of foreshocks and aftershocks relative to the mainshock magnitude for different mainshock magnitudes; 4) Spatial distribution relative to the mainshock hypocenter for different mainshock magnitudes.

We show that a new physical model of aftershocks we have recently introduced, based on rate-and-state friction applied to a fault zone consisting of a set of anastomosing rough fault strands, can reproduce all these observed features for some range of parameters. This model is, we believe, the first deterministic physical model capable of reproducing all these complex observations and passing this demanding validation test.


The SCEC Ventura Special Fault Study Area (SFSA) promotes interdisciplinary science investigating the prospects for large, multi-segment thrust fault earthquakes in southern California. The SFSA is centered on the north-dipping Ventura – Pitas Point fault and overlying anticline, which are located at the juncture of several of the largest and fastest slipping faults in the Transverse Ranges. Holocene marine terraces above the anticline suggest that it deforms in discrete 7-9 m uplift events, with the latest event occurring ~950 years ago.

Recent excavations across the fold scarp above the blind Ventura fault show evidence for at least two large-displacement (4.5 to 6m uplift), paleo-earthquakes in the Holocene that may be correlated with uplift of marine terraces along the coast. Geophysical studies of the larger fault system that extends offshore also document discrete Holocene seafloor deformation, but systematic efforts are focused on developing a comprehensive understanding of coastal uplift and subsidence patterns that record both the activity of the 140 km long Ventura – Pitas Point – North Channel fault system and a series of active north- and south-dipping faults in its hanging wall and footwall. Seismological studies show that thrust and strike-slip earthquakes occur throughout the region, and are consistent with NNE-SSW compression. Geodetic observations (GPS, InSAR, and leveling studies), and fault system models also indicate rapid shortening (2.7 to 8 mm/year) and uplift (> 2 mm/yr) rates across portions of this structure. Mechanical models of the Ventura fault system predict slip rates that agree with geologic estimates of fast slip, with the maximum slip predicted near the coast. Together, these results support the occurrence of large thrust fault earthquakes involving the Ventura fault system.

To assess the hazards posed by these earthquakes, the SFSA has supported numerical simulations that suggest ruptures of the Ventura – Pitas Point fault system will produce large surface displacements and significant, long duration ground motions (> 0.5 m/s, PGV) over a large area of southern California. As these ruptures will likely extend offshore, they also pose the threat of generating tsunamis. Recent studies examining sedimentary deposits along the coast have suggested possible paleo-tsunami deposits, as well as rapid coastal subsidence events that may be caused by paleo-earthquakes. Numerical modeling of tsunamis shows significant run-ups (up to 8 m) along large areas of the coastline for equivalent modeled seafloor offset. These studies confirm that large thrust fault earthquakes pose considerable seismic and tsunami hazards to coastal southern California. SCEC is at the forefront of efforts to better characterize these hazards.


Earthquake swarms, sequences of sustained seismicity, convey active subsurface processes that sometimes precede larger tectonic or volcanic episodes. Their extended activity and spatiotemporal migration can often be attributed to fluid pressure transients as migrating crustal fluids (typically water and CO2) interact with subsurface structures. Although the swarms analyzed here are interpreted to be natural in origin, the mechanisms of seismic activation likely mirror those observed for earthquakes induced by industrial fluid injection. Here, we use massive-scaffold waveform correlation to detect and precisely locate 3-10 times as many earthquakes as included in routine catalogs for recent (2014-2015) swarms beneath Mammoth Mountain, Long Valley Caldera, Lassen Volcanic Center, and Fillmore (Ventura Basin) areas of California. These enhanced catalogs, with location precision as good as a few meters, reveal signatures of fluid-faulting interactions, such as systematic migration, fault-valve behavior, and fracture mesh structures, not resolved in routine catalogs.

We extend this analysis to characterize frequency magnitude distributions and source mechanism similarity even for very small newly detected events. This information complements precise locations to define and understand fault complexities that would otherwise be invisible. In particular, although swarms often consist of groups of highly similar events, some swarms contain a population of outliers with different slip and/or orientation. These events highlight the complexity of fluid-faulting interactions.

Despite their different settings, the four swarms analyzed here share many similarities, including pronounced hypocenter migration suggestive of a fluid pressure trigger. This includes the July 2015 Fillmore swarm, which, unlike the others, occurred outside of an obvious volcanic zone. Nevertheless, it exhibited systematic westward and downdip migration on a ~1x1.5 km low-angle, NW-dipping reverse fault at midcrustal depth.

Derivation of 3D crustal deformation in southern California by combining GPS and InSAR LOS velocities, Zheng-Kang Shen and Zhen Liu (Poster 198)

We are developing a new approach to estimate 3D crustal motion velocity field by combining GPS velocity and InSAR line-of-sight (LOS) rate data. The InSAR LOS rate is based on our analysis of 18 years of ERS-1/2 and Envisat data from 1992 to 2010 for both ascending and descending tracks in the region. As a proof-of-concept, we focus our study on the region covering the Los Angeles Basin and the Mojave segment of the San Andreas fault. We resample InSAR grid into a coarser one and estimate a mean LOS rate at each grid. For each grid, we determine a 3D velocity vector with uncertainty by interpolating GPS velocity data available in its neighboring region, using a method developed by Shen et al. (BSSA, 2015). Both campaign and continuous GPS velocity solutions are incorporated to yield good spatial coverage and high data precision. A frame difference between the InSAR relative measurements and GPS velocities is resolved and removed from the InSAR data. We then estimate the 3D velocity components through a weighted least-square inversion by taking into account the interpolated GPS velocity vector and the InSAR LOS rate data available at the same grid location. Advantage of the method is that with the GPS data providing strong constraints to the horizontal velocity components, the InSAR data help effectively constrain the vertical. We present the initial application of the approach and the 3D velocity field produced in the selected region at the meeting.

Large-Amplitude, Scattered Tsunami Wave Mapping Enabled by Ocean Bottom Seismometer Array Recordings, Jian Shi, Monica Kohler, Pablo Ampuero, and Jeanette Sutton (Poster 152)

A deployment of ocean bottom seismometers off the coast of southern California recorded the March 2011 Tohoku tsunami on 22 differential pressure gauges (DPGs). The DPG tsunami records across the entire array show multiple large-amplitude, coherent phases arriving one hour to more than 36 hours after the initial tsunami phase. Analysis of the DPG
recordings reveals possible locations of the geographical sources that contributed to secondary tsunami arrivals in southern California. A beamforming technique is applied to the DPG data to determine the azimuths and arrival times of scattered wave energy. In addition, a backward ray tracing procedure is applied to a wide range of back azimuth starting values from the DPG array to map possible source locations. The results show several potential candidates of secondary tsunami source structures. These include the Alaskan Peninsula island chain producing a tsunami arrival ~60 minutes after the first arrival, and the Hawaiian Islands producing an arrival ~170 minutes after the first arrival.

Implications of Observed Fault Geometry and Stress Field on Rupture Dynamics Along the SGP Section of the San Andreas Fault, Zheqiang Shi and Steven M. Day (Poster 239)

We study the likelihood of through-going ruptures along the San Gorgonio Pass (SGP) section of the San Andreas Fault (SAF) from a mechanical point of view by preforming 3D dynamic rupture simulations. We investigate the effects of stress state and fault geometry on rupture propagation by adopting the SCEC Community Fault Model (CFM) and Community Stress Model (CSM) in our numerical study. Of the four currently available stress model candidates, SHELLS and FlatMaxwell provide absolute stresses while Hardebeck_FM and YHSM-2013 contain only deviatoric stresses and therefore require additional assumptions for use in dynamic rupture simulations. Our simulation study showed that there exist apparent discrepancies among current stress model candidates regarding their implications on the likelihood of through-going ruptures along SGP, which points to the need for further improvement of these models. We also assumed small-scale roughness on top of the fault geometry given by the SCECFM and explored their static and dynamic effects on rupture propagation and ground motions.

The SCEC Broadband Platform: Open-Source Software for Strong Ground Motion Simulation and Validation, Fabio Silva, Philip Maechling, Scott Callaghan, Christine Goulet, and Thomas Jordan (Poster 039)

The Southern California Earthquake Center (SCEC) Broadband Platform (BBP) is a carefully integrated collection of open-source scientific software programs that can simulate broadband (0-100Hz) ground motions for earthquakes at regional scales. The BBP scientific software modules implement kinematic rupture generation, low and high-frequency seismogram synthesis using wave propagation through 1D layered velocity structures, seismogram ground motion amplitude calculations, and goodness of fit measurements. These modules are integrated into a software system that provides user-defined, repeatable, calculation of ground motion seismograms, using multiple alternative ground motion simulation methods, and software utilities that can generate plots, charts, and maps. The BBP has been developed over the last five years in a collaborative effort by the scientific, engineering, and software development project involving geoscientists, earthquake engineers, graduate students, and SCEC scientific software developers.

The BBP can run earthquake rupture and wave propagation modeling software to simulate ground motions for well-observed historical earthquakes and to quantify how well the simulated broadband seismograms match the observed seismograms. The BBP can also run simulations for hypothetical earthquakes. In this case, users input an earthquake location and magnitude description, a list of station locations, and a 1D velocity model for the region of interest, and the BBP software then calculates ground motions for the specified stations.

The SCEC BBP software released in 2015 can be compiled and run on recent Linux systems with GNU compilers. It includes 5 simulation methods, 7 simulation regions covering California, Japan, and Eastern North America, the ability to compare simulation results against GMPEs, updated ground motion simulation methods, and a simplified command line user interface.

Recording Past Tsunamis in Prograding Coastal Plains: Examples from Tolowa Dunes, Northern California, Alexander R. Simms (Poster 107)

What methods are available for recording past tsunamis along coastlines without well-developed marshes such as the sandy beaches of Central and Southern California? One potential archive are prograding beach plains. The Cascadia Subduction Zone of western North America produced very large (M~8) earthquakes and tsunamis, which swept the coastal dunes and prograding beach plains of the region. I use one section of coastline within this region as a natural laboratory to determine the ground-penetrating radar (GPR) signature of tsunami erosion within a prograding beach plain. Fifteen km of high-resolution GPR profiles were acquired along the northern banks of the mouth of the North Fork Eel River near Crescent City, California. The most seaward extents of the GPR profiles contain a package of seaward-dipping reflections indicative of a prograding shoreface overlying a thin veneer of horizontal reflections indicative of eolian material. About 100 m inland from the modern coastline is a prominent unconformity cutting nearly horizontal across portions of the seaward dipping reflections. This prominent unconformity is overlain by a chaotic mix of reflectors dipping in all directions. This package is overlapped seaward by another set of undisturbed seaward dipping reflections. The prominent unconformity is tentatively attributed to the 1700 AD Cascadia Subduction Zone earthquake and resulting tsunami producing a stratigraphic signature for documenting the past record of tsunami erosion within prograding coastal plains. Two other older, more landward unconformities of similar character were also identified. This study demonstrates that coastal plains provide an additional archive of past tsunamis where marshes may not be formed or preserved in places such as Southern California.

Impact of Uncertainty in Magnitude-Area Scaling Relations on BBP Broadband Simulations, Andreas Skarlatoudis, Jeff Bayless, and Paul Somerville (Poster 023)

There is an unresolved debate about the way in which the rupture areas of large crustal earthquakes scale with seismic moment. This debate has its origins in Hanks and Bakun (2002; 2008) who proposed bilinear source-scaling relations assuming constant stress-drop scaling for Ms>6.7 and a transition to non-self- similar scaling for Ms>6.7. In self-similar models (e.g. Leonard, 2010), average fault displacement, fault length and fault width all increase uniformly together. The differences in magnitude estimates for a given fault rupture area from the different scaling models described above have a relatively minor impact on the estimation of ground motion amplitudes using empirical ground motion prediction models. However, for numerical simulations in which the fault area is fixed, a change in 0.2 units in magnitude has been shown to have a significant impact on the produced synthetic waveforms.

The SCEC Broadband Platform (BBP) provides the opportunity to study in detail the impact of different Magnitude-Area scaling relations using the already-implemented simulation methods and rupture generators. We utilize the simulated waveforms computed from the BBP Phase 1 validation project (Dreger et al., 2013.). To examine the sensitivity of the simulations to the scaling model, we recalculate the events of interest using alternative scaling relations. We also study the relative behaviors of the simulations using an appropriate suite of event scenarios. The first approach has the advantage of comparing the simulations against recorded data, and the second provides comparisons to the NGA-West2 GMPEs. To compute our preliminary results for the Landers (M 7.2) event, we used the Hanks and Bakun (2008) relations to estimate the fault area and we adjusted the fault length by keeping the original fault width used in the BBP Phase 1 validation project (Dreger et al., 2013.). We then used the pre-calculated 1D Green’s functions, appropriate for southern California, and the Graves and Pitarka (GP), ExSim and SDSU broadband simulation methods to produce new synthetic waveforms, using 50 source realizations of the rupture. Additionally, we simulated a forward scenario for an M6.6 strike-slip event. In the initial results for the GP method, Landers event, we do not observe any dramatic changes in overall RotD50 goodness of fit (GOF). The simulations exhibit lower amplitudes, on average, than those from Leonard scaling, especially at long periods.

