Southern California Earthquake Center: Research Program in Earthquake System Science, 2017-2022

Proposal to the National Science Foundation and U. S. Geological Survey

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Project Summary

Overview. The Southern California Earthquake Center (SCEC) was founded as a Science & Technology Center on February 1, 1991, with joint funding by the National Science Foundation (NSF) and the U. S. Geological Survey (USGS). Since 2002, SCEC has been sustained as a stand-alone center under cooperative agreements with both agencies in three consecutive, five-year phases (SCEC2-SCEC4). This proposal requests an extension of those agreements for the 5-year period from 1 Feb 2017 to 31 Jan 2022 (SCEC5). SCEC coordinates fundamental research on earthquake processes using Southern California as its main natural laboratory. Currently, over 1000 earthquake professionals are participating in SCEC projects. This research program is investigator-driven and supports core research and education in seismology, tectonic geodesy, earthquake geology, and computational science. The SCEC community advances *earthquake system science* by gathering information from seismic and geodetic sensors, geologic field observations, and laboratory experiments; synthesizing knowledge of earthquake phenomena through system-level, physics-based modeling; and communicating understanding of seismic hazards to reduce earthquake risk and promote community resilience.

SCEC5 Research Vision. Earthquakes are emergent phenomena of active fault systems, confoundingly simple in their gross statistical features but amazingly complex as individual events. SCEC's long-range science vision is to develop dynamical models of earthquake processes that are comprehensive, integrative, verified, predictive, and validated against observations. The science goal of the SCEC5 core program is *to provide new concepts that can improve the predictability of the earthquake system models, new data for testing the models, and a better understanding of model uncertainties.*

The validation of model-based predictions against data is a key SCEC activity, because empirical testing is the most powerful guide for assessing model uncertainties and moving models towards better representations of reality. SCEC validation efforts tightly couple basic earthquake research to the practical needs of probabilistic seismic hazard analysis, operational earthquake forecasting, earthquake early warning, and rapid earthquake response. Moreover, the risk-reduction problem—which requires actions motivated by *useful* information—strongly couples SCEC science to earthquake engineering. SCEC collaborations with engineering organizations are directed towards end-to-end, physics-based modeling capabilities that span system processes from "ruptures-to-rafters."

SCEC connects to the social sciences through its mission to convey authoritative information to stakeholders in ways that result in lowered risk and enhanced resilience. SCEC's vision is to engage end-users and the public at large in on-going, community-centric conversations about how to manage particular risks by taking specific actions. The SCEC Communication, Education, and Outreach (CEO) program seeks to promote this dialog on many levels, through many different channels, and inform the conversations with authoritative earthquake information. Towards this goal, the SCEC5 CEO program will continue to build networks of organizational partners that can act in concert to prepare millions of people of all ages and socioeconomic levels for inevitable earthquake disasters.

Intellectual Merit of the Proposed Research. Southern California is SCEC's principal natural laboratory for the study of earthquake physics and geology. Earthquake processes in this tectonically diverse stretch of the Pacific-North America plate boundary are closely monitored by instrumental systems of increasing density and resolution. Recent research has posed crucial questions about the current earthquake hazard of the San Andreas fault system. In particular, the observed open intervals (times since the last large ruptures) on major faults are skewed to higher values than expected from the latest Uniform California Earthquake Rupture Forecast (UCERF3). Random chance or subtle data or model bias are potential explanations, but another hypothesis of basic-research interest is the synchronization of fault ruptures into "seismic supercycles" modulated by the largest ruptures. Understanding the earthquake behavior of the San Andreas system is a fundamental problem for SCEC5 that has considerable practical implications.

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 strategic framework for the SCEC5 Science Plan has been cast in the form of five basic questions of earthquake science: (1) How are faults loaded on different temporal and spatial scales?

(2) What is the role of off-fault inelastic deformation on strain accumulation, dynamic rupture, and radiated seismic energy? (3) How do the evolving structure, composition and physical properties of fault zones and surrounding rock affect shear resistance to seismic and aseismic slip? (4) How do strong ground motions depend on the complexities and nonlinearities of dynamic earthquake systems? (5) In what ways can system-specific studies enhance the general understanding of earthquake predictability? These questions cover the key issues driving earthquake research in California, and they provide a basis for gauging the intellectual merit of proposed SCEC5 research activities.

Science Plan. Research priorities have been developed to address these five basic questions. Tied to the priorities are fourteen science topics distributed across four main thematic areas.

Modeling the fault system: We seek to know more about the geometry of the San Andreas system as a complex network of faults, how stresses acting within this network drive the deformation that leads to fault rupture, and how this system evolves on time scales ranging from milliseconds to millions of years.
- *Stress and Deformation Over Time*. We will build alternative models of the stress state and its evolution during seismic cycles, compare the models with observations, and assess their epistemic uncertainties, particularly in the representation of fault-system rheology and tectonic forcing.
- *Special Fault Study Areas: Focus on Earthquake Gates*. Earthquake gates are regions of fault complexity conjectured to inhibit propagating ruptures, owing to dynamic conditions set up by proximal fault geometry, distributed deformation, and earthquake history. We will test the hypothesis that earthquake gates control the probability of large, multi-segment and multi-fault ruptures.
- *Community Models*. We will enhance the accessibility of the SCEC Community Models, including the model uncertainties. Community thermal and rheological models will be developed.
- *Data Intensive Computing*. We will develop methods for signal detection and identification that scale efficiently with data size, which we will apply to key problems of Earth structure and nanoseismic activity.

Understanding earthquake processes: Many important achievements in understanding fault-system stresses, fault ruptures, and seismic waves have been based on the elastic approximation, but new problems motivate us to move beyond elasticity in the investigation of earthquake processes.
- *Beyond Elasticity*. We will test hypotheses about inelastic fault-system behavior against geologic, geodetic, and seismic data, refine them through dynamic modeling across a wide range of spatiotemporal scales, and assess their implications for seismic hazard analysis.
- *Modeling Earthquake Source Processes*. We will combine co-seismic dynamic rupture models with interseismic earthquake simulators to achieve a multi-cycle simulation capability that can account for slip history, inertial effects, fault-zone complexity, realistic fault geometry, and realistic loading.
- *Ground Motion Simulation*. We will validate ground-motion simulations, improve their accuracy by incorporating nonlinear rock and soil response, and integrate dynamic rupture models with wave-scattering and attenuation models. We seek simulation capabilities that span the main engineering band, 0.1-10 Hz.
- *Induced Seismicity*. We will develop detection methods for low magnitude earthquakes, participate in the building of hydrological models for special study sites, and develop and test mechanistic and empirical models of anthropogenic earthquakes within Southern California.

Characterizing seismic hazards: We seek to characterize seismic hazards across a wide spectrum of anticipation and response times, with emphasis on the proper assessment of model uncertainties and the use of physics-based methods to lower those uncertainties.
- *Probabilistic Seismic Hazard Analysis*. We will attempt to reduce the uncertainty in PSHA through physics-based earthquake rupture forecasts and ground-motion models. A special focus will be on reducing the epistemic uncertainty in shaking intensities due to 3D along-path structure.
- *Operational Earthquake Forecasting*. We will conduct fundamental research on earthquake predictability, develop physics-based forecasting models in the new Collaboratory for Interseismic Simulation and Modeling, and coordinate the Working Group on California Earthquake Probabilities.
- *Earthquake Early Warning*. We will develop methods to infer rupture parameters from time-limited data, ground-motion predictions that account for directivity, basin, and other 3D effects, and better long-term and short-term earthquake rupture forecasts for conditioning of early-warning algorithms.
- *Post-Earthquake Rapid Response*. We will improve the rapid scientific response to strong earthquakes in Southern California through the development of new methods for mobilizing and coordinating the core geoscience disciplines in the gathering and preservation of perishable earthquake data.

Reducing seismic risk: Through partnerships coordinated by SCEC's Earthquake Engineering Implementation Interface, we will conduct research useful in motivating societal actions to reduce earthquake risk. Two topics investigated by these engineering partnerships will be:

- *Risk to Distributed Infrastructure*. We will work with engineers and stakeholders to apply measures of distributed infrastructure impacts in assessing correlated damage from physics-based ground-motion simulations. An initial project will develop earthquake scenarios for the Los Angeles water supply.
- *Earthquake Physics of the Geotechnical Layer*. In collaboration with geotechnical engineers, we will advance the understanding of site effects and soil-structure interactions by incorporating nonlinear rheological models of near-surface rock and soil layers into full-physics earthquake simulations.

Communication, Education and Outreach Plan. The SCEC CEO program will manage and expand a suite of successful activities within four CEO focus areas. *Knowledge Implementation* will connect SCEC scientists and research results with practicing engineers, government officials, business risk managers, and other professionals in order to improve application of earthquake science. The *Public Education and Preparedness* focus area will educate people of all ages about earthquakes, tsunamis, and other hazards, and motivate them to become prepared. The *K-14 Earthquake Education Initiative* will improve earth science education in multiple learning environments, overall science literacy, and earthquake safety in schools and museums. The *Experiential Learning and Career Advancement* program will provide research opportunities, networking, and other resources to encourage students and sustain careers in STEM fields. Four long-term intended outcomes of the CEO program are improved application of earthquake science in policy and practice; reduced loss of life, property, and recovery time; increased science literacy; and increased diversity, retention, and career success in the scientific workforce. SCEC's vigorous promotion of workforce diversity will be augmented by a new *Transitions Program* that will provide students and early-career scientists with resources and mentoring at major steps in their careers.

Broader Impacts of the Proposed Research. California comprises about two-thirds of the nation's long-term earthquake risk, and Southern California about 40% of this total. SCEC5 will translate basic research into practical products that will inform efforts to reduce risk and build resilience in California and elsewhere. The Center will work with the USGS and California agencies to improve the two basic elements of seismic hazard analysis, earthquake rupture forecasting and ground-motion modeling. It will equip long-term seismic hazard analysis and short-term earthquake forecasting with physics-enabled, system-specific models that can provide authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes. This research will also lead to improvements in earthquake early warning as well as the delivery of post-event information about strong ground motions and secondary hazards, such as landsliding, liquefaction, and tsunamis.

Los Angeles Mayor Garcetti's plan to strengthen buildings, fortify the water system, and enhance reliable telecommunications has demonstrated how the quantitative characterization of seismic hazards can provide the scientific basis for strong civic actions to mitigate risk and improve resilience. SCEC5 will support the chain of scientific inference that proceeds from hazard characterization to loss estimation and eventually to implementation of effective mitigation options with well-defined costs and benefits.

SCEC, through its CEO program, will continue to manage the statewide Earthquake Country Alliance, which now comprises more than 200 partner organizations and sponsors a yearly preparedness campaign—the Great California ShakeOut—that has involved millions of California citizens. SCEC will coordinate ShakeOut activities in 51 U.S. states and territories as well as Canada, Japan, New Zealand, and a growing number of other countries. SCEC will be a leading organization in America's PrepareAthon, a new FEMA program modeled on ShakeOut. SCEC will also coordinate the EPIcenter Network of more than 60 museums, science centers, and libraries, and it will deliver public information through an extensive array of educational booklets, web-based resources, and social media.

SCEC is a center-without-walls that has developed the virtual organization needed to coordinate and sustain interdisciplinary, multi-institutional earthquake system science. The SCEC5 working groups, workshops, field activities, intern programs, and annual meeting will foster deep collaborations and strong interpersonal networks among earthquake scientists, earthquake engineers, and other professionals. SCEC5 will promote intellectual exchange and amplify the support for students and early-career scientists, giving them the organizational resources and experience to become the field's future leaders.

I. Introduction

The Southern California Earthquake Center (SCEC) was founded as a Science & Technology Center on February 1, 1991, with joint funding by the National Science Foundation (NSF) and the U. S. Geological Survey (USGS). SCEC graduated from the STC Program in 2002 and has been funded as a stand-alone center under cooperative agreements with both agencies in three consecutive phases: SCEC2, 1 Feb 2002 to 31 Jan 2007; SCEC3, 1 Feb 2007 to 31 Jan 2012; and SCEC4, 1 Feb 2012 to 31 Jan 2017. This proposal requests an extension of those agreements for the 5-year period from 1 Feb 2017 to 31 Jan 2022 (SCEC5).

Box 1.1. SCEC Mission Statement

- **Gather data** on earthquakes in Southern California and elsewhere
- **Integrate information** into a comprehensive, physics-based understanding of earthquake phenomena
- **Communicate understanding** to end-users and society at large as useful knowledge for reducing earthquake risk and improving community resilience

SCEC coordinates fundamental research on earthquake processes using Southern California as its main natural laboratory. This research program is investigator-driven and supports core research and education in seismology, tectonic geodesy, earthquake geology, and computational science. The SCEC community advances *earthquake system science* through three basic activities: (a) gathering information from seismic and geodetic sensors, geologic field observations, and laboratory experiments; (b) synthesizing knowledge of earthquake phenomena through physics-based modeling, including system-level hazard modeling (**Fig. 1.1**); and (c) communicating our understanding of seismic hazards to reduce earthquake risk and promote community resilience (**Fig. 1.2**). Our mission statement (**Box 1.1**) guides the SCEC5 project plan.

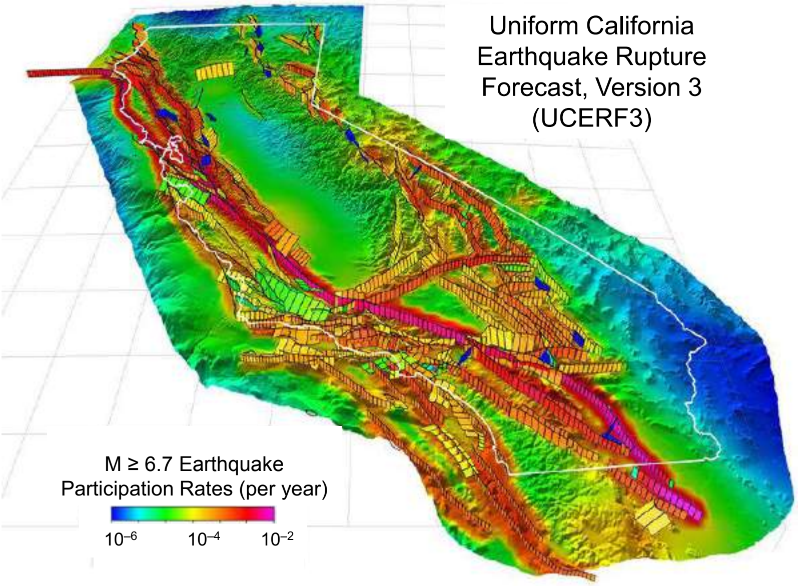
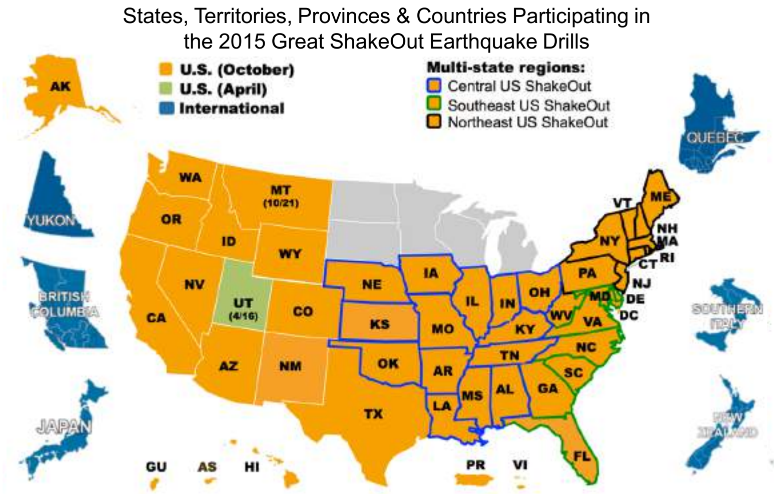


Figure 1.1. Three-dimensional map of the California fault system showing the Third California Earthquake Rupture Forecast. UCERF3 was developed by the Working Group on California Earthquake Probabilities through a USGS-CGS-SCEC partnership with major support from the California Earthquake Authority. The time-independent component of the model, UCERF3-TI, was incorporated into the 2014 update of the National Seismic Hazard Maps [*2*]. The long-term time-dependent component, UCERF3-TD, based on Reid renewal statistics, was released in March, 2015 [*3*]. The short-term component, UCERF3-ETAS, based on Omori-Utsu clustering, is under testing and will support operational earthquake forecasting in California.