Past Peak Ground Velocity within the Los Angeles Basin, Norman H. Sleep (Poster 238)

Ambient shallow rock is a potential fragile geological feature that may be damaged by strong surface waves and by the near-field velocity pulses. The dynamic strain for a velocity pulse is the particle velocity (peak ground velocity, PGV) divided by the rupture tip propagation velocity. The dynamic stress is the strain times the shear modulus at a given depth. Numerical calculations assuming linear elasticity by Böse et al. (2014)
calibrate the rupture tip velocity to ~2.8 m/s for a magnitude 7.75 earthquake on the Newport-Inglewood fault. Originally stiff rocks frictionally fail at the dynamic stress. Cracks form and eventually the rock mass becomes compliant enough that it barely fails during typical strong shaking. The shallow stiffness then increases linearly with depth and past PGV can be determined. However, accumulating clay-rich beds within the Los Angeles Basin were originally compliant and may have never been damaged by strong shaking. Stiff quartz-rich beds within the basin then provide fragile geological features that fail and crack before the rest of the clay-rich rock mass. Repeated cracking would reduce the shear modulus of the quartz-rich beds to the level that cracking barely occurred during strong events. When interpreted in this way, data from such stiff beds near LAX airport indicate PGV of ~1.6 m/s for a near-field pulse, comparable with near-field records from the strike-slip 2002 Denali and 1992 Landers earthquakes. The method yields 0.5 m/s for Love wave shaking from the San Andreas Fault on the LA side of Whittier Narrows and 0.6 m/s for a near-field velocity pulse in Tehran, Iran. The Newport-Inglewood numerical calculations predict 5 m/s horizontal PGV, higher than that inferred from the quartz-rich beds near LAX. The calculated dynamic strain from this event would take much of the uppermost few hundred meters of basin rock beyond its frictional elastic limit. Numerical calculations capable of representing nonlinear failure within shallow bedded rocks are warranted. They need to include that the coefficient of friction of clay-rich sediments is lower than that of quartz-rich sediments.

A 3D, Rotationally Invariant Form of Crustal Stress Relaxation Equations with Applications for Earthquake Simulators and Off-Fault Moment Release Estimates, Deborah E. Smith and James H. Dieterich (Poster 154)

A form of off-fault stress relaxation, based on rate-state seismicity equations, has been developed to resolve several problems associated with geometrically complex faults in elastic media. Slip on geometrically complex faults in elastic media produces fault interaction stresses that non-physically grow without limit. These stresses in turn suppress fault slip, break the linear slip vs. length scaling for ruptures, and result in nonconvergent solutions as model resolution increases. In the Earth, these fault interaction stresses cannot grow without limit, and yielding will occur; therefore, we build upon the suggestion by Dieterich and Smith [2008] that off-fault yielding relieves these stresses through pervasive secondary faulting in the brittle crust.

Starting with the rate-state seismicity equations that statistically describe the nucleation of seismicity in the brittle crust, we derive analytical expressions to represent stress relaxation as a time dependent, bulk yielding process. These expressions 1) regularize the simulations, 2) restore the linear slip vs. length scaling in ruptures, and 3) enable stress interactions to grow and relax about a long-term average instead of growing without limit. This model provides predictions of off-fault moment release as a function of time and space, arising from the stress relaxation.

In our recent work, we developed a rotationally invariant, 3D version of the stress relaxation equations based on the rate-state evolution equation. This involves calculating the inner product of 3D stress tensors with reference stress tensors (set by steady-state stability conditions), and employing the scalar results in the stress relaxation equations. This generates results similar to, but more general than, previous work that used shear and normal stresses resolved onto a reference plane for the equations.

An Effective Medium Theory for Three-Dimensional Elastic Heterogeneities: Application to the Upper Crust, Xin Song and Thomas H. Jordan (Poster 177)

A self-consistent theory for the effective elastic parameters of stochastic media with small-scale 3D heterogeneities has been developed using a 2nd-order Born approximation to the scattered wavefield [T.H. Jordan, GJI, in press]. Here we apply the theory to assess the isotropic variations in elastic structure affect seismic wave propagation through the upper crust. Our model assumes the medium can be represented as a spatially homogeneous, transversely isotropic random field with a covariance tensor that can be factored into one-point, tensor-valued variance and a two-point, scalar-valued correlation function. In the low-frequency limit, where the seismic wavenumbers are small compared to the characteristic wavenumbers of the heterogeneity, the stochastic medium can be replaced by a homogeneous “effective medium” with a transversely isotropic stiffness tensor that depends only the one-point variance and covariance of the two Lamé parameters and a dimensionless number $\eta$ that measures the horizontal-to-vertical aspect ratio of heterogeneity. If $\eta = 1$, the heterogeneity is geometrically isotropic; as $\eta \rightarrow 0$, the medium is stretched into a vertical stochastic bundle; and as $\eta \rightarrow \infty$, the medium is flattened into a horizontal stochastic laminate. In the latter limit, the expressions for the anisotropic effective moduli reduce to Backus’s (1962) second-order expressions for a 1D stochastic laminate. Comparisons with the exact Backus theory show that the second-order approximation predicts the effective anisotropy for non-Gaussian media fairly well if relative root-mean-square fluctuations in the moduli are smaller than about 30%, which should be adequate for most crustal studies. We also note that the 2nd-order theory is exact for heterogeneities that are gamma-distributed. We apply the theory to heterogeneities in the Los Angeles basin determined from well-log analysis and compare the predicted anisotropy with seismic constraints.

Strike-slip displacement on gently-dipping parts of the Hosgri fault and fold-related relief growth patterns above the blind oblique-slip North Channel-Pitas Point-Red Mountain fault system, Christopher C. Sorlien, Craig Nicholson, Marc J. Kamerling, and Richard J. Behl (Poster 220)

The Hosgri fault zone offshore south-central California and the North Channel-Pitas Point-Red Mountain fault system (NC-PP-RM) in Santa Barbara Channel are imaged with multiple grids of closely spaced 2D multichannel seismic reflection (MCS) profiles and seven 3D MCS surveys. From these data and precise stratigraphic age control, we constructed the geologic and fold faults and fold-related relief growth patterns above the blind oblique-slip North Channel-Pitas Point-Red Mountain fault system , with a 25° bend in fault strike so that the faults to the west are not perpendicular to the shortening direction. West of this bend, the Red Mountain fault strands merge with the underlying blind faults dipping 25° N. The shallow northern strand terminates into a north-stepping en echelon pattern on the sea floor, consistent with left-lateral shear. A component of left-lateral strike-slip motion is thus expected on the underlying gently-dipping blind faults.

Ten dated horizons ranging in age from 1,800 ka to 110 ka were interpreted across the 120 km-long offshore part of the NC-PP-RM fault-fold system. The horizons illustrate folding by progressive tilting, requiring continuously variable vertical motion perpendicular to strike. On scales of hundreds of kyr, or even during a single earthquake, the vertical motion will not be a step function across an active axial surface or an emergent fault. It will gradually increase from zero in the basin to a peak at the anticline crest. Some of the blind fault strands do not appear to have propagated updip during the last few hundred kyr. Wherever there is forelimb progressive tilt, if the faults propagate at all, they have to do so more slowly than the slip rate. For non-propagating (oblique) thrust faults, in any one earthquake or hundreds of quakes, the slip is gradually absorbed updip by folding across several km of the hanging wall. Thus, this folding should be incorporated in tsunami and strong ground motion modeling. The localized 6- to 8-m Holocene uplift events at Pitas Point are thus unlikely to be representative of the seafloor offset along the principal N-dipping fault system that extends offshore.

Update on SCEC Seismology Infrastructure at UCSC: The PBIC and Borehole Instrumentation Programs, Jamison H. Steidl, Haley Trindle, and Michelle Dunn (Poster 128)

The SCEC Portable Broadband Instrument Center (PBIC) was established to provide researchers in southern California with year-round access to a “pool” of portable seismic recording equipment. The PBIC maintains this equipment and also serves as a RAMP facility in the event of significant earthquakes. At other times PBIC equipment is used on projects related to SCEC science and data gathering goals. Instrumentation consists of two Quanterra 6-channel 24-bit data loggers and three Kinematics 8-channel 24-bit data loggers, all with real-time capabilities through cellular or Internet telemetry. Sensors consist of 15 high output 3-component L4C
velocity transducers to record very small ground motion and 5 Kinematics FBA ES-T and 15 FBA-23 accelerometers designed to stay on-scale for the strong ground motion expected from very large earthquakes (up to +/- 2G). A broad dynamic range of recording is obtained by pairing both types of sensors with a single 6-channel recorder. The PBIC sensor inventory also includes 5 Guralp CMG 40T broadband sensors suitable for recording long period teleseismic data. The SCEC borehole instrumentation program maintains existing borehole stations and facilitates the installation of new borehole stations in collaboration with other agencies responsible for earthquake monitoring in southern California. The borehole network consists of 18 stations funded through cost sharing between SCEC and EarthScope, CGS, USGS/Caltech, Caltrans, and the NRC. The instrumentation is used to gain a better understanding of the near-surface effects on ground motions, to improve our ability to account for these effects in simulations of ground motion, and to get a more detailed observation of the earthquake source by avoiding the near-surface layers that typically attenuate high-frequency radiation. Sites are located within the Los Angeles region and along southern California’s major fault systems. The instrumentation consists of 3-component Kinematics FBA ES-DH borehole package paired with 3-component Kinematics surface FBA ES-T. The Kinematics Episensor technology, when connected to a 24-bit data logger, provides quality recordings of earthquakes from M=2 and above. The upper limit is usually set to +/- 2G to enable recording of strong ground motion from damaging earthquakes. All sites provide data in real-time to the CISN and is archived at the SCEDC. Event data is available through the UCSB data portal (http://www.nees.ucsb.edu/data-portal).

Precarious Rocks & Design Ground Motions: From Research to Industry Application in New Zealand, Mark W. Stirling, David J. Barrell, Russ J. Van Dissen, Dylan H. Rood, and Albert Zondervan (Poster 092)
The Safety Evaluation Earthquake (SEE) spectrum for the Clyde Dam, the largest concrete dam in New Zealand, has been revised through consideration of the age and distribution of precariously-balanced rocks (PBRs) in the vicinity of the dam site. The preliminary SEE spectrum (10,000 year return period) showed a peak ground acceleration (PGA) of 0.96 g, largely controlled by proximity to the active reverse Dunstan Fault, and consideration of hanging wall effects on the fault. The existence of PBRs at nearby Cairnmuir Flats, 2 km from the dam and near the southwest end of the fault, was then seen as an opportunity to further constrain the SEE spectrum. Review of the SEE is based on the age and fragility of seven PBRs on ochotors at Cairnmuir Flats (fragility = quasi-static and dynamic topping accelerations for failure based on field measurements of the PBR geometry) and one PBR on the central part of the Dunstan Mountains where the Dunstan Fault shows greatest cumulative displacement (~2km vertical). The PBR fragility ages (time since the PBRs obtained their present unstable states) are modelled by way of 10Be cosmogenic isotope dating techniques, and are in the ranges of 20–30 ka and 50–70 ka for Cairnmuir Flats, and less than 12 ka for the central Dunstan Mountains. The fragility ages are consistent with the Cairnmuir Flats PBRs having survived multiple large Dunstan Fault earthquakes (identified in previous paleoseismic studies), whereas the PBR on the Dunstan Mountains post-dates all of these earthquakes. The Cairnmuir Flats PBRs therefore provide important constraints on ground motions close to the dam site. Points in Hazardspace-based comparisons of PBRs and hazard curves show that the preliminary SEE PGA is too strong to be consistent with survival of the PBRs, even when hanging wall effects are removed. Our recommended SEE has a magnitude-weighted PGA of 0.56g, which is based on the mean 10,000 year uniform hazard spectrum with hanging wall effects removed. This is still a conservative estimate of the SEE given the PBR data, but is appropriate given uncertainties associated with the modelled PBR fragility ages. Configuration of Miocene Basins Along the Santa Cruz-Catalina Ridge, California Continental Borderland, Alivia R. Stoller and Mark R. Legg (Poster 308) Miocene basins associated with the oblique rifting of the Inner Continental Borderland offshore Southern California are preserved along the flanks of the transpressional Santa Cruz-Catalina Ridge. Using 184 lines of two-dimensional seismic data including high resolution records from Oregon State University and deep penetration data from Western Geoco archived in USGS/NAOMSS, we were able to map the configuration of the Miocene basin for 90 kilometers along the northeast flank of the Santa Cruz-Catalina Ridge core complex. Our mapping area is 1,280 square kilometers. There are distinct middle and late Miocene basins along the flanks of the ridge, which we are using to try to define the initial configuration of the Inner Borderland Rift. Along the hinge, between the uplifted ridge and the sub-horizontal basement in the Santa Monica Basin, and adjacent to the Transverse Ranges lies the thickest parts of the late Miocene sequence, ranging from 750 to 950 meters thick. The middle Miocene basin has distinct sub-basins, with maximum thicknesses of 1400 to 1800 meters, between acoustic basement highs. Pliocene to Recent sediments lap on to the tilted and uplifted Miocene basin sequences and constrain timing of uplift when transpression commenced. Segmentation and other distinctive character of the Miocene basins along the ridge flank may be correlated with similar features in the Miocene basin on the conjugate margin of the rift. Our working model for oblique rifting in the Borderland resembles the Gulf of California, where right-stepping echelon transform faults link left-stepping extensional basins. The objective of our project is to reconstruct the configuration of the middle Miocene rift and to further our quest to understand the rifting process and tectonic evolution of the Pacific-North American plate boundary.

Resolving Stress Singularities: a Rate-and-State Japan Earthquake Forecast, Anne E. Strader, Hiroshi Tsuruoka, Naoshi Hirata, Yoshikoh Ogata, Danijel Schorlemmer, and David D. Jackson (Poster 056) Retrospective evaluations of rate-and-state Coulomb stress transfer have shown consistent associations between increased Coulomb stress and seismicity rates (Toda and Enescu, 2011; Hainzl et al., 2009; Dieterich, 1992, etc). However, stress singularities occurring at the ends of faults near active faults tend to provide an unrealistic calculated stress field near active faults, where most earthquakes occur. The effects of such stress calculation artefacts may be mitigated through implementation of an inverse rate-and-state model, where seismic rate variations are inverted to obtain Coulomb stress steps over time (modified from Dieterich, 2000). The resulting stress variations, from which expected seismicity rates are derived, show potential in a prospective Japan forecast due to low magnitude completeness thresholds, which allow for comprehensive delineation of the Coulomb stress field, particularly following the 2011 Tohoku earthquake.

Low stress drops observed for M1.5-4.8 Earthquakes During the 2011 Prague, Oklahoma sequence, Daniele F. Sumy, Corrie J. Neighbors, Elizabeth S. Cochran, and Katie M. Keranen (Poster 144) In November 2011, three M≥4.8 earthquakes and thousands of aftershocks occurred along the structurally complex Wilzetta fault system near Prague, Oklahoma. Previous studies suggest that fluid injection in aftershocks occurred along the structurally complex Wilzetta fault system near Prague, Oklahoma. Previous studies suggest that fluid injection in

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rupture plane with the fault plane associated with the M4.8 aftershock. The low stress drops observed for events on both the foreshock and mainshock fault plane may indicate both of these segments of the Wilzetta fault system were influenced by local wastewater injection. Our results echo those of several recent studies [Hough, 2014; Sun and Hartzell, 2014], which conclude that induced earthquakes have lower stress drops than tectonic events.

**Temporal variability in seismic velocity at the Salton Sea Geothermal Field, Taka’aki Taira (Poster 140)**

We characterize the temporal variability of ambient noise wavefield and search for velocity changes associated with activities of the geothermal energy development at the Salton Sea Geothermal Field. The noise cross-correlations (NCFs) are computed for ~6 years of continuous three-component seismic data (December 2007 through January 2014) collected at 8 sites from the CalEnergy Subnetwork (EN network) with MSNoise software (Lecomq et al., 2014, SRL). All seismic data are downloaded from the Southern California Earthquake Data Center. Velocity changes (dv/v) are obtained by measuring time delay between 5-day stacks of NCFs and the reference NCF (average over the entire 6 year period). The time history of dv/v is determined by averaging dv/v measurements over all station/channel pairs (252 combinations). Our preliminary dv/v measurement suggests a gradual increase in dv/v over the 6-year period in a frequency range of 0.5-8.0 Hz. The resultant increase rate of velocity is about 0.01%/year. We also explore the frequency-dependent velocity change at the 5 different frequency bands (0.5-2.0 Hz, 0.75-3.0 Hz, 1.0-4.0 Hz, 1.5-8.0 Hz, and 2.0-8.0 Hz) and find that the level of this long-term dv/v variability is increased with increase of frequency (i.e., the highest increase rate of ~0.15%/year at the 0.5-2.0 Hz band). This result suggests that the velocity changes were mostly occurred in a depth of ~500 m assuming that the coda parts of NCFs (~10-40 s depending on station distances) are predominantly composed of scattered surface waves, with the SoCal velocity model (Dreger and Helmberger, 1993, JGR). No clear seasonal variation of dv/v is observed in the frequency band of 0.5-8.0 Hz.

**Considering rupture directivity in selecting ground motion ensembles for seismic response analysis in the near-fault region, Karim Tarbali (Poster 003)**

Selecting appropriate ground motion ensembles is a key step in assessing the seismic performance of engineered systems through time-domain seismic response analyses. Recent developments in earthquake rupture forecast models and ground motion prediction equations provide the engineering community with advanced models to consider physical processes such as rupture directivity effect in seismic hazard calculations. This study presents an example application of such models to assess the seismic hazard in the near-fault region and subsequently select ground motion ensembles that appropriately represent the target hazard. Particular attention is given to a ground motion selection approach which is explicitly based on ground motion intensity measures (IMs), including pseudo-acceleration response spectrum (SA), duration, and cumulative measures; rather than a focus on implicit parameters (i.e. pulse or non-pulse classifications) that are conventionally used to heuristically distinguish between near-fault and far-field records. Importantly, it is shown that selection based on such an appropriate set of IMs will indirectly lead to an ensemble with the appropriate proportion of forward-directivity motions (representing the probability of occurrence of such motions). This result is due to the fact that the occurrence and predominant period of velocity pulses do affect the ground motion IMs, and hence are captured in this fashion. Example applications of this approach are presented for scenario and probabilistic seismic hazard analysis cases with different rupture characteristics, source-to-site geometry, and site conditions. The results indicate that the modification to SA ordinates to account for the directivity pulse effect and utilizing multiple IMs in the selection process based on the generalized conditional intensity measure (GCIM) methodology results in ground motion ensembles with an accurate representation of the target hazard and the predicted directivity ground motion characteristics.

**Remote triggering of small local earthquakes in the vicinity of the San Gorgonio Fault Zone, Jennifer M. Tarnowski and Abhijit Ghosh (Poster 160)**

The San Gorgonio Pass (SGP) is a structurally complex region along the southern California portion of the San Andreas fault system with several thrust and strike-slip faults dissecting the area. The role of the San Gorgonio Pass in southern California seismic hazard is somewhat ambiguous, partly because of the sheer number of faults in the region. One of these fault zones is the San Gorgonio fault zone (SGFZ). The SGFZ is a pre-existing strike-slip fault with right-lateral strike-slip faults that may influence the behavior of the San Andreas fault system. Despite its potential role in southern California seismic hazard, tectonic behavior and structure of the SGFZ and surrounding faults are not well characterized. We use data from a 4-month, temporary, passive network in Banning, CA to better understand the behavior of the SGFZ and adjacent faults. In particular, we investigate whether magnitude 6.0 and greater teleseismic events can remotely trigger seismic activity in and around the SGFZ. Locating triggered earthquakes will provide a better understanding of the triggering phenomenon in this region. Dynamic triggering of local earthquakes in the SGP could help determine the subsurface geometry of select thrust faults in the region based on the azimuth of the teleseismic events. We use earthquakes from the Advanced National Seismic System catalog and previously undetected earthquakes visible in our local network data to determine the background rate of seismicity and any deviation from that rate. Preliminary analysis shows an increase in seismic activity for several hours in the vicinity of the SGFZ immediately following large magnitude teleseismic events.

**Some thoughts on estimating maximum magnitude and corner magnitude, Matteo Taroni, Jeremy D. Zechar, and Warner Marzocchi (Poster 147)**

Mmax, the size of the largest possible earthquake in a region, is one of the least certain parameters used to assess seismic hazard. In a strict sense, Mmax can only be interpreted if you assume that the distribution of earthquake magnitudes has some upper limit, i.e., the truncated Gutenberg-Richter distribution. Unfortunately, you cannot estimate Mmax and its uncertainty using only the magnitudes recorded so far; you also need to incorporate independent data such as those from geodesy or paleoseismology, and these data have additional uncertainties. Rather than struggling with Mmax, some seismologists have suggested using a different parameterization of the magnitude distribution: one that is tapered rather than truncated, shifting the focus to the point at which the taper begins, the so-called “corner magnitude”. In this presentation, we describe frequentist and Bayesian methods for estimating the corner magnitude; we demonstrate that you can obtain a confidence interval for the corner magnitude using one or more earthquake catalogs of sufficient length; we suggest that the corner magnitude varies with tectonic regime; and we explain why our results are different from those of previous studies.

**Building a SCEC Community Thermal Model, Wayne Thatcher, David Chapman, Elizabeth Hearn, and Colin Williams (Poster 228)**

SCEC needs to develop one or a few standard 3D Community Thermal Models (CTMs) as common starting points for regional deformation modeling being planned for SCEC5. Here we illustrate this development by showing observational data relevant to constraining the temperature field beneath southern California and by computing several 1D geotherms with their likely uncertainties. We first note a strong inverse correlation between observed surface heat flow and lithospheric thickness beneath southern California estimated from Sp receiver function analysis (Lekic et al., 2011), suggesting the influence of lithosphere asthenosphere boundary (LAB) depth on the thermal field. Results from seismic imaging can also be used to bound the rock thermal properties that play a strong role in determining the geotherms.

We plan a phased approach to estimating the 3D temperature field, beginning with simple 1D steady state conductive models. We identify the most important parameters and disaggregate them, separately examining their likely uncertainties. We then plan a steady state approach that is not directly coupled to the geotherms.

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range of model parameters. Preliminary 1D geotherms and their uncertainties are illustrated for 3 points on the LARSE I profile. The derived geotherms predict the position of the lithosphere-asthenosphere boundary (LAB), which can be compared with the seismically estimated LAB depth.

Although other parameter uncertainties contribute, variability in heat sources produces the largest variation in model-predicted geotherms. Because heat production depends strongly on rock type, better characterization of crustal lithology using refined seismic imaging results now becoming available beneath southern California is likely to produce the largest improvements in thermal models. Nonetheless, substantial uncertainty will remain, arguing for adoption of one or a few standard thermal models.

Tsunami hazard from earthquakes on the Ventura-Pitas Point fault and adjacent structures, Hong Kei Thio, Kenny Ryan, Rick Wilson, Andreas Plesch, David Oglesby, and John Shaw (Poster 151)

Offshore faulting in the Continental Borderland poses a potential local tsunami hazard in Southern California. Although the hazard from most of the major structures is limited due to the fault geometry or long recurrence times, for some, such as the Ventura-Pitas Point structure this is not the case. Recent studies have shown the recurrence times for major earthquakes on this structure to be on the order of several hundred to several thousand years, well within the range of engineering interest. While the recurrence model (magnitude distribution and return periods) is not clearly established yet, we have estimated the tsunami impact of several scenarios of major earthquakes on the Southern California coastline.

As expected, large events on this system cause significant amounts of inundation along the coast in Ventura and, to a lesser degree, Santa Barbara counties. While local bathymetry of the Continental Borderlands causes energy focusing and reverberations with the Santa Barbara Channel, the tsunami waves outside of the Santa Barbara Channel attenuate rapidly, and therefore the tsunami hazard diminishes to the south and east. Details in the fault geometry and slip distribution are important for the tsunami simulations, and we will explore different models as well as events on the nearby Oak Ridge fault.

We will present these results in the context of the existing and upcoming (draft) tsunami hazard modeling and maps from the California Geological Survey as well as the tsunami evacuation zone used by the counties. Our preliminary results suggest that the hazard from the largest scenarios (M > 7.7) on the Ventura-Pitas Point structure in Ventura county is of the same order of magnitude as both the existing tsunami hazard and evacuation maps and the upcoming 2500 year draft maps. A better understanding of the recurrence model for this source is therefore essential in determining whether these fault systems will significantly add to the existing tsunami hazard models. Outside of Ventura County, the tsunami hazard from the Ventura-Pitas Point system is very limited and is unlikely to contribute much to the tsunami hazard maps of those areas.

Scale Dependence of Fault Roughness to Nanometer Length Scales, Christopher A. Thom, Thibault Candeia, David Goldsby, Robert W. Carpick, and Emily Brodsky (Poster 273)

Frictional properties of laboratory and natural fault surfaces are controlled by the collective behavior of microscopic asperity contacts. A fundamental parameter that determines the spatial distribution and average size of asperity contacts on a fault surface is the roughness at all length scales. Average contact sizes for laboratory friction experiments are inferred to be of order 1 to 10 µm, but contact sizes on natural faults are comparatively unknown. Previous studies have quantified surface roughness of exhumed faults over length scales of microns to tens of meters, but roughness at sub-micron length scales has rarely been determined. For length scales of tens of microns and larger, self-affine roughness is observed, exhibiting anisotropic scaling with a Hurst exponent of 0.6 in the slip-parallel direction and 0.8 in the slip-parallel direction (Candeia et al., 2012). Using intermittent contact atomic force microscopy (AFM), we have probed natural fault surfaces over profile lengths as large as ~100 µm with nanometer resolution in the slip-parallel and slip-perpendicular directions and sub-nanometer resolution in the third dimension. Surface roughness at length scales of tens of microns and smaller also demonstrates a self-affine character, but characterized by a Hurst exponent of 0.7 in both the slip-parallel and slip-perpendicular directions, in contrast to the different slip-parallel and slip-perpendicular values cited above. Taken together, our data and existing roughness data for several other faults demonstrate self-affine geometry over ~13 orders of magnitude in lateral length scale, to scales as small as 10 nm. Roughness measurements in the sub-micron regime allow us to use contact theory to estimate the real area of contact, the mean pressure, and the distribution of contact stresses on a rough fault surface. Calculations using our measured roughness show that contact stresses for asperities microns and smaller in size are large enough to induce plastic deformation. In addition, we hypothesize that the merging of values of the Hurst exponent for both slip-parallel and slip-perpendicular roughness that occurs below a length scale of tens of microns indicates a transition from predominantly brittle deformation at larger scales to plastic deformation at smaller scales.