The SCEC5 proposal is well aligned with the NSF and USGS strategic plans. The 2012 NRC Decadal Study for the NSF, *New Research Opportunities in the Earth Sciences* [*1*], recognized SCEC's contributions to the EAR core program (Finding 2): "Integrative multidisciplinary activities such as MARGINS, GeoPRISMS, and the Southern California Earthquake Center (SCEC) are particularly valuable for investigating fault zone and plate boundary environments. The SCEC has successfully bridged the earthquake science and earthquake engineering communities, including strong public outreach…" The Panel recommended that "EAR should pursue integrated interdisciplinary quantification of the spectrum of fault slip behavior and its relation to fluxes of sediments, fluids, and volatiles in the fault zone." This recommendation concisely states a major objective of the SCEC5 project plan.

Earthquake system science provides the disciplinary knowledge and computational tools needed to power a new generation of physics-based hazard models. Exemplars include the Uniform California Earthquake Rupture Forecast [*2*,*3*] (**Fig. 1.1**), earthquake rupture simulators [*4*,*5*,*6*] (**Fig. 1.4**), and the CyberShake simulation-based hazard model [*7*,*8*]. These projects contribute to key elements of the USGS National Hazards, Risk, and Resilience Assessment Program [*9*]. SCEC5 will address the six "Grand Challenges for Disaster Reduction" articulated by the National Science and Technology Council [*10*] and the three grand challenges of the NSF 2009 *GeoVision* Report [*11*]: (a) understanding and forecasting the behavior of a complex and evolving Earth system, (b) reducing vulnerability and sustaining life, and (c) growing the geosciences workforce of the future.


States, Territories, Provinces & Countries Participating in the 2015 Great ShakeOut Earthquake Drills

2015 Official ShakeOut Regions
28 Regions worldwide
22 U.S. regions spanning 51 states & territories
55 additional countries with independent registrations (individuals, schools, etc.)

Participation History (worldwide)
2014: 26.5 million (+ NM, KS, FL, Quebec, Yukon, more)
2013: 25.0 million (+ Southeast, Northeast, MT, WY, CO)
2012: 19.5 million (+ Japan, New Zealand, UT, WA, AZ)
2011: 12.5 million (+ Central US, BC, OR)
2010: 8.0 million (+ Nevada and Guam)
2009: 6.9 million (+ Northern California)
2008 5.4 million (Southern California)

Key Facts
- Participants practice "Drop, Cover, and Hold On" and other aspects of their emergency plans.
- Register at www.ShakeOut.org
- Largest component "America's PrepareAthon," sponsored by FEMA

Figure 1.2. Map showing regions that are participating in the 2015 ShakeOut Earthquake Drills. Statistics from 2008 to 2014 (right side) show how this SCEC-led program has expanded from Southern California to an international scale. In 2014, more than 26.5 million people registered to participate in ShakeOut drills worldwide. For countries with significant participation not shown on this map, see ShakeOut.org.

A. Intellectual Merit of the Proposed Research: Southern California as a Natural Laboratory

Southern California is SCEC's principal natural laboratory for the study of earthquake physics and geology. This tectonically diverse stretch of the Pacific-North America plate boundary contains a network of several hundred active faults organized around the San Andreas master fault (**Fig. 1.1**). Its geographic dimensions are big enough to contain the larger (M8) San Andreas events, which set the system's outer scale, but small enough for detailed surveys of seismicity and fault interactions. SCEC coordinates a broad collaboration that builds across disciplines and enables deeper investigations of fault system behavior than would be possible by individual researchers or institutions working alone. SCEC4 successes include the Special Fault Study Areas in the San Gorgonio Pass and Ventura regions, where interdisciplinary studies have changed our understanding of large fault ruptures and their hazards.

Recent research has posed crucial questions about the current earthquake hazard within this active plate-boundary deformation zone. **Fig. 1.3** plots the *open interval* on a fault section (years since the last major rupture) against the *mean recurrence interval* (average time between paleoseismic ruptures). We see that the open intervals along the southern San Andreas Fault have grown long compared to the mean rupture rate documented at paleoseismic sites. For example, the southern San Andreas Fault broke from Parkfield to Cajon Pass in the 1857 Fort Tejon earthquake (M7.8). This open interval of 158 years is longer than the paleoseismic estimates of the mean recurrence interval at four locations along the 1857 rupture: Bidart Fan (115 years), Frazier Mt. (149 years), Pallett Creek (149 years), and Wrightwood (106 years). Paleoseismic data indicate that the last major rupture (~M7.5) of the southernmost (Coachella) section of the San Andreas was circa 1680, implying an open interval more than 300 years, which compares with mean recurrence intervals of 178 years at Coachella and 277 years at Indio [*12*].

According to the Reid model, the San Andreas system has accumulated substantial elastic strain that will eventually be released in large earthquakes. UCERF3 gives a 75% probability of at least one large (M > 7) earthquake in Southern California in the next 30 years. However, in a UCERF3 world, the probability of observing an open-interval distribution as extreme as the present day would be small, less than 1% according to one estimate [*13*]. Paleoseismic data bias is a potential explanation under investigation, but another hypothesis of interest is the synchronization of fault ruptures into "seismic supercycles" modulated by the largest ruptures. UCERF3 does not explicitly model supercycles, but they emerge from long-term runs of physics-based rupture simulators [*6*]. 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 (**Fig. 1.4**). Are supercycles real? Do long open intervals imply that California has been near a supercycle minimum? What are the seismic hazard implications? SCEC5 will provide a framework for addressing these difficult, pressing questions about Southern California seismic behavior.

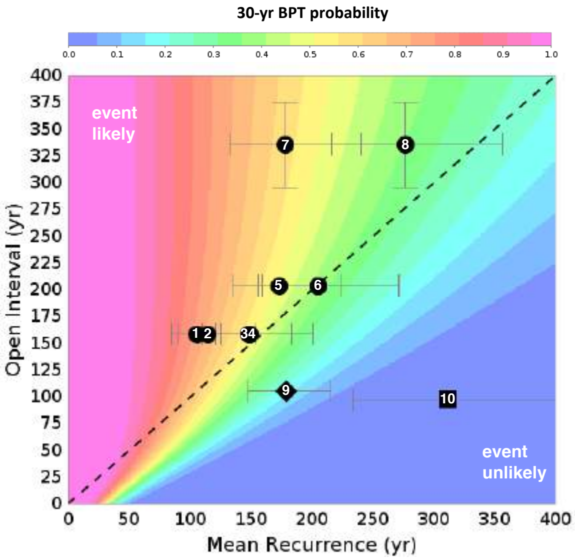


Figure 1.3. Seismic open interval versus mean recurrence interval for selected paleoseismic sites along southern San Andreas system. For most, the time since the last earthquake has been greater than the mean interval between earthquakes. The colors are 30-year probabilities from a Brownian Passage Time model with an aperiodicity of 0.3. The sites are (1) Wrightwood, (2) Bidart Fan, (3) Frazier Mountian, (4) Pallett Creek, (5) Pitman Canyon, (6) Plunge Creek, (6) Burro Flats, (7) Coachella, (8) Indio, (9) Elsinore-Glen Ivy, and (10) Hog Lake. The data are from Appendix G of the UCERF3 report [*2*].

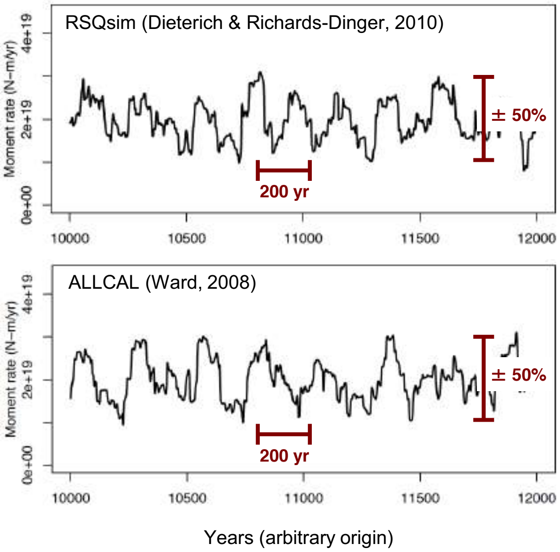


Figure 1.4. Seismic supercycles are observed in synthetic catalogs produced by the RSQSim and ALLCAL rupture simulators [*4,5*]. When run for thousands of model years on a UCERF-based fault geometry, the simulations show ± 50% variations in seismic energy release over time scales of 200 years or so. The plots are the release of seismic moment (which is proportional to energy) across the entire California fault system from 2000-year catalogs that have been a smoothed by a 100-yr moving average.

B. Broader Impacts of the Proposed Research: SCEC as a System-Science Organization

The SCEC community comprises one of the largest research collaborations in geoscience. There are currently 1096 active participants on SCEC projects, and more than half of them registered for SCEC's Annual Meeting in 2015 (**Fig. 1.5**). SCEC is organized as a consortium of 17 "core institutions", which commit sustained support, and a much larger set of "participating institutions" (52), which join through requests initiated by scientists wishing participate in SCEC (**Table 1.1**). All of the existing core institutions have committed resources to SCEC5, and Texas A&M University will join the core on Feb. 1, 2016 (see letters of commitment). Participating institutions will be solicited when the SCEC5 proposal is approved.

SCEC's core research program is investigator-driven and open to anyone who is willing to submit a qualified project plan for peer review. The core resources are allocated through an annual planning process that involves input from the entire SCEC community, as well as advice from an external Advisory

Council and the sponsoring agencies. About two-thirds of the SCEC science budget goes to students and early-career scientists engaged in investigator-initiated research. The roster changes constantly as new people and institutions become involved. The Center's working groups, workshops, field activities, and annual meeting enable scientists to work together over sustained periods, building "deep collaborations" and strong interpersonal networks that promote intellectual exchange and amplify the support for students and early-career scientists. SCEC encourages colleagues with creative ideas about earthquakes to formulate them as hypotheses that can be tested collectively. Researchers with new hypotheses are quickly brought together with experts who have observational insights, modeling skills, and knowledge of statistical testing methods.

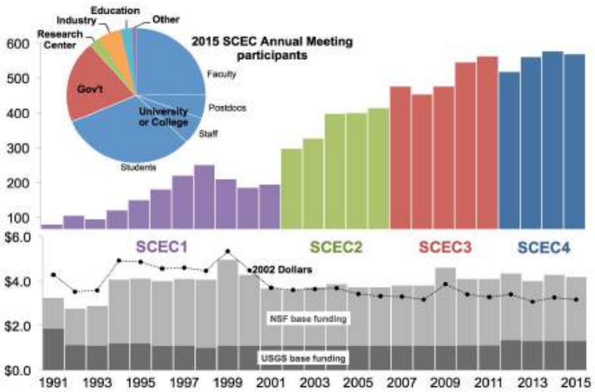


Figure 1.5. Registrants at the SCEC Annual Meeting (upper bar chart), history of base funding (lower bar chart), and breakdown of the 2015 registrants (pie chart). Dotted line is SCEC base funding in 2002 dollars.

Table 1.1. SCEC4 Member Institutions (August 1, 2015)

Core Institutions (17)	Participating Institutions (52)
California Geological Survey California Institute of Technology Columbia University Harvard University Massachusetts Institute of Technology San Diego State University Stanford University U.S. Geological Survey, Golden U.S. Geological Survey, Menlo Park U.S. Geological Survey, Pasadena University of California, Los Angeles University of California, Riverside University of California, San Diego University of California, Santa Barbara University of California, Santa Cruz University of Nevada, Reno University of Southern California (lead)	Academia Sinica (Taiwan); Appalachian State University; Arizona State University; Brown University; CalPoly, Pomona; CalState, Fullerton; CalState, Long Beach; CalState, Northridge; CalState, San Bernardino; Carnegie Mellon University; Centro de Investigación Científica y de Educación Superior de Ensenada (Mexico); Colorado School of Mines; Cornell University; Disaster Prevention Research Institute (Japan); Earthquake Research Institute (Japan); ETH Zürich (Switzerland); Georgia Institute of Technology; GNS Science (New Zealand); Indiana University; Lawrence Livermore National Laboratory; Marquette University; National Aeronautics and Space Administration Jet Propulsion Laboratory; National Central University (Taiwan); National Chung Cheng University (Taiwan); National Taiwan University (Taiwan); Oregon State University; Pennsylvania State University; Purdue University; Smith College; State University of New York at Stony Brook; Texas A&M University; University of Alaska, Fairbanks; University of Bristol (UK); University of California, Berkeley; University of California, Davis; University of California, Irvine; University of Canterbury (New Zealand); University of Cincinnati; University of Illinois at Urbana-Champaign; University of Kentucky; University of Massachusetts, Amherst; University of Michigan; University of New Hampshire; University of Oregon; University of Texas at Austin; University of Texas at El Paso; University of Wisconsin, Madison; URS Corporation; Utah State University; Utah Valley University; Western University (Canada); Woods Hole Oceanographic Institution

SCEC is a center-without-walls that has developed the virtual organization [*14*] needed to coordinate and sustain interdisciplinary, multi-institutional earthquake system science. Examples are the SCEC Community Fault Model (CFM) [*15*] and the SCEC Community Velocity Model (CVM) [*16*]. These two long-running projects have integrated information from countless investigations of the California crust into a Unified Structural Representation (**Fig. 1.6**), recently summarized by Shaw et al. [*17*]. During SCEC4, investigators initiated a Community Geodetic Model (CGM) and a Community Stress Model (CSM). Continuing improvements to these community models, sustained by SCEC, have led to a boom in physics-based hazard modeling of Southern California.

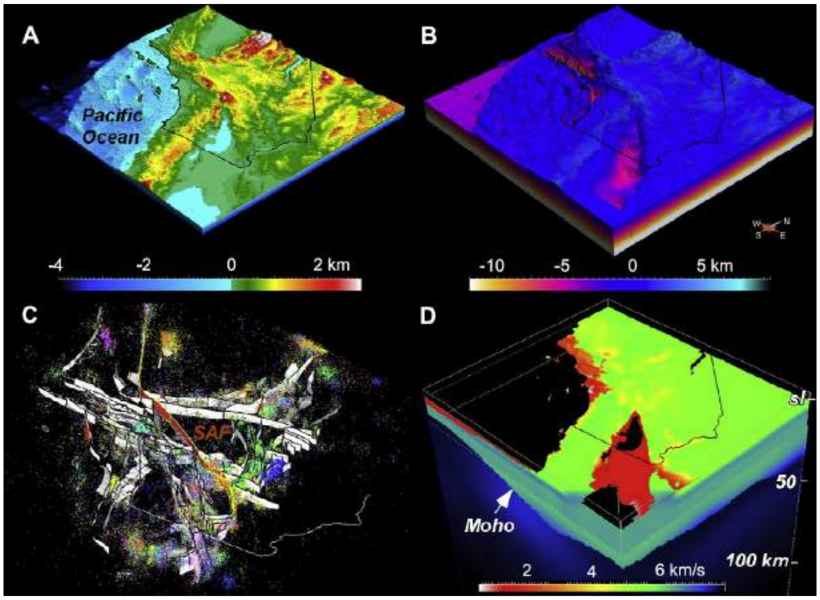


Figure 1.6. Perspective view of components of the Unified Structural Representation (USR). A. Topography and bathymetry; B. top basement surface; C. Community Fault Model (CFM); and D. USR showing compressional wave velocity. SAF is the San Andreas fault. Topographic and bathymetric surfaces are derived from USGS 3" digital elevation model and a National Oceanic and Atmospheric Administration 30" grid (TerrainBase).