Evolution of the Palos Verdes Fault near Lasuen Knoll, Offshore Southern California, Michael A. Thompson and Robert D. Francis (Poster 102)

The Palos Verdes Fault (PVF) is a subvertical, multi-stranded oblique dextral shear zone that extends from Santa Monica Bay in the north through the Palos Verdes Peninsula and across San Pedro Bay in Southern California. It is one of several Inner Borderland northwest-trending faults formed during middle Miocene rifting. Neogene deformation involved dextral slip on most northwest-trending faults and clockwise rotation of crustal blocks as a result of capture of fragments of the Farallon Plate by the Pacific Plate, leading to tectonic inversion of the PVF.

Recent seafloor expressions of the PVF are evident where the PVF forms a transpressional contact at Lasuen Knoll. The PVF appears to die out or undergo steps before slip continues along the Coronado Bank Fault Zone (CBFZ).

This study in seismic stratigraphy catalogs the evolution of the Lasuen Knoll segment of the Palos Verdes Fault, and analyzes where and how slip on the fault is transferred at its southern extent to the CBFZ. Analysis of structure and isochore maps of stratigraphic sequences generated using deep-penetrating seismic data, 2D high-resolution seismic data, well logs, paleontological reports, and high-resolution seafloor bathymetry and backscatter imagery summarizes the sedimentological and structural processes that have occurred locally over the lifespan of the basin and the mechanisms which have caused their occurrence. This study culminates synthesizing the relationship between the PVF to Lasuen Knoll and the CBFZ, as well as the effects of Inner Borderland tectonic evolution on the development of this southern segment of the PVF.

Joint inversion of direct P and S waves, head waves and noise dispersion data for the San Jacinto fault region, Clifford Thurber, Yehuda Ben-Zion, Haijiang Zhang, Hongjian Fang, Xiangfang Zeng, Zach Ross, Dimitri Zigone (Poster 186)

We are working to improve the structural model for the southern San Andreas-San Jacinto fault region, with a focus on Vs, bimaterial interfaces, attenuation, and zones with elevated rock damage and fluids associated with anomalous Vp/Vs ratios. Our study utilizes recently developed tomography methodologies that incorporate (1) fault zone head waves (FZHWs) and (2) an inversion scheme combining noise-based dispersion data and body-wave data. We also take advantage of new automatic phase picking algorithms that yield a high percentage of accurate S-wave arrivals (70% to 90% of the number of P waves) and, in one case, includes FZHW picking. The accuracy of the SCEC Community Velocity Model (CVM) will be assessed in our study region.

We present results from a preliminary joint inversion of existing body-wave arrival times and surface-wave dispersion data (from ambient noise). The body-wave and surface-wave data are quite complementary. The ambient noise data allow almost all station pairs to be used, meaning that model sampling is quite good. The body-wave data generally provide better resolution at depth whereas the surface wave data have greater sensitivity near the surface. There are two versions of the joint inversion method, one requiring an intermediate step of determining phase or group velocity maps, whereas the other models phase and/or group velocity travel times directly in a one-step inversion. A checkerboard test demonstrates the
We also present preliminary results from a comparison of two recently developed auto-picking algorithms. One uses a combination of parametric approaches including STA/LTA, kurtosis, and skewness calculations, and polarization filtering for S waves. The other uses a non-parametric approach assessing the similarity of a given time window of data to a set of reference picks relative to its similarity to a set of time windows of noise. In separate tests, the parametric approach reproduced reviewed manual picks to within 0.25 s 90% of the time, whereas the non-parametric approach reproduced reviewed manual picks to within 0.2 s more than 90% of the time. In contrast to the previous tests done on different datasets, we perform in the current study a "head-to-head" comparison on a single dataset.

Rupture Patterns Due to Aseismic Creep During the 2013-2014 California Drought Match Deformation Structures Observed in the 5000 Year Dry Lake ValleyPaleoseismic Record, Nathan A. Toke, Michael Bunds, James B. Salisbury, Andrew Lawrence, and J. R. Arrowsmith (Poster 110)

Ultra-high-resolution mapping and paleoseismic investigation of the Dry Lake Valley site (DLV: 36.4679, -121.0556) in San Benito County, California presents evidence of a > 5000 year record of San Andreas Fault (SAF) deformation due to creep. From January 2013 to October 2014 this area was historically dry, producing no hydrologic events capable of saturating the soil. Over this 1.8 year period the central SAF experienced ~6 cm of right lateral creep at depth. In the absence of significant exogenic soil disturbance, creep was manifest as sets of left-stepping, en-echelon, opening-mode, ground cracks accommodating 2.5 +/- 1 cm of right-lateral creep on the surface trace of the fault. On average, individual fractures were 54 cm long with 20% overlap between each fracture step.

Investigating 3D deformation of an evolving restraining bend using physical experiments and numerical models, Kevin Toeneboehn, Aviel Stern, Michele Cooke, and Alex Hatem (Poster 084)

We use physical experiments and numerical models to simulate the deformation around a 15° restraining bend that resembles bends along active faults within southern California. Hatem et al. (2015) show that scaled claybox experiments reveal the evolving efficiency of restraining bends. Wet kaolin clay has the benefit of producing long-lived fault structures that easily reactivate. This benefit, along with its low strength that permits crustal scaling, makes it an ideal material for modeling slip-partitioned systems. Building on the success of this method, we use the claybox to directly observe deformation during the evolution of a 15° restraining bend and use this data to calibrate a numerical simulation. The 15° restraining bend experiment highlights the slip partitioning between active strike slip and oblique slip along dipping outboard faults. During the experiments, the clay is placed over two metal plates with a 15° bend basally. A vertical fault is precut along the contact of the two plates to model an active strike slip system. We record continuous 3D deformation using 2D Particle Image Velocimetry (PIV) for horizontal displacements combined with computer stereovision for uplift. The addition of continuous uplift measurements allows us to quantify off-fault deformation and facilitates comparison of experimental observations to the numerical model results. The numerical models use a boundary element method deformation software (Poly3D) and are calibrated to the experiments. The simulations provide the 3D distribution of stresses and strains throughout the system from which the complete work budget is calculated. We compare uplift pattern, slip distribution and kinematic efficiency of the physical experiment with the uplift pattern, slip distribution and external work of numerical models at three different stages during the experiment. The stages investigate the evolution of the fault system. These results reveal how deformation is accommodated spatially and temporally as fault slip and off-fault deformation, including uplift. The stress results from the numerical models predict the propagation path of the evolving restraining bend. In addition, the numerical models provide external work that can be compared to the evolution of kinematic efficiency. The results confirm that the efficiency increases as faults evolve around the restraining bend.
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descending orbits. However, spatial coverage is limited to arid regions. Where both look directions are available one can separate the horizontal and vertical deformation. Because the InSAR velocity field is subject to orbital errors and/or ionospheric noise, we added constraints to the InSAR velocity field such that they agree with the GPS velocity field at spatial scales greater than about 40 km. The combined results consisting of a growing compilation of campaign and continuous GPS vector velocities as well as InSAR line-of-sight (LOS) velocities and uncertainties are archived at UNAVCO. All data are referenced to a fixed North America frame. The data will be most useful for constraining time-independent kinematic block models.

The InSAR line-of-sight velocity maps reveals new details in the deformation field including along-strike variations of the aseismic fault creep, localized subsidence in the sedimentary basins and fault step-overs, and anomalous velocity gradients along active fault strands. This accurate and high-resolution secular velocity field can be used to constrain the long-term fault slip rates, aseismic creep rates, and the rheology of the lithosphere.

A comparison of long-term changes in seismicity at the Geysers, Salton Sea, and Coso geothermal fields, Daniel T. Trugman, Peter M. Shearer, Adrian A. Borsa, and Yuri Fialko (Poster 139)

Geothermal energy is an important source of renewable energy for the state of California, yet the extraction and subsequent reinjection of fluids required for geothermal energy production carries with it the potential for induced seismicity and associated hazard. Here we provide a quantitative comparison of the temporal changes in seismicity in three of the largest geothermal fields in California - the Geysers, Salton Sea, and Coso - each of which has experienced a unique history of energy production and exists within its own distinct tectonic setting. Our central focus is upon the temporal evolution of seismicity rates, which provide important observational constraints on the ways in which the subsurface within each geothermal field responds to anthropogenic stresses and natural loading. We develop an iterative, regularized inversion procedure to partition the observed seismicity rate into two primary components: (1) the interaction seismicity rate due to earthquake-earthquake triggering, and (2) the time-varying background seismicity rate controlled by other time-dependent stresses, including anthropogenic forcing. We parameterize our seismicity model using an Epidemic-Type Aftershock Sequence (ETAS) framework with a background seismicity rate that varies smoothly with time. We apply our methodology to study long-term changes in seismicity rates at each geothermal field, and compare these changes to monthly records of fluid injection and withdrawal. At the Geysers, we find that the background seismicity rate is highly correlated with fluid injection, with the mean rate increasing by approximately 50 percent and exhibiting strong seasonal fluctuations following the completion of the Santa Rosa pipeline. In contrast, at both the Salton Sea and Coso geothermal fields, the background seismicity rate has remained relatively stable since 1990, though both fields experience short-term rate fluctuations that are not obviously modulated by geothermal plant operation. At each of the three geothermal fields, we also observe significant temporal variations in both the magnitude and depth distributions of earthquakes, consistent with previous observational and theoretical studies of induced seismicity.

The Brawley Seismic Zone: Geologic, Seismic, and Dynamic Constraints on Possible Through-going Rupture Scenarios, Drew Tulanowski, Christodoulos Kyriakopoulos, Aron Meitzner, Thomas Rockwell, and David Oglesby (Poster 309)

Seismicity in the Brawley Seismic Zone and the indistinguishable timing of large paleoseismic ruptures of the Imperial and southernmost San Andreas faults suggest that there is a possibility of through-going fault structures connecting the Imperial fault to the southern San Andreas fault. Using the Waveform Relocated Earthquake Catalog for Southern California from 1981 to 2011 (Hauksson et al., 2012), one can outline two general paths that a through-going fault might take if present. Using the 3D finite element method (Barall, 2009) and realistic fault geometry, we test if an earthquake rupturing on the Imperial Fault can travel along one or more of these possible through-going faults and allow slip to propagate to the San Andreas. We test the sensitivity of rupture propagation to nucleation location, determine which of the potential through-going structures is the more likely rupture path, and what the partitioning of slip might be in this system. In addition, the seismicity indicates a series of left-lateral cross fault structures that run through the Brawley Seismic Zone, possibly intersecting and connecting our two through-going fault structures. Future experiments will incorporate these cross faults and test how they play a role in this area. The results may have implications for seismic hazard not just in the Imperial Valley, but also throughout Southern California.

Kinematic rupture process of the 2014 Mw 6.0 Napa earthquake: A case study of the uncertainty of peak slip, Cedric Twczdzik, Mike Floyd, Chen Ji, and Gareth Funning (Poster 028)

The spatio-temporal rupture history of the 2014 South Napa earthquake is constrained using both near-fault strong motion records and GPS vectors. Our preliminary analysis with just strong motion data has revealed a mainly north-north-west (NNW) and up-dip propagation on a 13 km long fault patch, accompanying with secondary ruptures on two small and isolated slip patches. The latter excited the largest ground acceleration at stations south of the epicentre. A gradual increase in average rise time when the rupture propagates to shallower depth has been observed. Our result is generally consistent with published solutions but among them there is a factor of three difference in inverted peak slip. Here, we further constrain the uncertainty of important fault kinematic parameters, in particularly peak slip, using a newly developed object-oriented finite fault inversion approach and combined seismic and geodetic dataset.

Is there a “blind” strike-slip fault at the southern end of the San Jacinto Fault system?, Ekaterina Tymofyeyeva and Yuri Fialko (Poster 210)

We have studied the interseismic deformation at the southern end of the San Jacinto fault system using Interferometric Synthetic Aperture Radar (InSAR) and Global Positioning System (GPS) data. To complement the continuous GPS measurements from the PBO network, we have conducted campaign-style GPS surveys of 19 benchmarks along Highway 78 in the years 2012, 2013, and 2014. We processed the campaign GPS data using GAMIT to obtain horizontal velocities. The data show high velocity gradients East of the surface trace of the Coyote Creek Fault. We also processed InSAR data from the ascending and descending tracks of the ENVISAT mission between the years 2003 and 2010. The InSAR data were corrected for atmospheric artifacts using an iterative common point stacking method. We combined average velocities from different look angles to isolate the fault-parallel velocity field, and used fault-parallel velocities to compute strain rate. We filtered the data over a range of wavelengths prior to numerical differentiation, to reduce the effects of noise and to investigate both shallow and deep sources of deformation. At spatial wavelengths less than 2km the strain rate data show prominent anomalies along the San Andreas and Superstition Hills faults, where shallow creep has been documented by previous studies. Similar anomalies were also observed along parts of the Coyote Creek Fault, San Felipa Fault, and an unmapped southern continuation of the Clark strand of the San Jacinto Fault. At wavelengths on the order of 20km, we observe elevated strain rates concentrated east of the Coyote Creek Fault. The long-wavelength strain anomaly east of the Coyote Creek Fault, and the localized shallow creep observed in the short-wavelength strain rate data over the same area suggest that there may be a “blind” segment of the Clark Fault that accommodates a significant portion of the deformation on the southern end of the San Jacinto Fault.