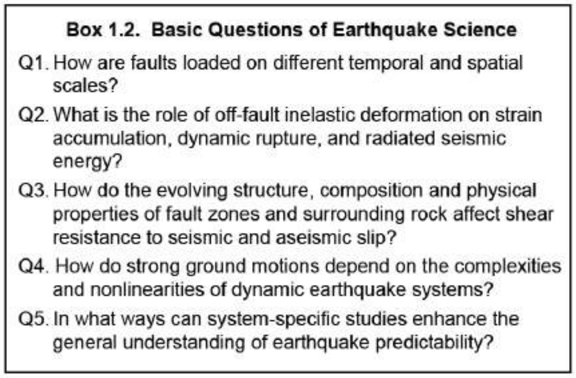
SCEC operates collaboratories for earthquake system science that include the Community Modeling Environment (CME), the Collaboratory for the Study of Earthquake Predictability (CSEP), and a new Collaboratory for Interseismic Simulation and Modeling (CISM), recently funded by the W. M. Keck Foundation. SCEC has become a world-leading virtual organization through the innovative use of high-performance computing (HPC) to solve system-level problems. In 2015, SCEC received allocations on national supercomputing facilities totaling 362 million service units through CME-led proposals to the NSF PRAC and XSEDE programs and the DOE INCITE program (see **Fig. 3.15**). These valuable allocations give SCEC researchers the HPC resources required for computationally intensive earthquake science, directly leveraging NSF's and DOE's huge investments in supercomputing. The current mean rate of computer usage by the SCEC collaboratories is almost 1 million CPU-hours per day.

SCEC is a reliable and trusted partner that works with other organizations to reduce earthquake risk and promote societal resilience to earthquake disasters. SCEC engages earthquake engineers through joint projects with the Pacific Earthquake Engineering Research Center, the California Earthquake Authority, and the Pacific Gas & Electric Company, and also directly through its Earthquake Engineering Implementation Interface. The EEII includes two standing activities run by professional earthquake engineers: the Ground Motion Simulation Validation Technical Activity Group (led by N. Luco and S. Rezaeian) and the Committee on the Utilization of Ground Motion Simulations (led by C. B. Crouse).

The SCEC Communication Education and Outreach (CEO) program manages the statewide Earthquake Country Alliance (ECA), which now comprises more than 200 partner organizations and sponsors a yearly preparedness campaign—the Great California ShakeOut—that has involved millions of California citizens. Through CEO efforts sustained by the SCEC core program and funded in part by FEMA and other agencies, SCEC now coordinates ShakeOut activities in 51 U.S. states and territories as well as Canada, Japan, New Zealand, and a growing number of other countries (**Fig. 1.2**). In 2014, more than 26 million people worldwide were registered in ShakeOut drills. As an indicator of ShakeOut's national impact, FEMA has modeled its new America's PrepareAthon on this program.

The CEO program has used SCEC research in developing effective new mechanisms to promote community preparedness and resilience, including the many publications branching from *Putting Down Roots in Earthquake Country*, installation of "Quake Catcher Network" sensors in schools and museums, and development of curricular materials. Partners in its K-14 Education Initiative include IRIS, UNAVCO, EarthScope, USGS, and CGS. Its EPIcenter Network of more than 60 museums, science centers, and libraries throughout California and a growing number of other states host public lectures, co-develop educational materials, and offer docent-led field trips. Some of SCEC's broadest and deepest impacts are through its highly successful Summer Undergraduate Research Experience (SURE) and Undergraduate Studies in Earthquake Information Technology (USEIT) intern programs, which have graduated more than 530 undergraduates of widely varying backgrounds since 1994.

SCEC is an international center that inspires interdisciplinary collaborations, and it involves many scientists from other countries. Currently, 11 leading foreign universities and research organizations are enrolled as participating institutions (**Table 1.1**), and others are involved through CSEP and CISM, bilateral memoranda of understanding, and multinational collaborations, such as the Global Earthquake Model (GEM) program [*18*]. The SCEC program is heavily leveraged by contributions from foreign participants who are supported through their own institutions.



Box 1.2. Basic Questions of Earthquake Science

Q1. How are faults loaded on different temporal and spatial scales?

Q2. What is the role of off-fault inelastic deformation on strain accumulation, dynamic rupture, and radiated seismic energy?

Q3. How do the evolving structure, composition and physical properties of fault zones and surrounding rock affect shear resistance to seismic and aseismic slip?

Q4. How do strong ground motions depend on the complexities and nonlinearities of dynamic earthquake systems?

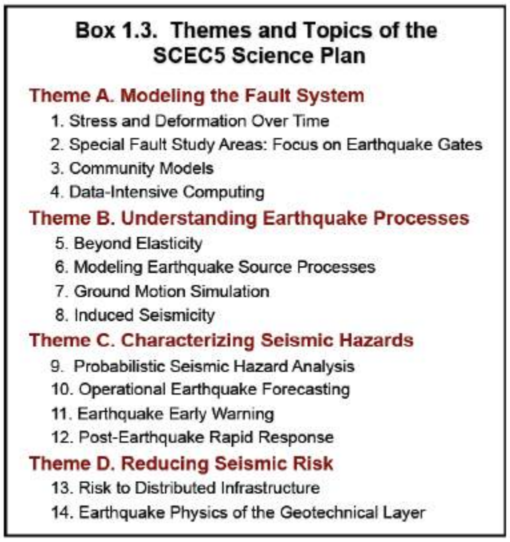
Q5. In what ways can system-specific studies enhance the general understanding of earthquake predictability?

C. Intellectual Merit of the Proposed Research: Basic Questions of Earthquake Science

Earthquakes are emergent phenomena of active fault systems, confoundingly simple in their gross statistical features but amazingly complex as individual events. The nonlinear processes of brittle and ductile deformation couple the long-term dynamics of fault systems to the short-term dynamics of fault rupture and ground motion. SCEC's vision is to develop community models of these dynamical processes that are comprehensive, integrated, verified, predictive, and validated against observations.

Prospective empirical testing is our most powerful guide for moving system models towards better representations of reality. The confirmation of predictive value is also essential in judging what information might be helpful in protecting society from future earthquakes. SCEC has become more capable in providing cyberinfrastructure for model development and testing. In SCEC5, the scientific goal of the core program will be *to provide new concepts that can improve the predictability of the earthquake system models, new data for testing the models, and a better understanding of model uncertainties*.

The strategic framework for the SCEC5 Science Plan has been cast in the form of five basic questions of earthquake science (**Box 1.2**). These high-level questions reflect the core issues currently driving earthquake research in California. Through them, we have refracted a spectrum of 14 topical elements that constitute the core of the Science Plan (**Box 1.3**).



Box 1.3. Themes and Topics of the SCEC5 Science Plan

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. Data-Intensive Computing

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. Earthquake Physics of the Geotechnical Layer

D. Broader Impacts of the Proposed Research: Anticipating Future Earthquakes

California comprises about two-thirds of the national long-term earthquake risk, with Southern California accounting for about 40% [*19*]. SCEC5 will translate basic research into practical products for reducing risk and improving community resilience. The Center will work with the USGS and California agencies to improve the two basic elements of seismic hazard analysis: earthquake rupture forecasting (e.g., UCERF and simulator-based forecasts) and ground-motion modeling (e.g., CyberShake and nonlinear earthquake simulations).

Experience in Southern California has demonstrated that the quantitative characterization of seismic hazards can provide the scientific basis for strong civic actions to mitigate risk and improve resilience. In December, 2014, Mayor Garcetti of Los Angeles released a major plan, *Resilience by Design* [*20*], to strengthen buildings, fortify the water system, and enhance reliable telecommunications. The plan was developed by a Seismic Safety Task Force, led by USGS scientist Lucy Jones, using the results of the 2008 ShakeOut Scenario. In that landmark study, SCEC ground-motion simulations of a M7.8 San Andreas earthquake [*21*] were provided to interdisciplinary teams, who used this detailed scenario to understand the impacts of a very large earthquake on the complex society of Southern California [*22*]. The Seismic Safety Task Force was able to apply the published results in making specific recommendations to retrofit for seismic safety and improve the disaster resilience of LA's urban systems. SCEC5 will continue to support the chain of scientific inference that proceeds from hazard characterization to loss estimation and—with the effort and leadership exemplified in the Jones Report—can lead to implementation of effective mitigation options with well-defined costs and benefits.

During SCEC4, substantial progress has been made in developing the time-dependent seismic hazard analysis needed to track earthquake cascades. Long-term probabilistic hazard analysis has been outfitted with new forecasting capabilities, such as UCERF3 [*2,3*], and new simulation-based ground-motion models, such as CyberShake [*7,8*]. Short-term forecasting methods have been prospectively tested by CSEP and are now being incorporated into operational systems in New Zealand [*23*], Italy [*24*], and the United States [*25*], as recommended by the International Commission for Earthquake Forecasting [*26*].

In SCEC5, we will continue to equip long-term seismic hazard analysis and short-term earthquake forecasting with physics-enabled, system-specific models that can provide authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes. This research will also lead to improvements in earthquake early warning—advanced notification that an earthquake is underway and predictions of when strong shaking will arrive at more distant sites [*27*]—as well as the delivery of post-event information about strong ground motions and secondary hazards, such as landsliding, liquefaction, and tsunamis.

II. Results from Prior NSF and USGS Support: SCEC4 Accomplishments

A. Science Accomplishments

Aftershocks, stress triggering, and induced seismicity are all indications that seismic hazard varies strongly with time. The time-dependence of seismic hazard motivated the current SCEC core research program of tracking earthquake cascades – understanding how seismic hazards change across all time scales of scientific and societal interest (**Fig. 2.1**). The SCEC4 science plan resolved the challenges of tracking earthquake cascades into six fundamental problems of earthquake physics (**Box 2.1**). We use this interdisciplinary framework to present the SCEC4 research accomplishments.

Box 2.1. Fundamental Problems of Earthquake Science

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

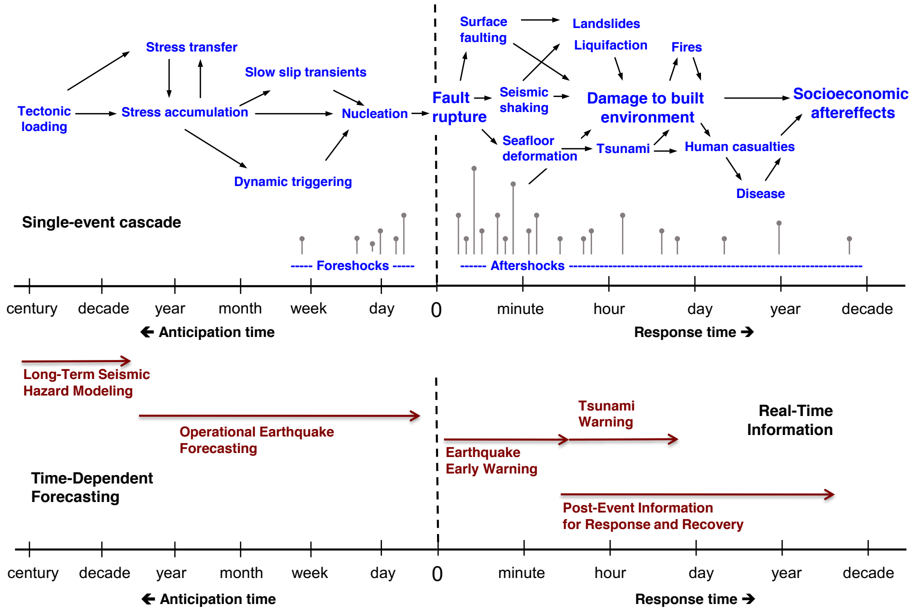


Figure 2.1. Earthquake processes (in blue) cascade through the natural and built environments, depicted here for a damaging event on a nonlinear time line. Red arrows indicate the time scales for long-term seismic hazard modeling, operational earthquake forecasting, earthquake early warning, tsunami warning and post-event response and recovery. SCEC has advanced the basic science that underlies these technologies, which is helping to reduce seismic risk and improve resilience. From the SCEC4 proposal.

1. Stress transfer from plate motion to crustal faults

The energy released in California earthquakes comes from steadily accumulating relative plate motion, but its manifestation in earthquake activity is spatially complex and temporally variable. To investigate the complex plate boundary across southern California, SCEC merged previous efforts that focused separately on crustal deformation modeling of geodetic data and lithospheric architecture and dynamics into the single interdisciplinary focus group, Stress and Deformation Over Time (SDOT), which develops and applies system-wide deformation models of lithospheric and mantle processes to acquire a better understanding of crustal deformation, the forces loading the lithosphere, rheology, structural heterogeneity, and the distribution of stress.

Stress and Deformation Over Time (SDOT). As a part of the UCERF3 effort, SCEC researchers developed a suite of kinematic deformation models for California from GPS measurements of horizontal velocities and geologic estimates of fault slip rates [*28*,*29*]. These models refine our understanding of the distribution of fault slip rates and are the culmination of decades of research into using geodetic data to constrain earthquake potential. This effort led to the surprising and significant result that as much as 20-30% of the total permanent deformation in southern California may be distributed through the crust, rather than localized on known active faults (**Fig. 2.2**).

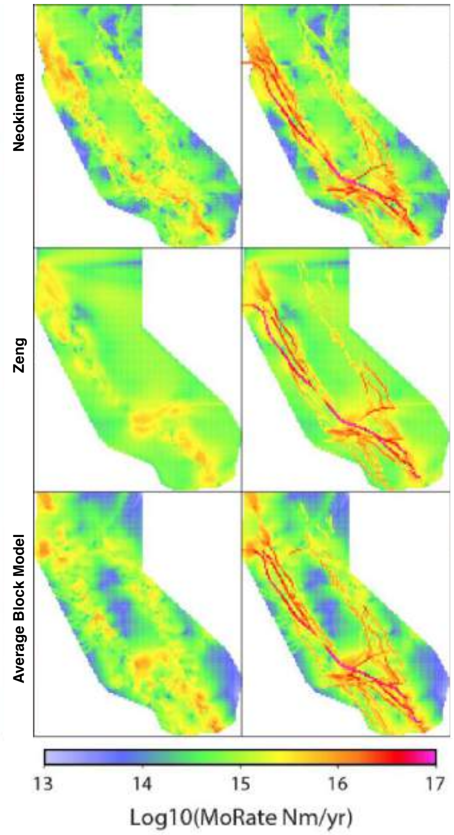


Figure 2.2. Off-fault (left) and total (right) moment rate from UCERF3 kinematic deformation models. Off-fault rate is computed from off-fault model strain rates using Kostrov summation. 20-30% of the total accumulation rate is off-fault. From Field et al. (2014).

The UCERF3 deformation models provide the highest-resolution representation of California crustal deformation to date. SCEC is now moving beyond kinematic models towards physics-based models of the plate boundary. These include finite-element models of a lithosphere cut by faults, allowing plastic deformation, and driven from the sides by far-field plate motion [*30*,*31*]. Lithospheric deformation and stress are controlled by friction and elasticity at low temperature and by viscous creep at high temperature. The predicted stress field shown in **Fig. 2.3** agrees well with the inferred principal stress directions from focal mechanism inversions in the SCEC Community Stress Model (CSM).

Understanding deformation in the crust over time and how plate-boundary faults are loaded requires an improved understanding of the rheology of the lithosphere and the transfer of stress between the elastic upper crust and the flowing lower crust and mantle. Numerical models of earthquake cycles on a strike-slip fault that incorporate laboratory-derived power-law rheologies with Arrhenius temperature dependence, viscous dissipation, conductive heat transfer, and far-field loading (**Fig. 2.4**) predict that deformation in the lower crust localizes in ~5 km-wide shear zones that broaden to ~15-20 km in the upper mantle [*32*]. The surface velocity field is relatively steady for much of the earthquake cycle, but has rapid post-seismic deformation for 10-20 years following large earthquakes. The models are broadly consistent with geodetic data and heat flow constraints across the central San Andreas. Future refinement could include better constraints on the depth distribution and temporal evolution of grain-size and rock fabric during shear zone evolution.