Evidence for elastic rebound and stress transfer in aftershock spatial distributions, Nicholas J. van der Elst and Bruce E. Shaw (Poster 057)

Aftershocks are driven by stress concentrations left within the mainshock rupture patch, and by static or dynamic stress transfer to adjacent fault sections or strands. The distribution of aftershocks both inside and outside the mainshock rupture may help constrain the processes of stress relaxation and transfer. Here we quantify two important features of the aftershock zone that illuminate the physical processes involved: 1) the tendency for large aftershocks to nucleate outside the mainshock rupture, and 2) the decay of smaller aftershocks within and away from the mainshock rupture. First, we use double-difference relocated earthquake catalogs to examine M=4 mainshocks in California and demonstrate that larger aftershocks occur farther away than smaller aftershocks, relative to
the centroid of early aftershock activity – a proxy for the mainshock rupture. Aftershocks as large or larger than the mainshock nucleate almost exclusively outside the initial rupture. This is evidence of stress relaxation on the mainshock rupture patch (elastic rebound), which leaves aftershocks on the interior with little room to grow. Second, we measure the spatial distribution of aftershocks smaller than the mainshock, using an explicit correction to take into account the dimensionality of the fault plane and the finite seismogenic thickness. We find that small aftershocks are distributed uniformly within the mainshock rupture, with a transition to power-law decay at the edge of the rupture. The distance to the transition is consistent with the theoretical $M_0 = 3\Delta\lambda L^3$ source scaling expected for the mainshock, with a stress drop $\Delta \sigma = 3$ MPa. The power-law decay beyond the rupture is consistent with the $r^{-\gamma}$ slope expected for static stress fall-off away from a double-couple dislocation. The distance decay is well fit by a model consisting of a single fault with a finite seismogenic thickness, with no need to appeal to complex fractal fault structures that have commonly been invoked. These observations can improve the spatial forecasting of large aftershocks, and validate the use of the elastic rebound concept in fault-based stochastic earthquake simulators (e.g. UCERF3-ETAS). Aftershock spatial distributions are influenced by the finite size of both the mainshock and aftershocks; probabilistic kernels must therefore treat magnitude and position together in order to best forecast the largest, most damaging aftershocks.


The NASA/Jet Propulsion Laboratory (NASA/JPL) InSight E/PO team and Southern California Earthquake Center (SCEC) along with California State University San Bernardino (CSUSB), and USGS-Pasadena engaged science educators in the Vital Signs of the Planet Professional Development Program, an NGSS aligned middle school and high school research experience and curriculum development program offering strong connections to STEM research. The program fellowships interacted with scientists at Caltech, JPL, and USGS-Pasadena. They were briefed on topics including seismic hazards, the Quake Catcher Network, Earthquake Early Warning Systems, GPS, and earthquake information technology at Caltech and USGS. While at JPL, they met with researchers in their labs and were briefed on the InSight (Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport) mission to Mars by the mission Principal Investigator. An important aspect of this experience was participation in a 4-day field research component, wherein teachers contributed to ongoing research on tectonic plate deformation along the San Andreas fault lead by Sally McGill of CSUSB. They plotted data collected through GPS and utilized modeling programs for analysis of slip rate around the fault. The combination of these experiences lead to the development and implementation of four lessons in Earth science and physics. Using the Lesson Study model, a professional development process where educators systematically examine their practice, participants identified where their students encounter learning challenges. Taking into consideration the Next Generation Science Standards (NGSS) and the Common Core State Standards, teachers collaborated to develop lessons that focused on what teachers want students to learn rather than on what teachers plan to teach.

Paleoseismic Trenching of the Alquist-Priolo Zoned Duarte Fault Reveals No Fault in Late-Pleistocene sediments, Danielle M. Verdugo Madugo, Tania Gonzalez, Eldon Gath, Maria Herzberg, and Matt Pendleton (Poster 120)

The Sierra Madre fault (SMF) zone marks the northern boundary of a series of west-trending blind and surficial faults that accommodate contraction across the LA and San Gabriel Basins. The Duarte fault is considered one of the better defined southern strands of the SMF, and as a result, has been zoned by the California Geological Survey (CGS) as an active fault in their Fault Evaluation Report 249 released in 2014. In response to this zoning, an approximately 500 ft long trench was excavated in the City of Bradbury across the geomorphically defined trace of the Duarte fault. This 2-4 m deep trench exposed no faulting or folding in late-Pleistocene deposits. Holocene depositions were common. These findings support the concern about the entire validity of the CGS’ zoning of faults based on no prior visual observations of the presence of a fault, let alone a Holocene fault. If the “best example” of a sufficiently active and well-defined fault “is revealed to have no fault-affected stratigraphy in Pleistocene sediments, then why was this “fault” ever zoned?  

Computing Spatial Correlation of Ground Motion Intensities for ShakeMap, Sarah A. Verros, David J. Wald, C. Bruce Worden, Mike Heaune, and Nick Horssoll (Poster 175)

Although much attention has been devoted to the prediction of ground motion intensity measures (IMs) at a set of individual sites, capturing the intraevent, or within-event, spatial correlation present within ground motions is not yet a standard practice. Modeling the spatial correlation of residuals (epsilon), caused by coherent contributions from source, path, and site, can provide valuable loss and hazard information, as well as a more realistic picture of ground motion intensities. A number of authors have developed models that describe the decay in spatially correlated epsilon as a function of increasing site-to-site separation distance. Using the distances between points on a ShakeMap grid, a spatially correlated random field may be conditioned on data from seismic stations, where it is expected that the random field will converge to zero near observations, or simulated without constraints for scenario purposes. The resultant correlated random field may then be added to a ShakeMap grid to obtain a realization of spatially correlated ground motions. Simulating the correlated fields is computationally expensive in terms of both time and memory. To optimize the computation, we explore the method of successive conditional simulations utilizing a radius of influence, beyond which point conditionation no longer significantly affects the field. This method parallelizes the method to maximize efficiency and bring the computational time closer to real-time speeds. To understand the impacts on losses, we apply the USGS PAGER (Prompt Assessment of Global Earthquakes for Response) system to estimate the fatalities and economic losses for realizations of the spatially correlated ground motions; for example, the earthquakes from which spatial correlations were captured observationally and losses are known. It is seen using the Northridge, Loma Prieta, and Chi-Chi earthquakes that adding spatial correlation to events constrained with many realizations does not significantly alter the distribution of loss estimates; however, for scenarios, the loss distribution noticeably changes with an increased mean and standard deviation.

Elastic block modeling of fault slip rates across Southern California using updated GPS velocity data from the San Bernardino Mountains and vicinity, Tiffany Vlahopoulos, Liam DiZio, Sally McGill, and Joshua Spinler (Poster 305)

We present fault slip rate estimates for Southern California based on GPS velocity data from UNAVCO, SCEC, and new campaign GPS velocity data from the San Bernardino Mountains and vicinity. Fault slip-rates were calculated using Tdefnode, a Fortran program used to model elastic deformation within lithospheric blocks and slip on block bounding faults (McCaffrey, 2015). Our block model comprised most major faults within Southern California. Tdefnode produced relatively similar slip rate calculations as compared to other geodetic modeling techniques. The fastest slipping faults are the Imperial fault (37.4±0.1 mm/yr) and the Brawley seismic zone (23.5±0.1 mm/yr). The slip rate of the San Andreas fault decreases northward from 18.7±0.2 mm/yr in Coachella Valley to 6.6±0.2 mm/yr along the Banning/Garnet Hill sections, as slip transfers northward into the Eastern California Shear Zone (9.4±0.3 mm/yr on the Camprock-Emerson-Homestead Valley faults and 3.4±0.5 mm/yr on the Calico-Pisgah-Bullion-Mesquite Lake faults). Slip remains slow on the San Gorgonio Pass and San Bernardion Valley sections (5.6±0.2 mm/yr and 4.3±0.2 mm/yr, respectively). North of the junction with the San Jacinto fault (10.5±0.2 mm/yr), the San Andreas fault slip rate increases to 14.2±0.1 mm/yr in the Mojave section. Tdefnode slip rate estimates match well with geologic estimates for SAF (Coachella), SAF (San Gorgonio)
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Pass), San Jacinto, Elsinore, and Whittier faults, but not so well for other faults. Our model improved on those of past SCEC interns and is another step in the use of the Tdefnode program as a viable modeling technique for undergraduate research studies.

**Plate Boundary Observatory GPS Network Status in California**, Christian Walls, Doerte Mann, Andre Basset, Ryan Turner, Shawn Lawrence, Ken Austin, Tim Dittman, David Kasper, Adam Woolace, Kathleen Hodgkinson, Karl Feaux, Glen Mattioli (Poster 192)

The EarthScope PBO GPS network, funded by the NSF and operated by UNAVCO, is comprised of 599 permanent GPS stations spanning three principal tectonic regimes and is administered by separate management regions (Subduction - Pacific Northwest [91 sites], Extension - East [41 sites], Transform - Southwest [467 sites]). Since the close of construction in September 2008 various enhancements have been implemented through additional funding by the NSF, NOAA, and NASA and in collaboration with stakeholders such as Caltrans, Scripps, and the USGS.

Initially, the majority of stations used first generation IP based cellular modems and radios capable of ~10KB/s data rates. The bandwidth limitation was a challenge for regional high-rate data downloads for GPS-seismology and airborne LIDAR surveys, and real-time data flow. Today, only 13 of the original cell modems remain with 297 upgraded cell modems providing 3G/4G/LTE data communications with transfer rates ranging from 80-400 KB/s. Ongoing radio network expansion and upgrades continue to harden communications. 32 VSAT and one manual download site remain. In CA, the network capabilities for 1Hz and 5Hz downloads or real-time streaming are ~95%, ~80% and ~85%, respectively.

During the past year, uptime ranged from 94-99% with data return for 15 s data exceeding 99%. Real-time (1 Hz) data from 204 sites are distributed in BINET and RTCM 2.3/3/1 formats with an average latency of 0.7 s and completion of 91%. A variety of geophysical sensors are co-located with the GPS stations and include: 21 MEMS accelerometers, 31 strong motion and broadband seismometers, 9 boreshole strainmeters and 1 long baseline strainmeter. Vaisala meteorological instruments are located at 60 sites of which 38 stream GPS/Met data.

In an effort to modernize the network, Trickle NetRS receivers are gradually being replaced with GNSS-capable/enabled receivers and antennas. Today, 11 stations are GLONASS enabled and 84 are GNSS capable.

**Inversions of surface displacement data for coseismic slip with Finite Element Models incorporating topography and 3-D rigidity structure: A case study of the 2010 Mw 7.2 El Mayor Cucapah (Mexico) earthquake**, Yongfei Wang, Steven Day, and Peter Shearer (Poster 168)

Earthquake source properties such as seismic moment and rupture extent are routinely estimated from far-field body-wave amplitude spectra. Low-frequency spectral level, corner frequency, and the high-frequency spectral slope are often measured and combined to make inferences about physical parameters such as stress drop and radiated energy. Based on theoretical models (e.g., Brune, 1970), some quantititative, but model-dependent, relations have been established between far-field spectra and such physical parameters.

Numerical simulations of dynamic rupture, of either artificial fixed rupture speed (Madariaga, 1976, Kaneko and Shearer, 2014) or physically spontaneous models, have extended the scope of available models. Rupture processes based upon rate and state frictional laws with dynamic weakening have been found from simulations to illustrate two different modes: the expanding crack and self-healing rupture, which result in distinct shapes for slip velocity function. In the expanding crack mode, a fault keeps slipping everywhere within the rupture zone until arrested by a strong stopping phase coming from fault unbroken edges. Thus, high-frequency energies can be radiated from such stopping phase. However, in the self-healing mode, rupture occurs as a slip pulse controlled by the local frictional stress rather than by rupture cessation signals.

Models with spontaneous propagation and stopping of rupture in expanding crack or self-healing modes, may improve our understanding of the relationship between spectral parameters and the physical parameters of rupture. We use a simplified model of rupture propagating and stopping spontaneously, in expanding crack and self-healing modes, to investigate the relationship of spectral slope and corner frequency to physical parameters of rupture. It is found that self-healing rupture mode may induce double slope or double corner frequency spectral shape and increase spherically average corner frequency.

**Relative Contributions of Geothermal Pumping and Long-Term Earthquake Rate to Seismicity at California Geothermal Fields, Deborah A. Weiser and David D. Jackson**

In a tectonically active area, a definitive discrimination between geothermally-induced and tectonic earthquakes is difficult to achieve. We focus our study on California’s 11 major geothermal fields: Amedee, Brawley, Casa Diablo, Coso, East Mesa, The Geysers, Heber, Litchfield, Salton Sea, Susanville, and Wendel. The Geysers geothermal field is the world’s largest geothermal energy producer. California’s Department of Oil Gas and Geothermal Resources provides field-wide monthly injection and production volumes for each of these sites, which allows us to study the relationship between geothermal pumping activities and seismicity. Since many of the geothermal fields began injecting and producing before nearby seismic stations were installed, we use smoothed seismicity since 1932 from the ANSS catalog as a proxy for tectonic earthquake rate. We examine both geothermal pumping and long-term earthquake rate as factors that may control earthquake rate.

Rather than focusing only on the largest earthquake, which is essentially a random occurrence in time, we examine how M>4 earthquake rate density (probability per unit area, time, and magnitude) varies for each field. We estimate relative contributions to the observed earthquake rate of M>4 from both a long-term earthquake rate (Kagan and Jackson, 2010) and field-related seismic events. We consider earthquake catalogs (NCEDC and SCESN) are complete above at least M3 during the test period (which we tailor to each site). We test the hypothesis that the patterns of slip distribution similar to those inferred in previous studies based on elastic half-space solutions. As expected, the slip model accounting for material heterogeneities has a deeper moment centroid, primarily due to an increase in elastic rigidity with depth. Surface topography seems to have little effect on the inverted slip distribution in case of El Mayor Cucapah earthquake, as elevation changes are relatively minor (< 1 km). The slip model is characterized by 3 asperities in the upper crust (depth < 10 km), with maximum slip up to ~4 m. Most of the aftershocks are located in areas of relatively low coseismic slip at the periphery of coseismic asperities.
observed earthquake rate at a geothermal site during the test period is a linear combination of the long-term seismicity and pumping rates. We use a grid search to determine the confidence interval of the weighting parameters.

**Physics-based Earthquake Forecasting: Encouraging Results from a Retrospective CSEP Evaluation of Forecasting Models during the 2010 Canterbury, New Zealand, Earthquake Sequence**, Maximilian J. Werner and the CSEP Canterbury Working Group (Invited Talk Tue 10:30)

Despite much progress in our understanding of the physical mechanisms of earthquake nucleation, clustering and triggering, physics-based earthquake forecasting remains a major challenge. For instance, evaluations of the predictive power of the static Coulomb stress change hypothesis for earthquake clustering have up to now concluded that Coulomb-based forecasts could not compete with statistical models, which exploit statistical regularities of observed seismicity patterns. In sharp contrast to previous results, a recent experiment by the Collaboratory for the Study of Earthquake Predictability (CSEP) suggests that newly developed and improved Coulomb-based models are now competitive alternatives that can outperform statistical models. The CSEP experiment consisted of a retrospective evaluation of time-dependent forecast models during the complex and fatal 2010-12 Canterbury, New Zealand, earthquake cascade. Fourteen models were developed by groups in New Zealand, Europe and the US, including statistical, physics-based and hybrid models. We evaluated the models from the time just after the Mw7.1 Darfield earthquake until February 2012 using three forecast durations (1-year, 1-month and 1-day). We found that the information content of physics-based and hybrid model forecasts is greater than or comparable to that of statistical model forecasts at all forecast horizons. Differences are greatest for 1-yr horizons, where variants of the Coulomb model and a hybrid model outperform a reference ETAS model by a probability gain per earthquake of about 7. These results offer some encouragement for a physical basis for earthquake forecasting. We speculate on further model developments as well as the use of finite earthquake rupture simulators for the purpose of earthquake forecasting.

**A Large Scale Automatic Earthquake Location Catalog in the San Jacinto Fault Zone Area Using An Improved Shear-Wave Detection Algorithm**, Malcolm C. A. White, Zachary E. Ross, Frank Vernon, and Yehuda Ben-Zion (Poster 134)

UC San Diego’s ANZA network began archiving event-triggered data in 1982. As a result of improved recording technology, continuous waveform data archives became available starting in 1998. The continuous dataset, from 1998-present, represents a wealth of potential insight into spatio-temporal seismicity patterns, earthquake physics and mechanics of the San Jacinto Fault Zone. However, the volume of data renders manual analysis costly. In order to investigate the characteristics of the data in space and time, an automatic earthquake location catalog is sought. To this end, a processing flow is being developed, consisting of standard techniques using a STA/LTA P-wave detector in cooperation with a newly improved S-wave detection algorithm and a location inversion that makes use of a 3D velocity structure. Improved S-wave detection capabilities are expected to result in a catalog with quality superior to those processed without the specialized S-wave detector. The resulting arrival time observations are processed with a grid based association algorithm to produce initial absolute hypocenter locations, which are refined with a location inversion method that accounts for 3D velocity heterogeneities. Precise relative locations are then derived from the refined absolute locations using the HypoDD double-difference algorithm. The resultant catalog of high quality automatic earthquake locations is expected to yield new insight into characteristics of the data collected by the ANZA network over the past 17 years. Further details on the results of processing will be presented at subsequent meetings.

**Exploration of a new paleoseismic site in the Cholame section of the San Andreas fault, CA ,** Alana M. Williams, J.R. Arrowsmith, Sinan O. Akciz, and James B. Salisbury (Poster 088)

The Cholame segment of the San Andreas Fault (SAF) poses a significant challenge to testing earthquake recurrence models along the central SAF. We need evaluations of offset distributions coupled with tightly constrained event age control to correlate spatial distribution of ruptures between the Parkfield and Carrizo sections of the SAF. We excavated five exploratory fault-perpendicular trenches within an abandoned gypsum mine (35.253478°, -119.585675°) in the southeastern portion of the Cholame segment. Trenches B, C, E, F, and G were chosen for excavation based on compelling tectonic landforms and geomorphology. These include the alignment of steep scarps, sag ponds and depressions, as well as the small alluvial fans draining across the fault trace, and inferred sedimentation rates. Trenches B and C, excavated in two proximal sag ponds, contained massive clay, clayey silt and pebbles. They lacked discernable unit boundaries and fault evidence. The sedimentary textures (clays + pebbles) are consistent with colluvial transport from the adjacent steep scarps. Trench E was located in the largest sag pond just north of a stepover in the fault trace, between an evaporite-encrusted playa and large alluvial fan draining south. It contained interfingering units of thick, massive clay, with thinner, occasionally discontinuous sand and gravel fan deposits. This four foot deep trench exposed liquefaction features ~10 cm high in the bedded sand and clay units ~15 cm below the evaporate-covered surface. Trenches F and G exposed massive sandy silt, was heavily bioturbated, and lacks distinct bedding and variable sedimentation. This is indicative of hundreds to thousands of years of surface stability, precluding the ability to preserve fine-scale evidence for recent events. A shale bedrock, likely Tertiary, was visible in the southwest end of Trench F. Trench G was located in a small depression and displayed evidence of potential tephra fall and fracturing, but multiple events are indistinguishable. The sub-surface data we have collected, combined with the age control we will obtain through the dating of collected charcoal samples, will be used to better interpret the geomorphological evolution of the Cholame section of the SAF and help us improve the identification of future exploration sites along it. Further exploration is needed to fill the paleoseismic gap along the south-central SAF.

**Development of a Workflow for Using PyLith-Generated Green's Functions with the Defnode Geodetic Inversion Code**, Charles A. Williams and Laura M. Wallace (Poster 214)

In our previous work (Williams and Wallace, 2015) we used Green’s functions generated with the PyLith finite element code (Aagaard et al., 2013) to examine the effects of material heterogeneity on geodetic inversions of slow slip events (SSEs) along the Hikurangi Margin, New Zealand. We are presently extending this work to include interseismic coupling models for the North Island of New Zealand. For both of these projects we have used PyLith to generate the Green’s functions and Defnode (McCaffrey, 1995; 2002) to perform the geodetic inversions. As part of our studies we have developed a workflow that allows us to perform the necessary tasks in a semi-automated way. We describe the current state of our workflow for both SSE inversions and interseismic coupling inversions.

The most difficult part of this work is the generation of the necessary meshes. We have developed Python scripts that allow us to create geometry for use with the Trelis meshing package, taking as input the nodal information provided by Defnode. We have additional scripts that generate an initial mesh, impose a user-defined sizing function, and then create a refined mesh suitable for generating the required Green’s functions. We then describe the process of performing the Green’s function generation with PyLith, and the integration procedure to provide the Green’s functions required by Defnode. Finally, once the necessary Defnode Green’s functions have been generated we use another script that allows us to launch many Defnode inversions in parallel. We are still improving our workflow, and once it is finished it will be made available to the public. Our initial research has shown that using material properties from a seismic velocity model can have significant effects on predicted SSE slip distributions, and the same is likely to be true for interseismic coupling models. The workflow that we are developing should allow others to explore these effects in other regions.

**Preliminary results of marine paleo-seismology from MCS, CHIRP, and coring off Catalina Island, Ethan F. Williams, Chris M. Castillo, Simon L. Klemperer, Kate Maher, Robert D. Francis, and Mark R. Legg (Poster 100)**
Submerged paleo-shorelines around Catalina Island record information about the paleo-seismicity and evolving morphology of the Channel Islands, and provide constraints on Quaternary sea-level history of Southern California. We acquired high-resolution uniboom seismic in 2014 across these paleo-shorelines and intervening marine terraces, with a particular focus on the Long Point Fault, a strike-slip fault subparallel to the San Andreas system. Each terrace corresponds to a low-stand in the Quaternary sea-level curve and can be used as paleo-horizontal datum for constraining the ages of Quaternary tsunamogenic landslides and major vertical offset on the Long Point Fault. Determining the age of the terraces is essential to understanding the slip history of the Long Point Fault and the potential for future tsunamogenic landslides. Radiometric dates are necessary to refine our sequence-stratigraphic interpretation and constrain terrace-cutting events.

Our SCEC-funded coring cruise off Catalina Island was conducted in June 2015 to retrieve datable material from subsidised terraces. We used high-resolution MCS and CHIRP data to locate outcrops of terrace deposits, which we then sampled using a gravity core and grab sampler while simultaneously running CHIRP to ensure that we successfully hit our target. Samples include carbonate-rich sands from depths of 32-250 m bsl and wave-rounded cobbles >8.75 km offshore at depths of >250 m bsl. At the time of writing, corals and mollusks recovered from the cores are undergoing U-series dating at the Stanford University ICP-MS/TIMS Facility and δ18O measurements at the Stanford University Stable Isotope Biogeochemistry Lab. Further samples have been sent to Lawrence Livermore National Labs for radiocarbon dating through their SCEC partnership.

Preliminary results from our SCEC cruise were used to motivate and guide two successful ROV dives off Catalina Island by the E/V Nautilus in August 2015. The dives yielded samples from outcrops of terrace deposits as well as high-definition video of these submarine features, and the fault-scarp of the Santa Cruz-Catalina strike-slip fault. Wave-rounded cobbles and intertidal fauna in deposits surrounding the island confirm the hypothesis that Catalina has experienced at least 250m of subsidence since its uplift during the Pliocene.

Verification of Earthquake Simulators Using Self-Consistency Metrics, John M. Wilson, John B. Rundle, and Mark R. Yoder (Poster 052)

We address the problem of verifying the consistency of earthquake simulators with the data from which their parameters are drawn. Earthquake simulators are a class of computational simulations which attempt to mirror the topological complexity of the earthquake fault system on which the earthquakes occur. In addition, the physics of friction and elastic interactions between fault elements can be included. In general, the parameters are adjusted so that natural earthquake sequences are matched in their scaling properties in an optimal way. Generally, these parameters choices are based on paleoseismic data extending over many hundreds and thousands of years. A problem encountered, addressed here, is the verification of the simulations applied to current earthquake seismicity. Physically-based earthquake simulators allow the generation of many thousands of years of simulated seismicity, allowing for robust capture of statistical properties of large, damaging earthquakes that have long recurrence time scales for observation. Following past simulator and forecast model verification efforts, we approach the challenges in spatial forecast verification for simulators; namely, that simulator output events are confined to the modeled faults, while observed earthquakes often occur off of known faults. We present two methods for overcoming this discrepancy: a simplistic approach whereby observed earthquakes are shifted to the nearest modeled fault element and a variation of the Epidemic-type aftershock (ETAS) model, which smears the simulator catalog seismicity over the entire test region. To test these methods, a Receiver Operating Characteristic (ROC) plot was produced by comparing the rate maps to observed m≥6.0 earthquakes since 1980. We found that the nearest-neighbor mapping produced poor forecasts, while the modified ETAS method produced rate maps that agreed with observations. These ETAS results were further analyzed by comparing them against catalogs of earthquakes randomly generated from the ETAS rate map. The observed ROC scores for all simulators were near or exceeded the 95th percentile of the distribution of random scores.