Community Geodetic Model. The need for improved spatial and temporal resolution of crustal deformation motivated development of a SCEC Community Geodetic Model (CGM) that combines data from continuous and campaign GPS data with Interferometric Synthetic Aperture Radar (InSAR) for Southern California. The CGM has been designed to be time-dependent, and it incorporates InSAR data to constrain the vertical deformation field and resolve small-scale regional deformations. It supports SCEC studies of earthquake physics and new methods for detecting time-dependent deformations [*33*,*34*]. The CGM uses GPS, InSAR, and combined time series to estimate secular deformation rates and to identify time-dependent processes. To develop the CGM, SCEC compiled and reprocessed campaign GPS data into a self-consistent position time series. This required identifying discrepancies among continuous GPS solutions provided by different processing centers, assessing time-dependent noise, and

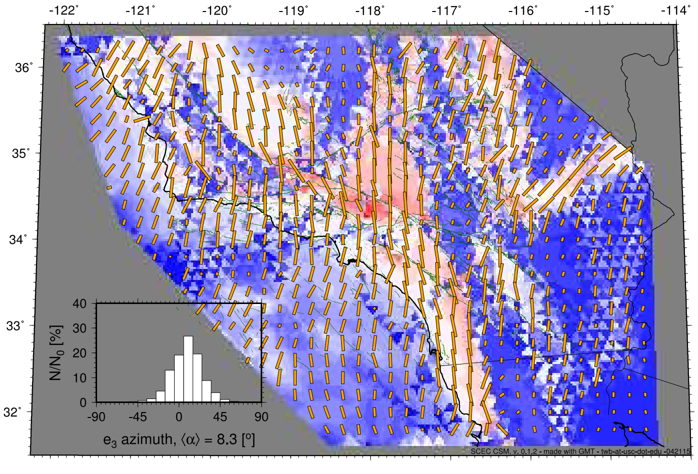


Figure 2.3. Stress at 3-km depth in Southern California from Bird's (2014) SHELLS model, a member of the CSM ensemble. Bars show direction of the maximum horizontal compressive stress; their lengths are scaled with the maximum shear stress. Background colors are mean horizontal normal stress. From Community Stress Model.

developing a strategy for merging solutions. A parallel effort reduced errors (**Fig. 2.5**) and reconciled InSAR time series analyses developed using different processing methods [*35*,*36*]. CGM development is currently focused on integrating GPS and InSAR components into a single model.

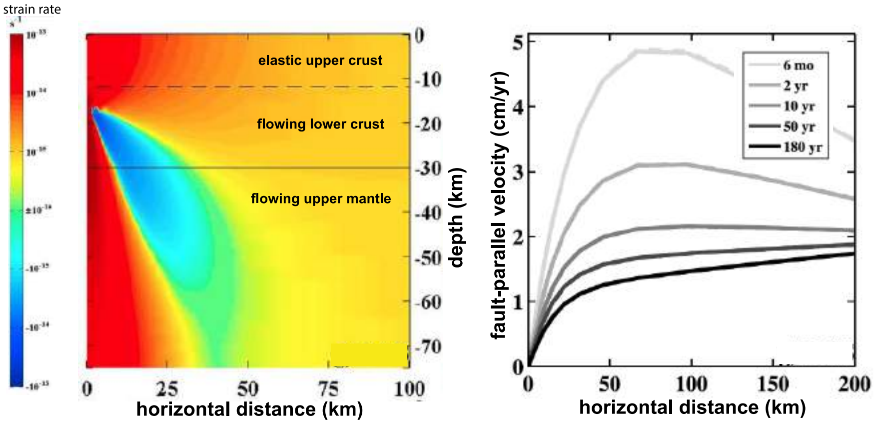


Figure 2.4. Numerical model of earthquake cycle deformation incorporating power law rheology with temperature dependence. Strain is localized within a ~10-20 km wide shear zone in the lower crust and uppermost mantle. The model predicts surface velocity field that varies with time since the last earthquake. From Takeuchi, & Fialko (2012).

The boundary between geodesy and precision measurement of surface features is blurring. LiDAR has revolutionized the measurement of fine-scale faulting and earthquake deformation features as expressed by topography. Extracting new information from such measurements has been an active research area in SCEC4 [*37*,*38*,*39*,*40*] and has led directly to important new insights into fault system behavior. It is also an important part of response planning for future earthquakes (Topic 12). Topographic differencing for the El Mayor-Cucapah earthquake (**Fig. 2.6)** [*41*] and for crustal earthquakes in Japan [*42*] documented strong variations in the continuity and expression of slip along faults in the uppermost crust. These results are complementary to InSAR results, and have the potential to inform larger scale geodetic deformation models. SCEC hosted a series of workshops with tutorials to support wider application of the various approaches to image processing.

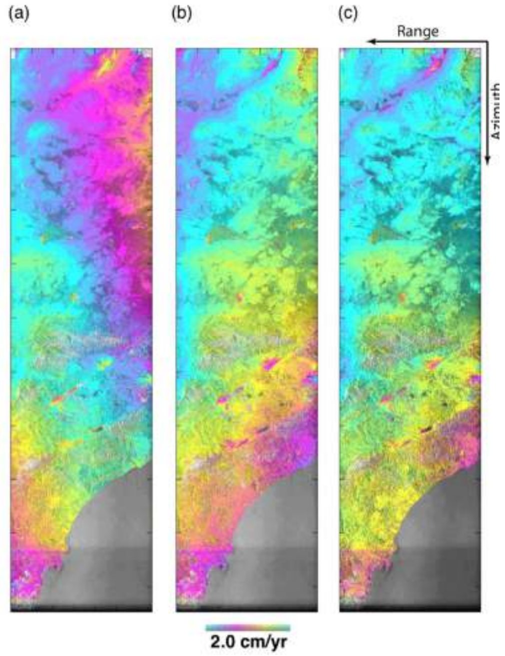


Figure 2.5. Average line-of-sight (LOS) velocity from Envisat data 2003-2010. (a) Initial velocity with significant error from oscillator drift; (b) velocity after empirical length-of-day phase-drift correction; (c) velocity after correcting each interferogram by GPS-based block model. Both approaches remove error, and the correction improves agreement between InSAR and GPS line-of-sight velocity. From Liu & Shen (2015).

Quantification of fault slip rates, and the time of past events identified through paleoseismology, depends on effective geochronology, for which SCEC has developed a coordinated approach. The geochronology infrastructure provides a community resource for SCEC researchers to draw from for dating using carbon-14, *in-situ* cosmogenic nuclides, and luminescence techniques. By pooling resources, the geochronology infrastructure program saves resources, increases flexibility, and allows investigators to adjust quickly to pursue unanticipated research opportunities. SCEC also supports basic research on laboratory techniques, sample collection protocols, and comparison of multiple dating methods at field sites. The geochronology infrastructure has helped SCEC scientists lead the way in building well-constrained, long paleoseismic event chronologies to test earthquake models [*43*,*44*,*45*], has developed the pIR-IRSL technique for luminescence dating of feldspar to meet dating needs in arid regions [*46*,*47*], and advanced the application of multi-chronometer techniques to expand capabilities and reduce epistemic uncertainty in the timing of events and slip rates [*48*,*49*,*50*,*51*]. The geochronology program also facilitates sharing of expertise among researchers and labs through interactions at the annual meeting and workshops, and provides opportunities for students to use world-class analytical facilities at participating laboratories. All SCEC geochronology infrastructure data is archived and openly available.

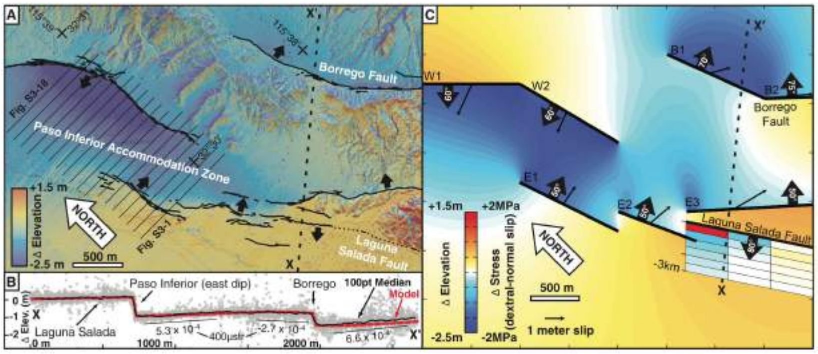


Figure 2.6. Differential LiDAR and elastic model for part of El Mayor-Cucapah rupture. (A) Elevation difference showing distributed deformation as slip steps from the NW Borrego Fault into the PIAZ. Arrows show dip direction. (B) Profile of elevation difference along line X-X′ in (A). (C) Elastic model, using rectangular dislocations, showing vertical surface deformation due to imposed slip along the PIAZ fault array. Slip vectors point in the direction of hanging wall motion. Modeled slip vectors match field observations, except for faults E1 to E3, where slip is 30% above the observed values. Coulomb stress change for oblique slip along the Laguna Salada Fault is shown from the surface to 3-km depth. From Oskin et al. (2012).

2. Stress-mediated fault interactions and earthquake clustering

Key to understanding earthquake cascades is understanding stress – both absolute stress levels, and the magnitude of stress changes – that influences the southern California fault system. Stress is a tensor quantity, and most measurements of it are only sensitive to some aspects of the total field. As a result, even the magnitude of stress in the Earth is poorly understood; however, the importance of stress in driving earthquake behavior and the need for better constraints on how faults are loaded motivated a SCEC collaboration to develop a community stress model (CSM). This effort is embedded in, and has proceeded collaboratively with, other SCEC initiatives such as SDOT and the CGM.

CSM products include a suite of models of the 4D stress and stressing-rate tensor in the California lithosphere. Community discussions and a series of four dedicated workshops led to a common CSM analysis framework and workflow. The CSM web site [*52*] hosts all of the models contributed by the community. These include four stress and five stressing-rate models that are available in a standardized, comprehensive format, and all models can be visualized and validated against available constraints in a consistent way. The CSM web page also provides plotting and validation scripts for user-driven reanalysis. Among the insights that arose from initial comparison efforts were that the stress state inferred from focal mechanisms shows a remarkable agreement among models, whereas other parameters, such as the absolute value of stress vary significantly and remain a research problem. The community advanced several candidate CSM models; a focal-mechanism based model (YHSM-2013) [*52*] was the first to be released (**Fig. 2.7**). Future challenges for the CSM include the expansion of the range of data available, in particular expansion of the borehole database (in collaboration with industry), and the examination of absolute crustal stress levels within the context of a rheologically realistic lithosphere and asthenosphere model.

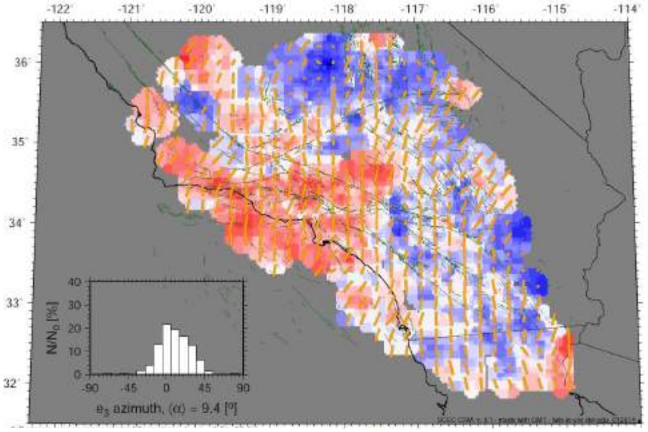


Figure 2.7. SCEC Community Stress Model YHSM-2013, inferred from focal mechanisms (Yang & Hauksson, 2013). Bars show direction of the maximum horizontal compressive stress; their lengths are scaled with the von Mises stress in arbitrary units. Background colors are mean horizontal normal stress.

Improved earthquake catalogs – new detections [*53*], precise locations [*54*], and improved source parameters [*55*] – are foundational to many SCEC activities. New techniques allow detection of far more earthquakes than in standard catalogs. This increased sensitivity reveals earthquake behaviors, such as the combined effects of dynamic triggering and static stress shadowing [*56*], that might otherwise not be apparent (**Fig. 2.8**). In this case, the triggered earthquakes were all small, but in the 2010-2012 Canterbury NZ sequence, a M 6.3 aftershock directly beneath Christchurch destroyed the city center, killing 185 people. Subsequent aftershocks compounded the damage and undermined recovery efforts. SCEC partnered with the REAKT project and New Zealand's GNS Science to conduct within CSEP a retrospective evaluation of forecasting models. The Canterbury experiment showed for the first time, that the short-term performance of the physics-based models, which update forecasts with Coulomb stress changes, significantly outperform models updated only with the conventional seismicity statistics [*57*]. Induced seismicity is a form of triggered seismicity, and a growing concern. The stressing rate from geothermal energy development locally exceeds the tectonic stressing rate [*58*], and hence has the potential to play an important role in earthquake triggering. Earthquake rates in the Salton Sea Geothermal Field, when interpreted in the context of an ETAS model, are correlated with the net extraction of fluid from the field [*59*].

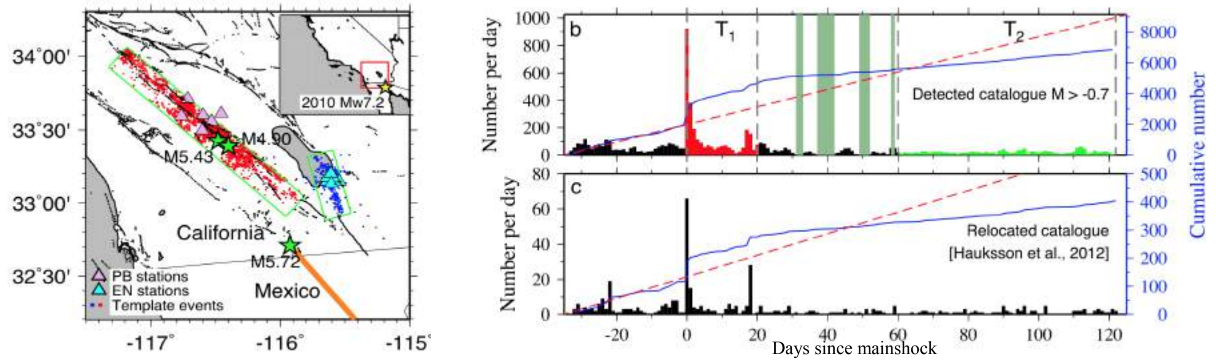


Figure 2.8. (a) Seismicity rate changes in the Salton Sea Geothermal Field (blue epicenters) following 2010 El Mayor-Cucapah earthquake. (b) Detected events per day versus time relative to the mainshock. Blue line is cumulative number of detected events; red dashed line is from the average pre-mainshock rate. (c) Same as (b) using only events in the relocated catalogue. The seismicity rate initially increased due to dynamic triggering and then decreased due to static stress shadowing. Green areas flag data gaps. The detected catalog shows more than an order of magnitude more events than the relocated catalog. From Meng & Peng (2014).

Development of long-term earthquake chronologies is an explicit SCEC4 goal. Outstanding examples are the Mystic Lake and Hog Lake sites on the San Jacinto Fault. These two 2000+ year records of earthquakes [*43*,*44*,*60*,*61*] lend support for the role of segmentation in earthquake rupture forecasting by showing that most events did not cross the Hemet step-over. Comparison with work on the San Andreas suggests that these faults could rupture in a single earthquake, raising complex scenarios where an earthquake starts on one fault then propagates onto the other [*62*].

Despite progress in constraining slip rates and earthquake chronologies, important inconsistencies remain, even for the San Andreas Fault. UCERF3 event rates on the southern SAF average about 25% less than the most reliable paleoseismic estimates [*28*]. Such discrepancies, and also those between geologic vs. geodetic slip rates on individual faults, point to possible inconsistencies in assumptions that we should strive to understand and resolve. Among the most prominent is that between geologic and geodetic slip-rate estimates for the Garlock Fault. High-resolution LiDAR, coupled with advances in OSL dating of feldspar, reveal strong temporal earthquake clustering on the Garlock Fault [*63*], which could explain the discrepancy. Similar clustering is found for the faults of the eastern California shear zone (ECSZ), although results from the Panamint Valley Fault [*64*] suggest more complex behavior than simply alternation with the activity of the Garlock. Distributed off-fault deformation surrounding active faults is another potential contributor to this discrepancy [*65*]. Modeling of the ECSZ [*66*] suggests that substantial slip occurs as distributed deformation around fault tips within the Mojave block.

The Earthquake Simulator TAG focused on the comparison, validation, and verification of results from earthquake simulators that characterize interaction among earthquakes in a complex fault system through physics-based simulations. Because they have the potential to extend the ~100-year instrumental, several 100-year historical, and scant 1000-year paleoseismological records to 10,000-year and longer durations, simulators represent a promising pathway for physics-based earthquake forecasting. Results of this activity are documented in seven papers published in a special issue of *SRL* [*67*]. These efforts indicate that it is not uncommon for 200-year periods of seismic activity to vary by a factor of 3 in seismic moment, which could help to explain differences in historical vs. geologically documented seismic activity.

3. Evolution of fault resistance during seismic slip

Processes that determine frictional resistance and its evolution during co-seismic slip are critical to understanding earthquake behavior because they determine how, when, and where ruptures initiate, propagate, and stop. The lack of heat-flow anomalies, principal stress directions and their rotations due to earthquake stress drops, the geometry of thrust-belt wedges, as well as recent measurements from rapid response drilling [*68*] all point to effective friction during slip on mature, well-developed faults of less than 0.2, while quasi-static friction coefficients for most rock materials are 0.6-0.8. Understanding the origin of this difference is critical to understanding earthquake cascades.

Dynamic weakening remains a focus. Platt et al. [*69*, *70*] found that thermal pressurization and decomposition provide multiple rupture modes. Slip pulses dominated by thermal decomposition have a distinctive slip rate profile, with peak slip rates near the trailing edge of the rupture. Simulations of the influence of flash heating and thermal pressurization on earthquake nucleation and rupture for faults with low background stress suggest that thermal pressurization is required to explain the observed relationship between fracture energy and slip [*71*]. New experiments have characterized the processes responsible for flash weakening in gouge [*72*] and thermal pressurization (**Fig. 2.9**) [*73*] – the latter being documented in the lab for the first time. SCEC activities provided synergy between analysis of these data and the physical models for dynamic weakening, new insights into the physical processes responsible for dynamic weakening, and a rationale for their inclusion into earthquake cycle and rupture models. Further constraints on stress levels on natural faults may be enabled by newly developed fault slip thermometers that evaluate thermally induced changes in organic compounds within gouge [*74*] and reduction of iron (Fe^{3+} to Fe^{2+}) and associated conversion of hematite to magnetite on fault surfaces [*75*].

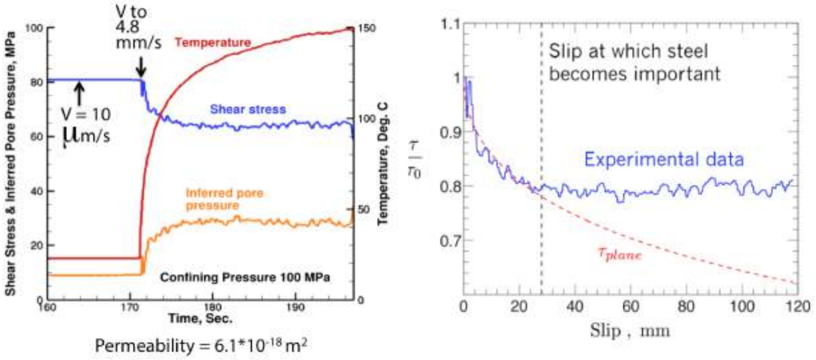


Figure 2.9. Reduction in strength and increase in pore pressure for experiment with a velocity step change, assuming changes of shear stress are due to changes in fluid pressure. Right panel shows experimentally measured stress decays as predicted, demonstrating thermal pressurization in the lab for the first time. Deviation from theory after ~28 mm is attributed to steel sample grip conducting heat and preventing temperature from rising as it would for a half-space. From Tullis & Goldsby (2013).

A strong theme that emerged in SCEC4 is how heterogeneous fault stress and fault geometry influence rupture propagation. SCEC scientists have done pioneered research on fault roughness [*76*]. Studies of the effect of fault roughness on the frictional resistance of faults undergoing dynamic weakening, found that rough, immature faults operate at higher stress levels, while mature, smoother faults operate at lower stress levels [*77*], as expected. New calculations indicate that supershear ruptures are more likely on rough faults [*78*], an effect contrary to expectations (**Fig. 2.10**). Fault roughness was also found to influence the distribution of seismicity in laboratory experiments where the power-law exponent that describes the decay of acoustic emission with distance from the slip surface depends on roughness as well as normal stress [*79*]. New models also show the limitations of modeling multi-strand fault surfaces with a single fault surface [*80*]. Introduction of complex fault geometry led to an increased appreciation for the importance of inelastic, "off-fault" deformation, which was studied in idealized scenarios [*81*] and in the field [*82*]. Off-fault plasticity was found to be important not only to rupture dynamics, but also to crustal deformation modeling [*30*] and ground-motion prediction [*83*].

Understanding the base of the seismogenic zone is critical for evaluating the potential for large events. These properties have been studied by incorporating thermally activated power-law creep rheologies into earthquake cycle models [*84*]. The history of such ruptures may be identified by lack of microseismicity at the base of the seismogenic zone [*85*,*86*]. Recent developments in source inversion and imaging including advances in uncertainty quantification in finite source inversion, accounting for uncertainties in the crustal velocity model, and high-frequency back-projection rupture imaging allow us to rapidly extract robust information about large strike-slip earthquakes worldwide [*87*].

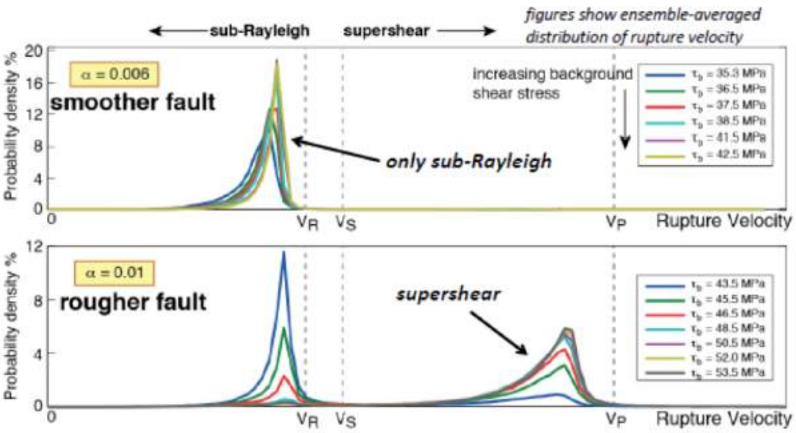


Figure 2.10. Rupture velocities from 1000 rupture simulations of smoother faults (upper) and rougher faults (lower) are shown as probability density functions. Supershear rupture is favored on rougher faults. From Bruhat et al. (2015). .

Computational Science. SCEC4 established a new disciplinary group in Computational Science to develop and apply state of the art computation to earthquake science problems. 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.

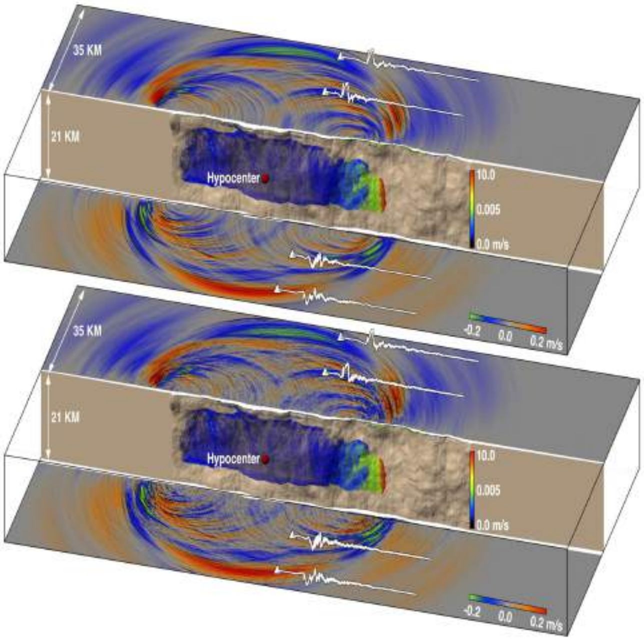


Figure 2.11. Snapshots of propagation of 10 Hz wavefield for a crustal model without (top) and with (bottom) small-scale heterogeneity. Fault complexities were included in the simulation. Strike-parallel seismograms are superimposed as white traces at selected sites. The part of the crustal model located in front of the fault is lowered for a better view. Note strongly scattered wavefield in bottom snapshot due to small-scale heterogeneity. Simulation run by Cui et al. (2014) on Cray XK7 GPUs on Titan at ORNL and Blue Waters at NCSA . Visualization by A. Chourasia.

Key advances in HPC during SCEC4 enabled new capabilities in modeling source physics – particularly geometric fault complexity as the origin of rupture variability that generates high-frequency radiation in earthquakes [*88*,*89*]. Dynamic rupture simulations, involving thousands of realizations of the stochastic fault geometry, helped quantify the range of stress levels at which earthquakes occur, with contributions to resistance coming from both friction and geometric complexity [*77*]. Correlations between slip and rupture velocity fluctuations were linked to the fault geometry, offering new approaches to pseudo-dynamic rupture modeling [*90*]. The short spatial and temporal scales over which fault strength and slip rate vary near the rupture front motivated introduction of a refined mesh to track the rupture front and other sharp features like wavefronts. Both static and adaptive mesh refinement (AMR) were first applied to rupture dynamics problems during SCEC4 [*91*,*92*,*93*], and show great promise for future modeling studies.

Additional advances enabled by HPC include the ability to model high-frequency ground motions and inelastic material response (**Fig. 2.11**). Both scattering and intrinsic attenuation reduce seismic wave amplitudes. Fine-scale material heterogeneities, as spatially correlated random perturbations to existing velocity models, significantly alter simulated ground motions, particularly at high frequencies (>2 Hz) [*94*]. With scattering directly modeled, it became necessary to alter intrinsic attenuation used in simulations by making the quality factor Q dependent on both frequency and depth [*95*,*96*]. User-driven validation studies [*97*,*98*] are bringing predicted ground motions into closer agreement with observations. A major break-through in SCEC4 was the demonstration that inelastic material response, in both the near-fault and near-surface regions, can substantially decrease ground motions. Predicted ground motions from the 2008 M 7.8 ShakeOut earthquake scenario were reduced by up to 70% compared to the linear case [*83*].

SCEC has integrated its CyberShake, Broadband, High-F, and F3DT computational platforms into a software ecosystem for physics-based seismic hazard analysis [*99*,*100*,*101*,*102*]. It has developed highly efficient codes that run efficiently on the largest GPU-enabled supercomputers [*103*,*104*,*105*,*106*,*107*,*108*]. Combined with workflow efficiencies gained through our collaborations with the National Center for Software Applications and the Oak Ridge Leadership Computing Facility, these HPC capabilities have made it possible to run CyberShake at seismic frequencies up to 1 Hz. This milestone takes CyberShake from the low-frequency simulations relevant to the design of tall buildings, dams, and bridges up to the edge of the 1-10 Hz frequency band of primary interest for most smaller structures. CyberShake site and path effects unexplained by the Next Generation Attenuation (NGA) models [*109*] account for 40%–50% of total residual variance, suggesting that improvements to simulation-based hazard models could reduce the unexplained variability in current GMPEs by up to 25% [*95*].

4. Structure and evolution of fault zones and systems

Plate-boundary fault systems are geometrically complex, even though they may be organized around a master fault that takes up most of the plate motion. A major problem in earthquake physics is how rupture is influenced by geometrical complexity. The ability of ruptures to navigate geometrically complex fault systems is documented for some large earthquakes [*110*,*111*,*112*], and increasingly realistic numerical simulations are illuminating the conditions under which this can occur [*113*,*114*,*115*,*116*,*117*]. Simulations over multiple cycles result in stress buildup at geometrical heterogeneities, which will impact the rupture. To develop a better understanding of the interplay of earthquake physics with fault complexity, the SCEC4 collaboration established two Special Fault Study Areas (SFSAs), which are both scientifically rich targets that are the focus of integrated multi-disciplinary research teams that carry out a coordinated research agenda.

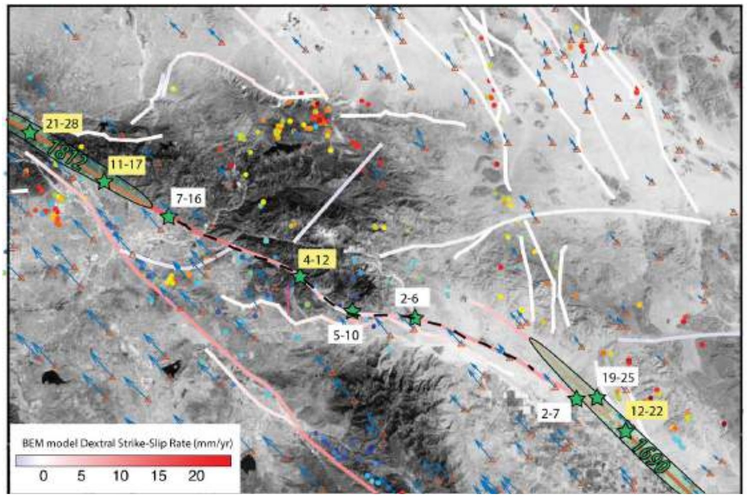


Figure 2.12. Boxes show dextral slip rates from geologic studies (stars) along the San Andreas through the San Gorgonio Pass (SGP) Special Fault Study Area. White boxes are data obtained in SCEC4. Green ellipses with year show extent of known surface rupture during most recent, large San Andreas Fault events. Extent of most recent earthquake in SGP likely involved the entire southern San Andreas. Blue/red lines show dextral slip rates from crustal deformation BEM. Dashed segments were used in dynamic simulations. Triangles show GPS stations with CMM4 velocity arrows in blue. Circles show seismicity M > 3 since 2000 with cooler colors indicating greater depth.

San Gorgonio Pass Special Fault Study Area. The largest discontinuity along the San Andreas Fault occurs in the San Gorgonio Pass (SGP) where active strands form a distributed zone of faulting [*118*], in contrast to regions outside of the SGP, where deformation is restricted to a single active strand (**Fig. 2.12**). Forecasting 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 took a multi-disciplinary approach to address these questions. The emerging view is that the complex structure of SGP typically arrests ruptures, yet occasional events rupture all the way through as very large earthquakes.

Through an array of field studies [*119*,*120*,*121*,*122*,*123*], microseismicity [*124*], geodetic inversions for slip rate [*125*] and crustal deformation models [*126*], we improved our understanding of slip partitioning through the SGP fault system. Field studies added key strike-slip rates, that filled gaps within previous coverage (**Fig. 2.12**) [*119*,*49*,*123*]. Dynamic rupture models in realistic fault geometry [*127*] demonstrated that the rupture through the SGP is sensitive to initial stress levels as well as fault geometry, and microseismicity shows a systematic change in stress drop north and south of the SGP thrust [*128*]. The question of through-going rupture potential has also been addressed through deep trenches that show that the last event to rupture through the SGP may have been ~1400 AD [*129*]. This is consistent with strain accumulation [*125*], measured strike-slip rates [*130*] and modeled strike-slip rates [*131*] within the SGP.

Ventura Special Fault Study Area. The Ventura SFSA (**Fig. 2.13**) was established to promote interdisciplinary investigations of the prospects for large, multi-segment thrust fault ruptures in southern California, and to address the hazards posed by these potentially devastating events. Several recent earthquakes (1999 M7.6 Chi-Chi, Taiwan; 2005 M7.6 Kashmir, Pakistan; and 2008 M7.8 Wenchuan, China) demonstrate the potential for thrust fault ruptures to breach segment boundaries and involve multiple, stacked fault splays. Prior to UCERF3, these large, multi-segment events were generally not considered in seismic hazard assessments. Larger events may pose great risks due to the intensity, duration, and potential for offshore thrust faulting to trigger tsunamis. Results from the Ventura SFSA support the notion of infrequent, but extremely large earthquakes on this fault system.