Broadband (0–8 Hz) Ground Motion Variability From Ensemble Simulations of Buried Mw 6.7 Thrust Earthquakes Including Rough Fault Descriptions and Q(f), Kyle Withers (Poster 007) Ground motion can be deterministically calculated more realistically at higher frequencies with the recent addition of realistic fault topography in 3D simulations of earthquake source models. However, the earthquake source is not the only source of complexity in the high-frequency ground motion; there are also scattering effects caused by small-scale velocity and density heterogeneities in the medium that can affect the ground motion intensity. Here, we model blind thrust scenario earthquakes matching the fault geometry of the 1994 Mw 6.7 Northridge earthquake up to 8 Hz. We use a support operator method (SORD) to perform dynamic rupture propagation and extend the ground motion to further distances from the fault by the finite difference wave propagation code AWP-ODC, which incorporates frequency-dependent attenuation. We also include small-scale medium complexity in both a 1D layered model and a 3D medium extracted from SCEC CVM-S4 including a surface geotechnical layer (GTL). We model several realizations of the scenario with similar moment magnitude by varying the hypocenter location. We observe that while the ground motion pattern changes, the median ground motion is not affected significantly, when binned as a function of distance, and is within 1 interevent standard deviation from the median GMPEs. We find that intra-event variability for the layered model simulations is similar to observed values of single-station standard deviation. We show that small-scale heterogeneity can significantly affect the intra-event variability at frequencies greater than ~1 Hz, becoming increasingly important at larger distances from the source. We perform a parameter space study by varying statistical parameters and find that the variability is fairly independent of the correlation length. The intra-event variability of our simulations in the CVM is typically larger than that for the observations at frequencies > 1 Hz. However, this discrepancy tends to decrease when small-scale heterogeneity in the medium is included in the simulations, suggesting the need for a highly complex velocity model to fit ground motion variability.

Geologic swath map of the Lavic Lake fault from remote sensing, Ryan D. Witkosky, Paul Adams, Sinan Akciz, Kerry Buckland, Janet Harvey, Ken Hudnut, Patrick Johnson, Katherine Kendrick, Dave Lynch, Kate Scharer, Frank Sousa, Joann Stock, David Tratt, (Poster 112) The Lavic Lake fault ruptured in the 1999 Hector Mine earthquake, producing up to 5 m of coseismic dextral slip. No estimates of total displacement on this fault are published. We aim to constrain the total offset of bedrock along the Lavic Lake fault by producing a geologic swath map. Field access to the study area, however, is highly restricted, subsequently we utilize remote sensing techniques to map the lithology along the active fault. We collected airborne hyperspectral imagery with 2 m pixel resolution (collected using a sensor which measures surface radiance at 128 bands covering wavelengths from 7.8-13.4 μm) over a 1.8 km-wide, 11 km-long swath centered along the Lavic Lake fault and through the 1999 earthquake’s maximum slip zone in the Bullion Mountains. The sensor’s high spatial and spectral resolution, along with the lack of significant vegetation cover in the study area, allows for differentiation of lithologic units through the use of supervised and unsupervised classification methods. We assessed the accuracy of our map with two methods: (1) for the supervised classification, a ~5000 m² zone was mapped during brief, permitted access to the study area. Using the field map as a basis for ground-truth, a few pixels from the hyperspectral imagery with known lithology were compared with all other pixels within the field-mapped area. Every pixel was then assigned a lithology based on the most closely representative pixel of known lithology. The resulting pixel-based classification map showed that >70% of the pixels were classified correctly when compared to the geologic map. (2) For the unsupervised classification, in a separate region of the fault, a visual/qualitative assessment was performed to determine how well boundaries between similarly grouped pixels correlate with lithologic contacts from a published geologic map. One such unit is well classified in the hyperspectral imagery and correlates with a lithologic unit mapped adjacent to the Lavic Lake fault. In map view, this unit has an apparent dextral separation of ~1 km.
We hypothesize the map-view separation is the total slip on the Lavin Lake fault because the strike of proximal bedding is sub-parallel to the strike of the fault, thus minimizing the potential for complex and misleading patterns created by the intersection of structural features.

Hydrogeologic Architecture of the San Andreas Fault near the Logan Quarry, Lian Xue, Emily E. Brodsky, Jon Erskine, and Patrick M. Fulton (Poster 237)

Hydrogeologic properties of fault zones are critical to the faulting processes; however, they are not well understood and difficult to measure in situ. Recording the tidal response of water level is a useful method to measure in-situ properties. We utilize an array of wells near the San Andreas Fault zone in the Logan Quarry to study the fault zone hydrogeologic architecture by measuring the water tidal response. The measured specific storage and permeability show that there is a localized zone near the fault (within 40 m of the fault) with higher specific storage and larger permeability than the surrounding region. This change of properties might be related to the fault zone fracture distribution. Surprisingly, the change of the specific storage is the clearest signal. The inferred compliance contrast is consistent with prior estimates of elastic moduli change in the near-fault environment, but the hydrodynamic effects of the compliance change have never before been measured on a major active fault. In addition, the measured diffusivities of all the sites are about $10^{-2}$, which is comparable to the post-earthquake hydraulic diffusivity measured on the Wenchuan Earthquake Fault. As a competing effect of permeability and specific storage, the resulting diffusivity is uniform inside the fault zone. This uniform diffusivity structure might suggest that the accumulated pore pressure during the interseismic period distributes over a broad region. Moreover, the observed response to earthquakes suggests the place which is closer to the fault zone has a larger enhancement of permeability by seismic waves. Our study shows the utility of the water tidal response for measuring the fault zone hydrogeologic architecture in situ and studying the response behavior of fault zone hydrogeologic properties to earthquakes.

Earthquake Source Parameters Relationships in 3D Rough Fault Dynamic Rupture Simulation, Qian Yao, Steven M. Day, and Zheqiang Shi (Poster 257)

Fault surface roughness has a strong influence on the distribution of stress around the fault, and affects the dynamics of the earthquake process. In particular, roughness influences the distribution of the parameters conventionally used to describe fault slip in, for example, kinematic modeling of strong ground motion. We explore the effect of the fault roughness on earthquake source parameters through the statistical analysis of a large suite of 3D rupture simulations. We have built a database of more than 1000 simulated dynamic ruptures based on different rough fault profiles, and have quantitatively analyzed the correlation between earthquake source parameter pairs. In the subshock propagation-speed regime, we find relationships between some parameters. Rise time, total slip and peak slip rate each decrease with increasing roughness. Rupture velocity is weakly positively related to slip, and the relationship is stronger with increasing roughness. We also explore how peak slip rate, rise time and different pairs of source parameters correlations are affected by fault roughness. This work may give useful guidance for use in kinematic rupture-source generators and help improve methods for ground strong motion prediction.

Strike-slip Faulting Energy Release and Supershear Rupture, Lingye Li and Thorne Lay (Poster 254)

Large strike-slip faulting earthquakes tend to have complex, predominantly unilateral ruptures, commonly with either limited or extensive segments of supershear rupture propagation. High-frequency radiated energy from such events is strongly affected by radiation pattern and source directivity effects; as a result, estimates of total energy budgets and seismic efficiency for this class of events have large scatter and uncertainty. Thus, improved empirical understanding of radiated energy from this class of events is desirable both for evaluating seismic hazard and for assessing potential for enhanced energy release accompanying supershear rupture failures. We systematically estimate the overall seismic energy release and source spectra using teleseismic broadband recordings for 27 globally distributed large strike-slip earthquakes. The data set is comprised of 24 events with $M_w > 7.5$ since 1990 including 4 supershear earthquakes, the 1992 Mw 7.3 Landers earthquake, and two reported moderate supershear earthquakes, the 1999 Turkey Mw 7.1 Turkey, and 2010 Mw 6.9 China earthquakes. The azimuthally distributed single-station radiated energy measurements are evaluated with empirical radiation pattern correction and rupture directivity from finite-fault slip models.

Virtual Quake: Using Simulators to understand earthquake predictability and an Open Source model for scientific software development, Mark R. Yoder, Kasey W. Schultz, Eric M. Heien, John B. Rundle, Donald L. Turcotte, and Jay W. Parker (Poster 049)

We introduce a framework for developing earthquake forecasts using Virtual Quake (VQ), the generalized successor to the perhaps better known Virtual California (VC) earthquake simulator. We discuss the basic merits and mechanics of the simulator, and present several statistics of interest for earthquake forecasting. We also show that, though the system as a whole (in aggregate) behaves quite randomly, (simulated) earthquake sequences limited to specific fault sections exhibit measurable predictability in the form of increasing seismicity precursory to large $M > 7$ earthquakes. In order to quantify this, we develop an alert based forecasting metric similar to those presented in Keilis-Borok (2002); Molchan (1997), and show that it exhibits significant information gain compared to random forecasts. We also discuss the long standing question of activation vs quiescent type earthquake triggering. We show that VQ exhibits both behaviors separately for independent fault sections; some fault sections exhibit activation type triggering, while others are better characterized by quiescent type triggering. We discuss these aspects of VQ specifically with respect to faults in the Salton Basin and near the El Mayor-Cucapah region in southern California USA and northern Baja California Norte, Mexico.

The simulator code is Open Source and available to the public from the Computational Infrastructure for Geodynamics (CIG) and via GitHub: https://geodynamics.org/cig/software/vq/ https://github.com/geodynamics/vq

Evolution of the Ventura Avenue Anticline as a Flexural Slip Fold, Ryan Yohler and Kay Johnson (Poster 244)

The Ventura Avenue Anticline (VAA) is an active fault-propagation fold that has developed over the Ventura-Pitas Point fault system in the western Transverse Ranges. Folded terraces record uplift rates of ~5 mm/yr since at least 600 Ka (Rockwell, 1988). The fault appears to have formed over a propagating ramp fault that flattens into the Sisar decollement at about 7-8 km depth which steps down again to a blind thrust (Hubbard et al. 2014). Previous work on the area has shown that the fault coring the VAA has recently ruptured the surface in discrete events with 5-10 m of uplift (Hubbard et al. 2014).

In this study we assume the VAA formed as a flexural-slip fault-propagation fold and examine the evolution of the VAA over time using a boundary element model. The model consists of faulting in a viscoelastic layered medium with frictional bedding contacts. We explore the influence of fault geometry (orientation and fault ramp length and detachment depth), number of mechanical layers, and coefficient of friction between layers, on predicted fold geometry and evolution and surface uplift patterns and rates. To produce a relatively tight, high amplitude fold like the VAA, the models require mechanical layering of 1 km thickness or less with relatively low coefficient of friction at interbeds (<0.3) and the fold must initiate and grow over a relatively deep fault tip below several km depth. The best fitting model occurs when the initial fault depth is 6km with a coefficient of friction of 0.1. We are also beginning to compare predicted surface uplift rates and tilt rates with measurements from terraces across the VAA (Rockwell, 1988).

A new lower limit of self-similarity in source scaling relationships estimated from laboratory-scale repeating events, Nana Yoshimitsu, Hironori Kawakata, and Takahashi Naoki (Poster 164)
MEETING ABSTRACTS

Ultra-micro event which is called acoustic emission (AE) are observed in a fracturing rock sample, and it shows some common features to natural earthquakes. However, it remains to be shown whether or not AE can be equated with an ultra-micro-earthquake because limited frequency bands of the observation kept us away from the source parameter estimation of AE. To address this issue, we developed a new robust measurement system, which achieved multi-channel, broadband, and high-speed continuous recording under seismogenic stress conditions. With this system, we conducted a compression test using a cylindrical Westerly granite sample under a confining pressure of 10 MPa. After the location of 6794 hypocenters, we defined AE clusters in which the hypocenters of each AE was within 2 mm from another member of the group and their correlation coefficients larger than 0.80 for four or more channels. Then, the members of each cluster can be recognized to be repeating events. We estimated seismic moment and corner frequency of AE in the largest clusters including 142 events and the second largest clusters including 913 events, while both time periods of the clusters were within 3 minutes and occurred after the peak stress.

As a result, AE source parameters in each cluster showed very clear scaling relationship similar to natural earthquakes in which the seismic moment is inversely proportional to the cube of the corner frequency. The stress drop values of two clusters ranged from 0.4 MPa to 11.8 MPa. Neither transition of event size nor corner frequency showed time dependency in both clusters. This indicates source characteristics of foreshock-like repeating AE did not show the strong temporal change during the fault growing process.

The result of this study suggests millimeter-scale laboratory fractures are self-similar to much larger kilometer-scale natural earthquakes, and AE events can be interpreted as ultra-micro-earthquakes having a magnitude of about -7. This result also demonstrates the effectiveness of the experimental approach in studying natural earthquake. Here we used an intact rock which environment is alike inland rather than subduction zone, thus the behavior of repeating events in laboratory could help to understand the fault status of the natural inland earthquakes.

Products and Services Available from the Southern California Earthquake Data Center (SCEDC) and the Southern California Seismic Network (SCSN), Ellen Yu, Prabha Acharya, Aparna Bhaskaran, Shang-Lin Chen, Jennifer Andrews, Valerie Thomas, Egill Hauksson, Robert Clayton (Poster 127)

The SCEDC archives continuous data from 9200 data channels and 495 SCSN recorded stations, and has triggered event waveforms from 642 stations in 2015. The SCEDC processes and archives an average of 16,000 earthquakes each year. The SCEDC provides public access to these earthquake parametric and waveform data through its website scedc.caltech.edu and through client applications such as STP and web services. This poster will describe the most significant developments at the SCEDC in the past year.