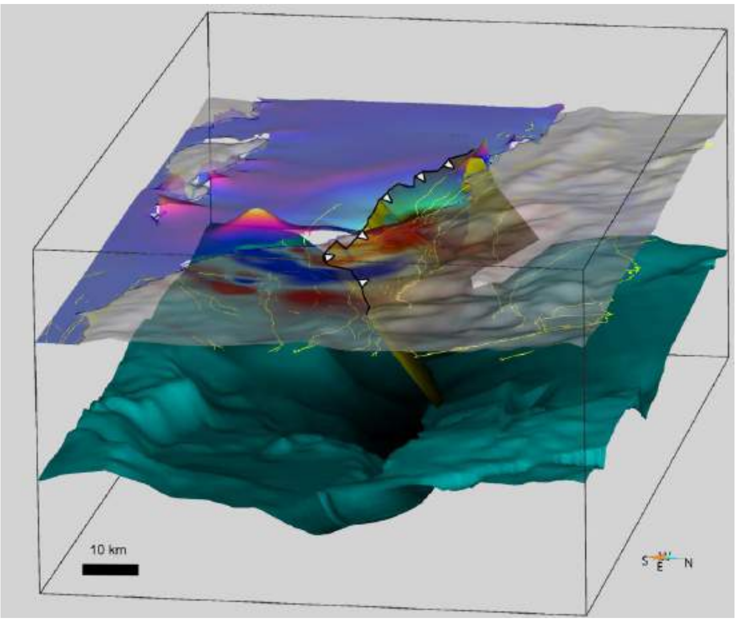


Figure 2.13. Perspective view of the Ventura-Pitas Point-Southern San Cayetano Fault system, showing ground motion and tsunami simulations for M7.8 scenario. Vertical component of velocity (red to blue) at time step 27s is shown onshore; vertically exaggerated water elevation at time step 20 min shown offshore. Qfault traces are yellow. Lower image includes perspective view of the top basement horizon from the SCEC USR, highlighting co-location of the Ventura basin and the source fault. Graphic by A. Plesch.

The Ventura Fault and overlying Ventura Avenue anticline [*132*] occupy a unique position at the juncture of several of the largest and fastest slipping faults in the Transverse Ranges (e.g., San Cayetano and Red Mountain Faults). Holocene terraces on the anticline suggest that it deforms in discrete 5-10 m uplift events, with the latest occurring ~900 years ago [*133*;*134*]. The magnitude of these uplifts implies rupture of adjacent faults, yielding large (M 7.5 to 8), multi-segment earthquakes. The SFSA effort integrated geology, paleoseismology, exploration geophysics, seismology, geodesy, rupture dynamics, strong ground-motion simulations, and tsunami studies [*135*,*136*].

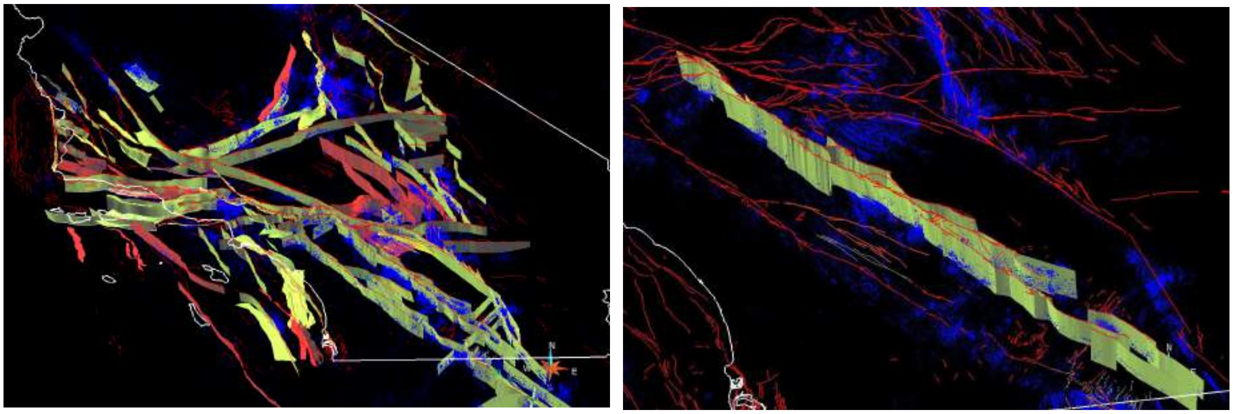


Figure 2.14. Left panel shows Community Fault Model, Version 5.0 (Nicholson et al., 2014). Faults in red are new representations; others are refined using Qfault traces and seismicity. Right panel shows detail of San Jacinto Fault, which is more complex and segmented in the improved representation. Graphic by A. Plesch.

An initial focus of the SFSA was to understand the structures in this system using seismic reflection data and well control [*137*]. The Ventura, Pitas Point, San Cayetano, and Red Mountain Faults are likely connected along strike at seismogenic depths, despite >10-km offsets of their surface traces [*138*,*139*,*140*,*141*,*142*,*143*,*144*]. Excavations across the fold scarp above the blind Ventura Fault, reveal at least two large (4.5 to 6 m uplift), Holocene earthquakes [*145*,*134*]. These events correlate with marine terrace uplift at the coast [*133*]. Studies of the offshore extent of the fault system document Holocene seafloor folding [*146*]. Geodetic observations and fault system modeling constrain the rapid shortening (2.7 to 8 mm/year) and uplift (> 2 mm/yr) rates across the structure [*147*,*148*,*149*]. Together, these observations all support the occurrence of very large multi-segment thrust fault earthquakes on this fault system, as illustrated in the M7.8 scenario of **Fig. 2.13**.

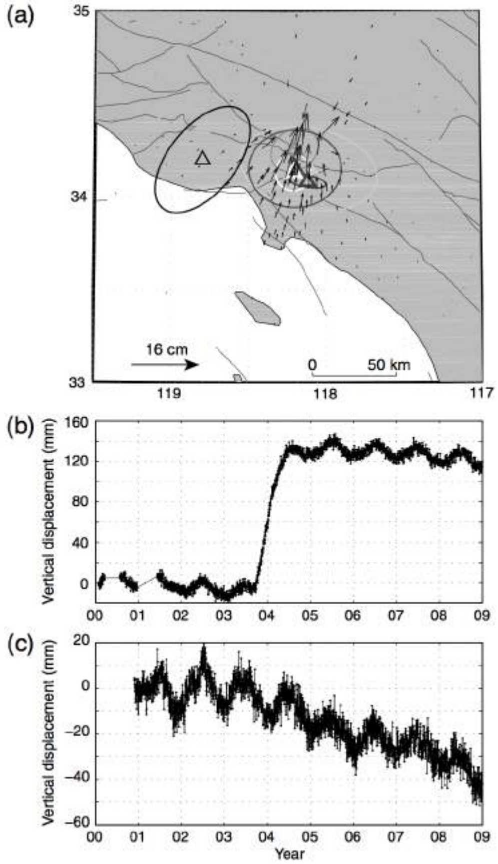


Figure 2.15. Phase IIa of the transient detection exercise showing (a) Predicted horizontal deformation during the simulated transient (vectors). Triangles and ellipses indicate location and deforming region found by the detectors. (b) Vertical displacement history at station with maximum displacement, showing the large signal (detectable by eye). (c) Vertical displacement for a more subtle case that resulted in no detections. From Lohman and Murray (2013).

Community Fault Model. The SCEC Community Fault Model (CFM 5.0) includes several major improvements (**Fig. 2.14**). Among these are refinement of fault geometries using the USGS Qfault traces and relocated seismicity [*52*, *54*]. CFM 5.0 provides improved representations in the Santa Maria and Ventura Basins, Santa Barbara Channel, Inner Borderlands, E Transverse Ranges, Peninsular Ranges, San Gorgonio Pass, and the Mojave Desert. Fault representations are precise, and often more segmented than in previous models, and there are now simplified, meshed representations intended to aid modeling studies.

5. Causes and effects of transient deformations

The 21st century has seen the discovery of a new mode of fault motion: episodic tremor and slow slip. Although primarily observed in subduction zones, it has also been reported in continental settings, including the San Andreas Fault. Triggered tremor driven by dynamic stresses in the long period wavetrain of large earthquakes has been observed widely in California [*150*]. A continuing goal of SCEC has been to document the occurrence of tectonic tremor in Southern California, and to search systematically for possibly related aseismic deformation transients.

Between 2001 and 2011, only the M_w 7.8 Denali earthquake triggered tremor on the San Jacinto Fault, even though closer earthquakes, such as the 2009 Gulf of California event, resulted in larger dynamic stresses [*151*]. No tremor has been discerned on the San Andreas south of Cholame. The continuing effort to find tremor has driven development of new, computationally efficient approaches to detect isolated low frequency earthquakes [*152*] that should see wider application to improving catalogs. Another new approach to detect precursors applied to 10,000 southern California earthquakes yielded only a handful of newly recognized foreshocks [*153*]. A search for transients by combining ETAS and rate-state models of seismicity, on the other hand, detected a large transient in the Salton Trough – also seen with geodetic data – and an anomaly associated with the 2009 Bombay Beach swarm, suggesting it may have been accompanied by aseismic deformation [*154*]. Systematic analysis of foreshock sequences suggest a role for aseismic forcing [*155*], and perhaps fluid diffusion [*156*]. The Aseismic Transient Detection TAG developed systematic searches for aseismic transients. The effort began with a community blind-test exercise to detect transient signals in synthetic data (**Fig. 2.15**) [*157*]. A subset of the detection algorithms are now systematically mining GPS data in Southern California for deformation transients.

6. Seismic wave generation and scattering

SCEC continues to champion the use of numerical simulations in seismic hazard analysis. Simulations incorporate the best available geoscientific understanding of faulting and wave propagation – including the effects of directivity, basin response, small-scale structure, topography, and nonlinearity. There has been a strong trend in SCEC4 to validate simulations against data. Much of this effort has been led by engineering seismologists and engineers, who recognize the potential of SCEC's efforts in physics-based ground-motion prediction [*158*].

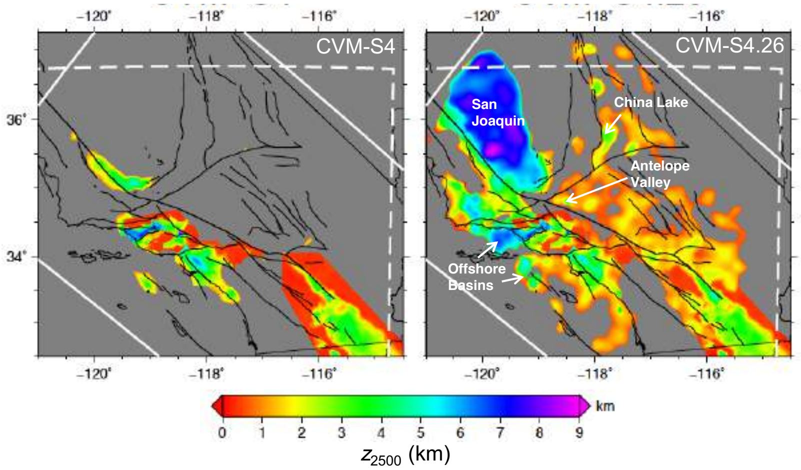


Figure 2.16. Maps of Southern California showing improvements in basin structure obtained by full-3D tomography (F3DT). Colors represent z_{2500} (iso-velocity surface at v_S = 2.5 km/s), a common measure of basin depth. Left panel is z_{2500} for the SCEC Community Velocity Model, CVM-S4, which was used as the starting model. Right panel is z_{2500} for CVM-S4.26, the 26th iteration of a dataset comprising over half a million waveform measurements from earthquake seismograms and ambient-field correlagrams. Basin structures from the CVM-S4.26 are consistent with seismic reflection and refraction data. From Lee et al. (2014).

<u>Community Velocity Models and Unified Structural Representation</u>. SCEC has pursued the systematic integration of seismological and geological information into a unified structural representation [*159*] (**Fig. 1.6**). A new USR was recently released for the San Joaquin Basin, which incorporates tens of thousands of well-log measurements, seismic reflection, and geologic constraints. This model will be embedded into future versions of the CVMs.

During SCEC4, the CVMs were improved using the techniques of full three-dimensional waveform tomography (F3DT) [*160*]. This required improving computational capabilities and workflows [Small et al., 2015; Cui et al., 2013a,b] and incorporating ambient-field data, which provide strong sensitivity to the shallow Earth structure that governs strong ground motion [*161*] The basin structures in **Fig. 2.16** come from CVM-S4.26, which assimilated more than a half-million misfit measurements from 38,000 earthquake seismograms and 12,000 ambient-noise correlagrams [*162*]. This high-resolution tomography provides insight into the crustal structure and has improved earthquake ground motion simulations, including the latest CyberShake model (**Fig. 3.20**). SCEC is working to quantify the predictive value of the new CVMs.

Additional innovations include incorporating anisotropy, attenuation, and small-scale heterogeneity [*163*], which are needed to push simulations to higher frequencies.

High-Frequency Simulations. SCEC is pushing ground motion predictions to higher frequencies (*f* > 1 Hz). Accurate simulations require new levels of knowledge about fault complexity and crustal structure, and the computational demands are substantial. Characterizing the source at high resolution and modeling wave propagation at short wavelengths is a dual challenge. High-frequency ground motion simulations are currently done using kinematic source models with stochastic variability (**Fig. 2.11**), crustal velocity models with short-wavelength components constrained by limited observations (**Fig. 2.16**), and scattering operators to represent unmodeled structure.

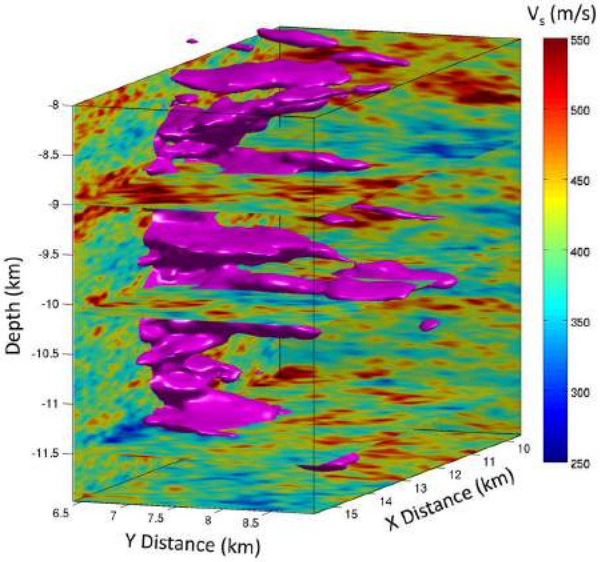


Figure 2.17. Snapshot of 0-2.5 Hz waves in a realistically heterogeneous structure. Wave surfaces of constant particle velocity (magenta) are guided through lower-velocity material (blue) and circumvent higher velocity material (red). Similar behavior on a much larger scale channels waves from scenario San Andreas earthquakes into the Los Angeles Basin through a series of low-velocity sedimentary basins . From Olsen (2014).

The kinematic/stochastic source can be tuned to agree with empirical ground motion metrics but this leads to high-variance predictions (because we lack a physical basis to constrain parameters and correlations) and provides an inadequate basis for scaling to large earthquakes. Scattering formulations depend on assumptions about the scattering process, e.g., whether coda is due to trapping within layers or scattering from heterogeneities; whether Q is frequency dependent; whether scattering is anisotropic and/or concentrated near the surface, and where single- vs. multiple-scattering dominates. Small-scale heterogeneity from analysis of sonic logs and Vs30 measurements in the Los Angeles Basin indicate a von Kármán heterogeneity spectrum. When these heterogeneities added to the SCEC CVM-S ground motion intensities for 0-2.5 Hz waves are amplified/de-amplified by up to a factor of two. The results also suggest a trade-off between Q and the strength of heterogeneity. SCEC4 implemented new research initiatives at the engineering interface, which broadened the impact of SCEC's work and provided an important feedback loop for focused refinement of scientific models. Three examples of these activities are: i) the development and validation of the Broadband Platform for ground motion simulation, ii) the Ground Motion Simulation Validation Technical Activity Group, and iii) the Committee for Utilization of Ground Motion Simulations.

Broadband Platform and Collaboration with PEER. SCEC4 developed the Broadband Platform (BBP) to simulate ground motion from finite faults for frequencies up to 100 Hz using different methods. An issue of *Seismological Research Letters* [*164*] includes nine papers describing the motivation for the BBP, validation, computational aspects and basic science underlying the different methods [*167*]. A critical element of the BBP is that different methods are validated against ground motion prediction equations [*165*, *166*] (**Fig. 2.18**) and against data for particular earthquakes [*167*]. The BBP has been used to examine ground motions for the Nuclear Regulatory Commission requirement that all nuclear plants in the US be evaluated for seismic safety. For the central and eastern US, where there are no data from large earthquakes, simulation provides guidance on scaling ground motions to large magnitudes. SCEC keeps pace with the ongoing evolution of the methods as they are subjected to validation against new data and new metrics through formal releases of the BBP on a regular basis.

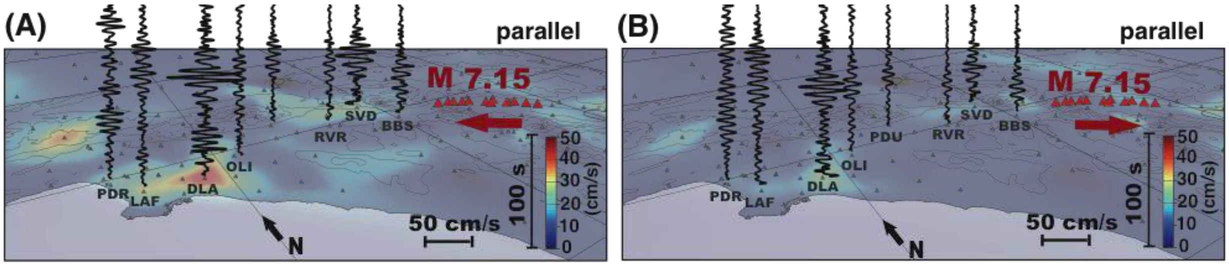


Figure 2.18. Predicted PGV in Los Angeles using ambient-field ground motions to synthesize "virtual earthquakes." Left panel is for a M 7.1 San Andreas rupture towards downtown Los Angeles (SE→NW); right panel is for the same event with the opposite directivity (NW→SE). These observation-based seismograms will be used in SCEC5 to validate 3D ground-motion simulations. From Denolle et al. (2015).

Collaboration between SCEC and the Pacific Earthquake Engineering Research Center (PEER) grew substantially during SCEC4. We undertook collaborations than included: 1) development of additional BBP computational capabilities, 2) validation for Central and Eastern North America (CENA) ground motions, and 3) forward simulation for CENA ground motions. The compilation of a final version of the BBP including the latest features and the simulation data were needed by NGA-East due to the lack of recorded ground motions for magnitudes larger than 6. A strong collaboration between teams from SCEC and PEER made this project successful.

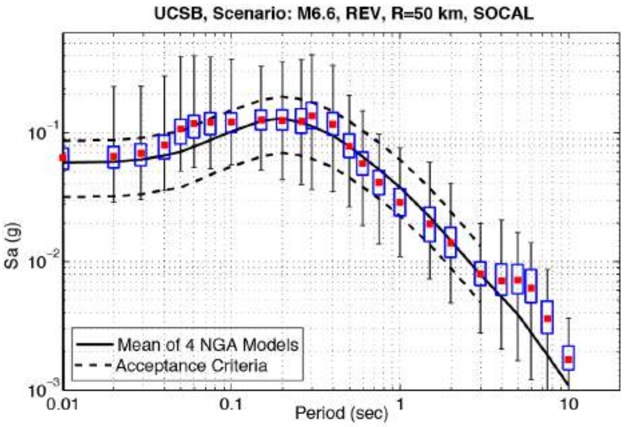


Figure 2.19. Broadband Platform validation results. Predictions of UCSB method for mean acceleration response spectrum derived from four GMPE's for NGA West. The mean is based on the ground motion at 30 stations and 50 scenario MW 6.6 earthquakes on a reverse fault. All stations were within 50 km of the fault. From Dreger et al. (2015)

Ambient-Field Studies. SCEC scientists pioneered a new approach for predicting the strength of shaking using the ambient seismic field [*168*]. This approach is possible because the waves that comprise the ambient field and those from large earthquakes propagate through the same complex geologic structure. While this "virtual earthquake" method does not account for nonlinear, high-amplitude effects, it provides a new way to predict complex wave-propagation effects that influence strong earthquake shaking. We have used it to validate predictions of a strong waveguide-to-basin amplification (**Fig. 2.18**) predicted by simulations of a large San Andreas earthquake for Los Angeles [*226*]. Scientists in France [*169*] and Japan [*170*] have applied this approach, and similar efforts are underway in Mexico, South Korea, New Zealand, Switzerland, and the Netherlands in settings ranging from subduction zones to gas reservoirs.

Ground Motion Simulation and Validation. GMSV is a TAG within SCEC to develop and implement validation methods for simulations. The GMSV focused on how simulations, such as those produced by the BBP, could be used in probabilistic seismic hazard analysis, structural nonlinear response history analysis, and site response analysis. Validating simulations is daunting, as they are of greatest interest for conditions that are not well observed (e.g., close to large earthquakes). The TAG developed "validation gauntlets" that simulated motions should pass to be deemed suitable for application. Gauntlets have been developed for single- and multi-degree-of-freedom oscillators and for geotechnical systems, and they are being extended to complex problems; e.g., the validation for applications that are frequency and duration sensitive, such as nonlinear structural response analysis of slope displacements and liquefaction.

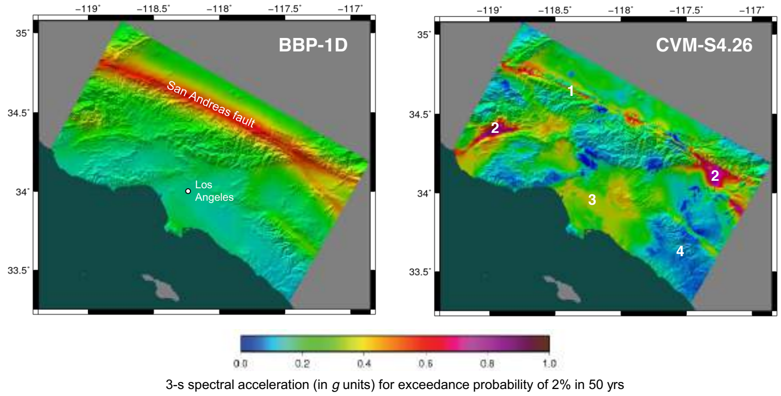


Figure 2.20. CyberShake seismic hazard maps for the Los Angeles region, showing the 3-s spectral acceleration response (in units of surface gravity, *g*) at an exceedance probability of 2% in 50 years. Left panel calculated using an average 1D seismic velocity model; right panel using SCEC's latest 3D community velocity model, CVM-S4.26. Both models include all fault ruptures in UCERF2; spectral response probabilities are computed from ~240 million seismograms. Amplitude differences are annotated on the right panel: (1) lower near-fault intensities due to 3D scattering; (2) much higher intensities in near-fault basins due to directivity-basin coupling; (3) higher intensities in the Los Angeles basins; and (4) lower intensities in hard-rock areas. From Jordan et al. (2015).

Committee for Utilization of Ground Motion Simulations. This committee, chaired by C. B. Crouse, is working within the framework of the Building Seismic Safety Council's *Project 17* to develop long-period, simulation-based response spectral acceleration maps for LA region for future inclusion in the NEHRP and ASCE 7-10 Seismic Provisions and the Los Angeles City Building Code [*171*]. The goal is to use CyberShake simulations to quantify the effects of sedimentary basins and other 3D structures on the seismic hazard. By averaging over thousands of simulated earthquakes, we have constructed prototype CyberShake hazard maps for Los Angeles (**Fig. 2.20**). Prototype risk-targeted maximum considered earthquake (MCE$_R$) response spectra have also been mapped using the CyberShake model.

B. Communication, Education & Outreach Accomplishments

1. Overview

SCEC's Communication, Education, and Outreach (CEO) program facilitates learning, teaching, and application of earthquake research. In addition, SCEC/CEO has a global public safety role in line with the third element of SCEC's mission: "Communicate understanding of earthquake phenomena to end-users and society at large as useful knowledge for reducing earthquake risk and improving community resilience." The theme of the CEO program during SCEC4 has been *Creating an Earthquake and Tsunami Resilient California*. Our geographic reach has expanded far beyond the Golden State via partnerships across the country and worldwide. The goal is to prepare people for making decisions about how to respond appropriately to changing seismic hazards, including tsunami warnings and new technologies such as operational earthquake forecasting and earthquake early warning.

SCEC/CEO has been very successful in leveraging its base funding with additional support. For example, since 2010, FEMA has provided SCEC nearly $1.5 million to coordinate the Earthquake Country Alliance in California (at the request of the California Office of Emergency Services, CalOES) and for national ShakeOut coordination. ShakeOut regions in the U.S. and internationally have also provided funding, and the California Earthquake Authority (CEA) has spent several million dollars on advertising that features ShakeOut promotions each year. SCEC's intern programs have been supported with more than $1.3 million in additional funding from several NSF programs and a private donor, and NASA supports SCEC's "Vital Signs of the Planet" teacher development program (via JPL) as part of the NASA InSight mission. NOAA (via CalOES) now provides funding to SCEC for developing the TsunamiZone.org website.

Box 2.2. Summary of 2015 CEO Evaluation

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

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" comprising members of the SCEC Advisory Council as well as SCEC community stakeholders was established to help guide and support SCEC/CEO activities and partnerships, which have significantly expanded during SCEC4. In addition, an experienced program evaluator has reviewed the CEO program overall including its evaluation structures [*172*]. Analyses for each CEO area were provided along with recommendations for how to expand and improve evaluation, including a new comprehensive logic model to tie all CEO activities to a set of long term intended outcomes. The results indicate that the SCEC/CEO program plays an important role in earthquake education and preparedness (**Box 2.2**), and the evaluation's recommendations have influenced the CEO program plan for SCEC5 (see §III.D).

2. Major Activities and Results

a. Global network of Great ShakeOut Earthquake Drills, and related campaigns

Great ShakeOut Earthquake Drills began in southern California in 2008, based on the USGS-led "ShakeOut Scenario" for a large (M7.8) San Andreas earthquake. ShakeOut communicates scientific and preparedness information with the mission to motivate everyone, everywhere to practice earthquake safety ("Drop, Cover, and Hold On"), and to promote resiliency through preparedness and mitigation.

Working with a small committee of Earthquake Country Alliance (ECA) leaders, SCEC created an online registration system and resource site (ShakeOut.org) where more than 5.4 million southern Californians were registered to participate in 2008, building to 10.4 million people statewide in 2014 (**Box 2.3**). While K-12 and college students and staff comprise the largest number of participants, ShakeOut has also recruited businesses, non-profits, government agencies, neighborhoods groups, and individuals.

In addition to leading the California ShakeOut, SCEC manages a network of ShakeOut Regions worldwide, and hosts the website for each of their drills (except Japan). As of 2015, 26 Official ShakeOut Regions span 51 states and U.S. territories, three Canadian provinces, New Zealand, Southern Italy (U.S. Naval bases), and Japan. People and organizations in any other state or country can also register to be counted in the overall global total. More than 26.5 million people were registered in 2014. SCEC's Associate Director for CEO, Mark Benthien, was recognized as a "White House Champion of Change" for leading these efforts, and FEMA has based its national "America's PrepareAthon!" multi-hazard campaign on ShakeOut to assess preparedness activities for other hazards (and contracts with SCEC for consultation).

ShakeOut has become a global infrastructure for providing earthquake information to the public and involving them in community resiliency. New countries are being actively recruited to join the ShakeOut movement, which serves to coordinate earthquake messaging internationally. Participants receive monthly ShakeOut newsletters and more frequent content via social media. Millions more learn about ShakeOut via broad news media coverage that encourages dialogue about earthquake preparedness. Surveys of ShakeOut participants show increased levels of mitigation and planning, and encouragement of peers to participate and get better prepared [*173*]. In the near future, ShakeOut will be utilized for educating Californians about Earthquake Early Warning, with yearly tests to be held on ShakeOut day.

Box 2.3. Growth of ShakeOut Drills

2008: 5.4 million
Southern California
2009: 6.9 million
California, New Zealand West Coast
2010: 7.9 million
California, Nevada, Guam
2011: 12.5+ million
CA, NV, GU, OR, ID, BC, and Central US (AL, AR, GA, IN, IL, KY, MI, MO, OK, SC, TN)
2012: 19.4 million
All above plus: AK, AZ, SouthEast (DC, GA, MD, NC, SC, VA), UT, WA, Puerto Rico, Japan (Tokyo), New Zealand, Southern Italy, and a new "Global" site for all other areas.
2013: 24.9 million
All above plus: CO, DE, HI, MT, OH, WV, WY, NorthEast region (CT, PA, MA, ME, NH, NJ, NY, PA, RI), American Samoa, U.S. Virgin Islands, Commonwealth of Northern Marianas Islands. Charlevoix region of Quebec, and expansion across Japan.
2014: 26.5+ million
All above plus FL, KS, NM, Yukon, Quebec, participation in 20+ other countries via Aga Khan Development Network.
2015: 30+ million?
All above plus IA, LA, NE, TX, and partnerships with several new countries.

As a result of its leadership of ShakeOut, SCEC now also receives NOAA funding provided through the California Office of Emergency Services to create and manage TsunamiZone.org. This international site adapts the ShakeOut registration system to assess participation in Tsunami activities, whether as part of their ShakeOut activities or during local tsunami preparedness weeks or months. Primary participation in 2015 included California, Oregon, Washington, Hawaii, and the Caribbean.

b. Extensive collection of public education and preparedness resources and activities

Partnerships. The *Earthquake Country Alliance* (ECA) was created in southern California by SCEC with many partners in 2003 and is now a statewide coalition with similar groups in the Bay Area and North Coast. ECA's sector-based committees develop consistent messaging and resources distributed via activities led by each regional alliance. SCEC's Associate Director for CEO Mark Benthien is ECA's Executive Director. In 2012 ECA received FEMA's "Awareness to Action" award and also the "Overall National Award in Excellence" at the National Earthquake Conference, both for its creation of ShakeOut and other activities. In 2014 ECA was given an award from the American Red Cross for "Excellence in Disaster Preparedness".

SCEC also coordinates the *Earthquake and Tsunami Education and Public Information Center (EPIcenter) Network* of more than 60 museums, science centers, and libraries, some of which host SCEC-developed exhibits and programming. SCEC has also established "EPIcenters" in other states (Oregon, Alaska, Maine, and others), and is working with the Central United States Earthquake Consortium (CUSEC) to create a Central U.S. EPIcenter network. CUSEC also manages the Central U.S. and Southeast multi-state ShakeOut regions.

Figure 2.21. EarthquakeCountry.org, one of several websites managed by SCEC/CEO for the Earthquake Country Alliance.

Resources. In addition to the SCEC.org website, SCEC develops and maintains all ECA websites—EarthquakeCountry.org, DropCoverHoldOn.org, and Terremotos.org (**Fig. 2.21**)—and the global websites ShakeOut.org and TsunamiZone.org. These sites allow SCEC to promote consensus-based messaging. In 2014 a "Northridge Earthquake 20th Anniversary Virtual Exhibit" was added to the ECA site, including "Northridge Near You" animations created by SCEC UseIT interns. Similar animations plus related graphics were made for the Loma Prieta 25th anniversary, again by UseIT interns. In addition, SCEC's social media presence has greatly expanded since 2013 with active Twitter, Facebook, YouTube, and other accounts for SCEC, ECA, ShakeOut, and TsunamiZone distributing SCEC and ECA messaging globally.

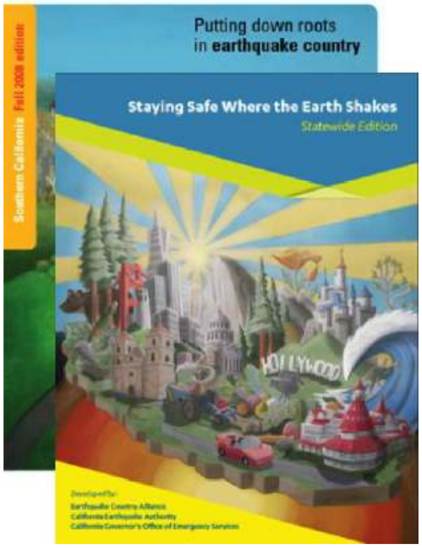


Figure 2.22. Public education booklets distributed by the Earthquake Country Alliance and SCEC.