New data holdings:
- In addition to the real-time GPS displacement waveforms now archived at SCEDC, the SCEDC is now archiving seismogeodetic waveforms displacement and velocity waveforms produced by the California Real Time Network (CRTN http://spac.ucsd.edu/projects/realtime). These waveforms are computed by combining the 1 sps real time GPS solutions with 100 Hz accelerometer data. They are archived at regular intervals and converted into minised format by SCEDC. This project was funded by the NASA Advanced Information System Technologies program.
- In response to data management needs of the SCEC community, the SCEDC is now hosting a registry of synthetic seismic waveform datasets that have been created by SCEC researchers. The aim is to facilitate the use of synthetic waveforms by the SCEC community.

Changes to the SCSN Catalog:
- Starting October 1, 2015 SCEDC will begin reporting earthquake depths relative to the geoid depth datum. Past earthquake depths will be also listed relative to the geoid depth datum.

New infrastructure:
- SCEDC has moved its website to the Cloud. The Recent Earthquake Map and static web pages of http://scedc.caltech.edu are now hosted by Amazon Web Services. This enables the web site to serve large number of users without competing for resources needed by SCSN/SCEDC mission critical operations.
- The Data Center is implementing the Continuous Wave Buffer (CWB) to manage its waveform archive. This software was developed and currently in use at NEIC. Implementation will simplify and streamline waveform archival, and thus allow the SCEDC to maximize the completeness of its waveform archives as well as making continuous data available within minutes of real time.

Development of Parallel IO Interface for High Performance SEISM-IO Library, Jiying Yu, Daniel Roten, and Yifeng Cui (Poster 040)

In the last years numerical simulations of dynamic rupture and wave propagation have been scaled up to run on petascale supercomputers, enabling researchers to simulate the wavefield during large earthquakes for frequencies up to 5 Hz. With grid dimensions of several 100 billion mesh points, the performance of input and output (I/O) operations during such computations has always represented a major concern, and significant effort has been expended to optimize and tune the I/O performance of parallel wave propagation codes. Many HPC applications based on structured meshes used within SCSE share similar requirement in terms of I/O operations (e.g., AWP-ODC, SORF, or Hercules). Examples of such operations include initialization of the geophysical properties in the computational mesh, the input of the moment-rate time histories for a kinematic source, output of velocity time series at selected sites or saving of stresses for the computational volume.

In order to simplify the I/O operations for each application while achieving high performance in file system access, we developed generalized IO interfaces as part of the SEISM-IO (SEISmic Input Output) library, which provide highly condensed, easy-to-understand APIs for users to choose. To simplify the programming of parallel I/O for code developers, the interface implemented in C hides complex low-level operations in the SEISM framework (i.e. grid partition and buffering of output for improved performance) and high-level operations in filesystem access libraries including MPI-IO, HDF5, netCDF and ADIOS. To accommodate the generalized interface, the earlier SEISM-IO library is modified to integrate different initialization/open/write processes in MPI-IO, HDF5, netCDF and ADIOS. The generalized interface has been tested using the wave propagation AWP-ODC solver on the NSF TACC Stampede system, by calling the interface for file access instead of calling the SEISM-IO library directly. We are currently validating the modeling results and observed data processed using the generalized SEIS-I0 interface and testing the portability under different file systems. The interface and modified SEISIM- IO library will be released to code developers in the near future.

The geologic slip budget of the San Gorgonio Pass Special Fault Study Area and implications for through-going San Andreas earthquakes, Doug Yule (Poster 078)

The San Gorgonio Pass (SGP) Special Fault Study Area encompasses a broad area that extends from Cajon Pass on the northwest to Indio on the southeast and includes the southernmost San Andreas Fault (SAF) system, northern San Jacinto Fault zone, and southern Eastern California Shear Zone (ECSZ). Impressive progress has been made during SCEC4 to obtain geologic slip-rate data that supplements rates from previous studies. The wealth of available slip rate information produced by many researchers (W. Behr, K. Blisniuk, K. Frankel, T. Fumal, P. Gold, J. Harden, R. Heermann, K. Kendrick, J. Matti, S. McGill, N. Onderdonk, M. Oskin, C. Prentice, T. Rockwell, K. Scharer, among others) invites a system-wide view of how slip changes and transfers along strike and between faults. Across the faults listed above, I have simply summed the reported geologic slip-rate data (including reported error values) along seven transects taken perpendicular to N45°W, the average GPS motion rate for the total of the seven transects taken perpendicular to N45°W; and the average GPS motion rate for the total of the seven transects taken perpendicular to N45°W, the average GPS motion rate for the total of the seven transects taken perpendicular to N45°W, the average GPS motion rate for the total of the seven transects taken perpendicular to N45°W, the average GPS motion rate for the total of the seven transects taken perpendicular to N45°W, the average GPS motion rate for the total of the seven transects taken perpendicular to N45°W, the average GPS motion rate for the total of the seven transects taken perpendicular to N45°W. If the slip rate for each transect is read SE at places where they cross the SAF: Cajon Pass (27.3-39.1), San Bernardino (17.3-37.1), Yucaipa (25.3-45.1), Cabazon (21.3-34.7), Whitewater (22.3-39.1), Thousand Palms (31.9-45.3), and Indio (22.9-39.3). Slip rates of 31.9-34.7 mm/yr satisfy all seven transects and support a uniform slip model for the system. But the average rates for each transect show more variability. Averages are 33, 27, 35, 28, 31, 40, and 31 mm/yr, from NW to SE along the system, respectively. These averages reach a minimum value of 28 mm/yr in SGP (Cabazon transect) that is 10-
such as geodetic deformation, geomagnetic signal, earth resistivity, ground water level, ground water temperature, water radon, etc. The frequency band of the anomalies varies from 10e-8HZ to 10e-2HZ. Since 2000, the networks of geophysical observation for monitoring earthquake precursors in China mainland have been digitalized gradually to the sampling rate of 1/minute or 1/second from the original sampling rate of 1/hour. The Capital Area around Beijing (E113°-120°, N38.5°-41°) is the area with the densest geophysical observation network with 140 stations. Each station has different observational items, and the total number of items is about 400. Four earthquakes above ML4.5 occurred during 2000-2014.

In this study, wavelet analysis was employed to mine possible earthquake precursors before the four earthquakes above ML4.5 in the Capital Area during 2000-2014. Among the 400 observational items in 140 stations, only 57 items in 28 stations were selected due to their continuous rate above 99%, that were important for easier data preprocessing and higher authenticity and reliability of observational data. Those unselected items with lower continuous rate data were caused by interference of observation environment due to urban expansion or instrument malfunction.

Firstly the data were preprocessed to continuous data by interpolation method. Secondly the preprocessed data were analyzed by wavelet method and different components of wavelet orders were obtained. By comparison of earthquakes with the time series of different components of wavelet orders, those components with abnormal amplitudes prior to earthquakes were selected for possible earthquake precursors. Thirdly, the normalizations that combine all the selected components of the 57 items were obtained during 2000-2014. The results show that obvious short term anomalies existed before all the four earthquakes above ML4.5 in the Capital Area, which implies that the wavelet analysis might be a prospective approach for earthquake anomalies detection. More cases in other regions and other periods need to be examined for the validity of this method.

Large spontaneous stick-slip events in rotary-shear experiments as analogues to earthquake rupture, Ximeng Zu and Ze’ev Reches (Poster 256)

Experimental stick-slips are commonly envisioned as laboratory analogues of the spontaneous faults slip during natural earthquakes (Brace & Byerlee, 1966). However, typical experimental stick-slips are tiny events of slip distances up to a few tens of microns. To close the gap between such events and natural earthquakes, we develop a new method that produces spontaneous stick-slips with large displacements on our rotary shear apparatus (Reches & Lockner, 2010). In this method, the controlling program continuously calculates the real-time power-density (PD = slip-velocity times shear stress) of the experimental fault. Then, a feedback loop modifies the slip-velocity to match the real-time PD with the requested PD. In this method, the stick-slips occur spontaneously while slip velocity and duration are not controlled by the operator.

We present a series of tens stick-slip events along granite and diorite experimental faults with 0.0001-1.3 m of total slip and slip-velocity up to 0.45 m/s. Depending on the magnitude of the requested PD, we recognized two types of stick-slip events: (1) Stick-slips with foreshocks and aftershocks under relatively low power density; (2) Events resembling slip-pulse behavior of abrupt acceleration and intense dynamic weakening and subsequent strength recovery. The energy-displacement the events shows good agreement with previous slip-pulse experiments and natural earthquakes (Chang et al., 2012). Numerical modeling shows good agreement with the experimental data (Liao and Reches, 2013). The present experiments indicate that power-density control is a promising experimental approach for earthquake simulations.
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ZU Ximeng, OU 256
ZUZA Andrew, UCLA
The Southern California Earthquake Center (SCEC) is an institutionally based organization that recognizes both core institutions, which make a major, sustained commitment to SCEC objectives, and a larger number of participating institutions, which are self-nominated through the involvement of individual scientists or groups in SCEC activities and confirmed by the Board of Directors. Membership continues to evolve because SCEC is an open consortium, available to any individual or institution seeking to collaborate on earthquake science in Southern California.

### Core Institutions and Representatives

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<td>Nadia Lapusta</td>
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<tr>
<td>CGS</td>
<td>Chris Wills</td>
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<td>Columbia</td>
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<td>Harvard</td>
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<td>USGS Menlo Park</td>
<td>Ruth Harris</td>
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Core institutions are designated academic and government research organizations with major research programs in earthquake science. Each core institution is expected to contribute a significant level of effort (both in personnel and activities) to SCEC programs, as well as a yearly minimum of $35K of institutional resources (spent in-house on SCEC activities) as matching funds to Center activities. Each core institution appoints an **Institutional Director** to the Board of Directors.

SCEC membership is open to participating institutions upon application. Eligible institutions may include any organization (including profit, non-profit, domestic, or foreign) involved in a Center-related research, education, or outreach activity. As of August 2014, the following institutions have applied for and approved by the SCEC Board of Directors as participating institutions for SCEC4.

### Domestic Participating Institutions and Representatives

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<td>Michael Oskin</td>
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<td>Doug Yule</td>
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<td>UC Berkeley</td>
<td>WHOI</td>
<td>Jeff McGuire</td>
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<td>Sally McGill</td>
<td>Ting Lin</td>
<td>Roland Bürgmann</td>
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<td>U Canterbury (New Zealand)</td>
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<td>Western Univ (Canada)</td>
<td>Canada</td>
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**Apply as a Participating Institution**

E-mail application to John McRaney [mcraney@usc.edu]. The application should come from an appropriate official (e.g. department chair or division head) and include a list of interested faculty and a short statement on earthquake science research at your institution. Applications must be approved by a majority vote of the SCEC Board of Directors.
SATURDAY, September 12
09:00-17:00 Workshop: Community Rheology Model (Plaza A&B)
09:00-17:00 Workshop: CSEP/USGS/GEM (Plaza C&D)

SUNDAY, September 13
07:00-18:00 Registration and Check-In (Lobby)
07:00-08:00 Breakfast (Poolsid)
08:00-12:00 Workshop: CISM (Palm Canyon)
10:00-12:00 Discussion: Estimating Fault Zone Properties (Oasis 3)
12:00-13:00 Lunch (Restaurant and Poolsid)
13:00-17:00 Workshop: Community Stress Model (Horizon)
13:00-15:00 Workshop: Community Modeling Environment (Palm Canyon)
14:00-20:00 Poster Set-Up (Plaza)
15:00-17:00 Workshop: Earthquake Response Training Session 1 (Oasis 2)
17:00-18:00 Annual Meeting Ice-Breaker (Lobby, Harvey’s, Plaza)
18:00-19:00 Distinguished Speaker Presentation (Horizon)
19:00-20:30 Welcome Dinner (Poolsid)
19:00-21:00 Scec Advisory Council Dinner Meeting (Teapetry)
21:00-22:30 Poster Session (Plaza)

MONDAY, September 14
07:00-08:00 Registration and Check-In (Lobby)
07:00-08:00 Breakfast (Poolsid)
08:00-10:00 Session: The State of Scec (Horizon)
10:30-12:30 Session: Scec Special Fault Study Areas (Horizon)
12:30-14:30 Lunch (Restaurant and Poolsid)
14:00-16:00 Session: Scec Community Models (Horizon)
16:00-17:30 Poster Session (Plaza)
19:00-21:00 SCEC Honors Banquet (Hard Rock Hotel Ballroom)
21:00-22:30 Poster Session (Plaza)

TUESDAY, September 15
07:00-08:30 Breakfast (Poolsid)
08:00-10:00 Session: Earthquake – From the Lab to the Field (Horizon)
10:30-12:30 Session: Physics-Based Forecasting and Ground Motions (Horizon)
12:30-14:00 Lunch (Restaurant, Tapestry, Poolsid)
14:00-16:00 Session: Connecting Hazard to Risk (Horizon)
16:00-17:30 Poster Session (Plaza)
19:00-21:00 Dinner (Poolsid)
21:00-22:30 Poster Session (Plaza)
22:30-23:00 Poster Removal (Plaza)

WEDNESDAY, September 16
07:00-08:00 Breakfast (Poolsid)
08:00-10:00 Session: Post-Earthquake Rapid Scientific Response (Horizon)
10:30-12:30 Session: The Future of Scec (Horizon)
12:30 Adjourn 2015 SCEC Annual Meeting
12:30-14:30 SCEC PC Lunch Meeting (Palm Canyon A)
SCEC Board Lunch Meeting (Palm Canyon B)