SCEC's *Putting Down Roots in Earthquake Country* handbook (**Fig. 2.22**) has provided earthquake science and preparedness information to southern Californians since 1995. The 2004 update introduced the Seven Steps to Earthquake Safety, the main organizing structure for SCEC, ECA, and CEA preparedness messaging. Related versions are now available in multiple languages, for businesses, and for the San Francisco Bay Area, California's North Coast, Nevada, Oregon, Utah, the Central U.S., and Idaho. In 2014 the California Earthquake Authority, California Office of Emergency Services, and ECA created a simpler booklet, *Staying Safe Where the Earth Shakes*, with customized versions for 10 regions of the state and multiple language editions (Spanish and Chinese to start).

Additional resources developed by SCEC and ECA Associates during SCEC4 include earthquake safety materials and ShakeOut guidelines for seniors and people with disabilities, higher education, government agencies, businesses, and healthcare facilities. A poster with "Drop, Cover, and Hold On" translated into many native American languages, as well as a video telling a native American earthquake legend, were developed in partnership with Sherman Indian high School in Riverside, California.

Activities. SCEC and its partners coordinate a broad range of public education and collaboration activities. Each ECA Regional Alliance holds several workshops each year featuring guest speakers and outreach planning. The ECA Speakers Bureau holds monthly trainings at SCEC, and members speak to community groups, businesses, and other organizations, and staff tables at preparedness fairs. ECA sector-based committees presented a series of ECA webinars in 2015 to nationwide audiences. EPIcenter locations hold public lectures and host day-of ShakeOut events. SCEC staff also participate in local government, non-profit, and business meetings throughout the year, and host foreign groups interested in our best practices.

News media coordination. In 2014 SCEC developed new procedures for post-earthquake media coordination, because the breadth of SCEC's research, including its information technology programs and the development of time-dependent earthquake forecasting, is increasing the need for expanded media relations. New strategies and technologies are being developed to meet these demands, such as the use of a media relations service for identifying and connecting with reporters nationwide and then tracking resulting news coverage (used for both SCEC and ShakeOut media coordination). SCEC also partners with USGS, Caltech, and other partners to offer programs that educate the media on how to report earthquake science. Examples include a media training workshop at Caltech and a press conference at USC as part of the 20th Anniversary of the Northridge Earthquake in January 2014. 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", a parody of our standard Seven Steps messaging (*www.earthquakecountry.org/moviesafety*).

c. Broad range of K-14 educator partnerships, programs, and resources

Workshop Partnerships. SCEC is an active participant in the science education community including local and national organizations such as the California Science Teachers Association (CSTA). In 2011 and 2013 SCEC participated in the planning committee for CSTA's Annual Conference and sponsored a 2013 keynote talk by SCEC intern alumnus Emmett McQuinn. Since 2009, SCEC has hosted earthquake-oriented field trips and workshops for more than 150 teachers. In addition, SCEC and the California Geological Survey co-host a booth at CSTA meetings that draw ~2000 attendees each year.

Figure 2.23. InSIght participants Kim Kocaya (Van Avery Prep, Temecula) and Yolanda Seebert (Vernon Middle School, Montclair) occupy a GPS site in Perris, CA, enjoying UNAVCO playing cards..

SCEC also collaborates in this area with other Earth science organizations such as its active role in EarthScope's workshops for park and museum interpreters since 2008. SCEC has participated in all four of the Cascadia EarthScope Earthquake and Tsunami Education Program (CEETEP) workshops in the Pacific Northwest, which have served over 100 educators, emergency managers and park interpreters. SCEC is co-hosting the final workshop in Arcata, California, in fall 2015.

SCEC's EarthScope partners have found that the ShakeOut is an important event that helps promote their program (and vice versa).

InSight Vital Signs of the Planet (VSP) Professional Development Program. SCEC has a lead role in the education program for *InSight* (Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport), a NASA mission that will place a geophysical lander on Mars in 2016. SCEC developed the VSP program, a research experience and curriculum development program for K-12 teachers that expands on a collaboration between SCEC and the Cal State San Bernardino/EarthScope RET program led by Dr. Sally McGill. Since 2013 VSP has provided 30 educator fellows (and select students) experiences in scientific inquiry including a 5-day field experience using GPS to monitor tectonic deformation in Southern California (with instruments provided by UNAVCO). Participants then develop and test lesson plans and convene a workshop held during the SCEC Annual Meeting.

Quake Catcher Network (QCN). SCEC has expanded QCN with installations of low cost seismometers at over 26 EPIcenter museum locations in California and Oregon, and at more than 100 schools in each west coast state including Alaska. The goal is to establish several K-12 sensor stations around a local museum hub as a means to build long-term educational partnerships around the ShakeOut, citizen science, and enrich K-12 STEM curriculum. 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 14 schools and museums in the Central U.S.

Plate Tectonics Kit. This teaching tool created and distributed by SCEC was developed to make plate tectonics activities more accessible for science educators and their students. SCEC developed a user-friendly version of the *This Dynamic Planet* puzzle map, which is used to teach about plate tectonics. 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.

d. Well-established undergraduate research experiences

The SCEC Experiential Learning and Career Advancement (ELCA) program enhances the competency and diversity of the STEM workforce by engaging students in research experiences at each stage of their academic careers and by providing leadership opportunities to students and early career scientists that engage them in the SCEC Community. ELCA manages two undergraduate internship programs that involve over 30 students each summer:

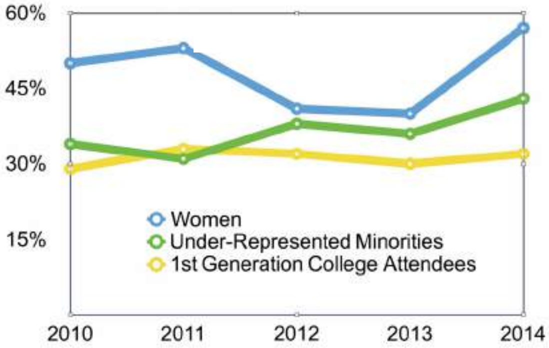


Figure 2.24. Demographics of SCEC intern classes (percentage by year), illustrating the involvement of women, under-represented minorities, and first-generation college attendees in SCEC research.

- The *Summer Undergraduate Research Experience* (SURE) program places undergraduate students with SCEC scientists around the country. More than 270 interns have participated since 1994. Projects have spanned all areas of earthquake science, engineering, and education.
- The *Undergraduate Studies in Earthquake Information Technology* (USEIT) program brings together students from across the country to an NSF Research Experience for Undergraduates Site at USC. The eight-week program develops 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" each year that entails developing software and resources for use by earthquake scientists or outreach professionals. The 2014 Grand Challenge 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).*

Since 2002, over 1600 eligible applications have been submitted to the SCEC internship programs (at www.scec.org/internships). Since 2010, underrepresented minority interns averaged 36.4% of each year's class, with a high of 43% in 2014 (**Fig. 2.24**). Women represented an average of 48% of interns, with a high of 57% in 2014. First-generation college attendees have averaged 31% 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 working in research and education, which coupled with networking at the SCEC annual meeting, gave them the inspiration and confidence to pursue earth science and career options within the field.

e. SCEC Earthquake Engineering Implementation Interface

SCEC produces a large body of knowledge about the seismic hazard in California that enhances 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 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.

Figure 2.25. 2014 Buildings at Risk Summit co-sponsored by SCEC.

The Implementation Interface also develops mechanisms for interacting with technical audiences that make decisions based on an understanding of earthquake hazards and risk, including practicing engineers, geotechnical consultants, building officials, emergency managers, financial institutions, and insurers. An example is the annual SEAOSC *Buildings at Risk Summits*, which SCEC has co-organized since 2011 in both Los Angeles and San Francisco (with SEAONC). The 2014 conference was titled "Strengthening our Cities" (**Fig. 2.25**). In 2014 SCEC/ECA also helped create the "Earthquake 2014 Business Preparedness Summit" with FLASH, Safe-T-Proof, Simpson Strongtie, and several other partners, which launched a new QuakeSmart recognition program for businesses that demonstrate mitigation they have implemented. These summits have since been offered in several locations nationwide.

III. SCEC5 Project Plan

The SCEC5 Project Plan is divided into a Science Plan (§III.B), a CEO Plan (§III.C), a Diversity Plan (§III.D), and an Information Technology Plan (§III.E). The latter is coupled to the SCEC5 Data Management Plan, contained in a separate proposal document.

A. SCEC Vision Statement

Three main problems of earthquake science are coupled through the nonlinear processes of brittle and ductile deformation: (1) *dynamics of fault systems*—how forces evolve within fault networks on time scales of hours to millennia to generate sequences of earthquakes; (2) *dynamics of fault ruptures*—how forces produce fracture and slip on time scales of milliseconds to minutes when faults break chaotically during earthquakes; (3) *dynamics of ground motions*—how seismic waves propagate from rupture volumes to shake the surface of the strongly heterogeneous, inelastic crust. SCEC's long-range science vision is to develop dynamical models of earthquake processes, applicable to the San Andreas fault system, that are comprehensive, integrative, verified, predictive, and validated against observations.

The validation of model-based predictions against data is a key SCEC activity, because empirical testing is the most powerful guide for assessing model uncertainties and moving models towards better representations of reality [*174*]. The process begins with the question, "Valid for what purpose?" [*175*]. In the case of earthquakes, the general answer is to provide society with the best available science to reduce earthquake risks (potential losses) and to maximize community resilience (recovery capability) [*176*]. Effective management of risk and resiliency requires a deep understanding of local seismic hazards. In California, the primary earthquake hazards are ground shaking and failure. Validating models that forecast ground motions as well as fault ruptures tightly couples basic earthquake research to the practical issues of probabilistic seismic hazard analysis, operational earthquake forecasting, earthquake early warning, and rapid earthquake response (**Fig. 2.1**).

The goal of risk reduction poses a fourth problem: (4) *earthquake dynamics of the built environment*—how seismic phenomena cause damage to structures, lifelines, critical facilities, and other engineered systems. This problem couples earthquake science to engineering, and it has inspired SCEC partnerships with the Pacific Earthquake Engineering Research Center [*177*], the DesignSafe-CI Center of NSF's new Natural Hazards Engineering Research Infrastructure Program [*178*], the Building Seismic Safety Council's *Project 17* [*179*], and other earthquake engineering activities. The SCEC vision is to collaborate with earthquake engineers to develop end-to-end, physics-based modeling capabilities that span system processes from "ruptures-to-rafters."

The fifth problem couples earthquake science to the social sciences: (5) *social dynamics of communicating earthquake knowledge*—how to convey scientific information to society in ways that result in lowered risk and enhanced resilience. Our approach is to engage end-users and the public at large in ongoing, community-centric conversations about how to manage particular risks by taking specific actions [*180*]. The SCEC vision for Communication, Education, and Outreach (CEO) is to promote this dialog on many levels, through many different channels, and inform the conversations with authoritative earthquake information. Towards this goal, SCEC/CEO program will continue to build and lead extensive networks of organizational partners that act in concert to prepare millions of people of all ages and socioeconomic levels for inevitable earthquake disasters.

B. SCEC5 Science Plan

The status of knowledge and prospects for research advances in earthquake science have been summarized in a number of strategic planning documents by the National Research Council [*1*,*176*,*181*], the USGS National Hazards, Risk, and Resilience Assessment Program [*9*], the NSF Advisory Council for Geosciences [*11,*182], the Incorporated Research Institutions for Seismology [*183*], and UNAVCO [*184*]. The findings and recommendations in these reports underscore the overarching rationale for SCEC5: Basic earthquake research conducted through interdisciplinary collaborations has become more essential to meeting the practical challenges of risk mitigation and disaster preparedness for an exponentially expanding, urbanized society. This tight connection between basic and applied science places the SCEC5 program squarely in "Pasteur's quadrant" [*185*].

1. Basic Questions of Earthquake Science

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 P. 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 (**Box 1.2**). Here we describe these questions as scientific problems and derive from them the SCEC5 research priorities.

Q1. How are faults loaded across temporal and spatial scales?

Problem Statement: Fault systems are externally loaded, primarily by the relatively steady forces of plate tectonics, but also by mass transfers at the surface due to long-term interactions of the solid Earth with its fluid envelopes (climate forcing) and by short-term gravitational interactions (tidal forcing). Much is yet to be learned about the stress states acting on active faults and how these stress states evolve through external loading and the internal transfer of stress during continuous deformation and discontinuous faulting.

In SCEC4, we initiated research on a Community Stress Model to describe our current knowledge about the stress state of the San Andreas fault system. The ensemble of stress and stress-rate models comprised by the current CSM [*186*] is a quantitative representation of how well we have been able to answer Q1. Empirical models have been developed for stress orientations in the upper crust based on abundant focal mechanisms [*187*] and more limited *in-situ* data [*188*,*189*], as well as 3D dynamic models of stress; e.g., from finite-element simulations of long-term tectonics, including nonlinear laboratory rheologies [*190*]. A new approach [*191*] builds 3D stress models as sums of analytic solutions that satisfy momentum conservation everywhere, while approximating the previous stress-direction and stress-amplitude models in a least-squares sense (**Fig. 3.1**). Though we are encouraged by our recent progress, understanding stress is a long-term proposition. Continued work will be guided by five research priorities.

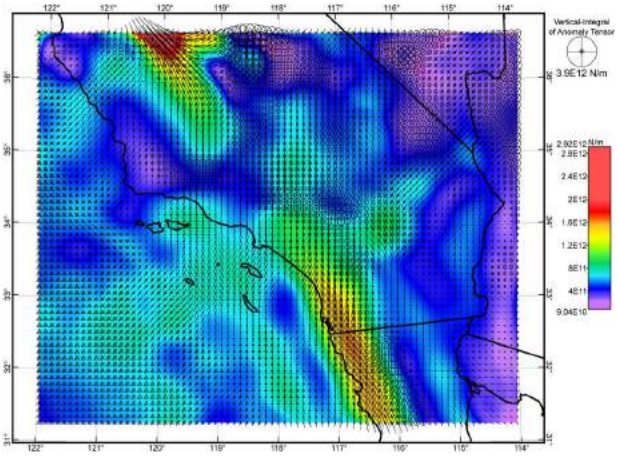


Figure 3.1. Representation of a 3D tensor model of the long-term average stress from the SCEC CSM (FlatMaxwell model of Bird [2014]). Colors represent vertical integrals of greatest shear stress through the lithosphere in N/m. Tensor symbols represent vertically-integrated stress anomalies. This model predicts highest deviatoric stresses where the heat flow is low.

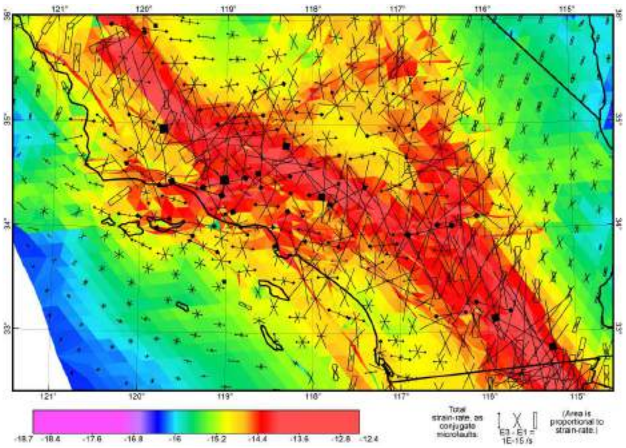


Figure 3.2. Secular strain rates from one of the UCERF3 deformation models (NeoKinema NSHM-WUS2013001). Colors show log(magnitude) of the largest principal strain rate. Tensor symbols portray the strain rate as equivalent distributed faults.

Research Priorities:

P1.a. Refine the geologic slip rates on faults in Southern California, including offshore faults, and optimally combine the geologic data with geodetic measurements to constrain fault-based deformation models, accounting for observational and modeling uncertainties.

P1.b. Determine the spatial scales at which tectonic block models (compared to continuum models) provide descriptions of fault-system deformation that are useful for earthquake forecasting.

P1.c. Constrain how absolute stress and stressing rate vary laterally and with depth on faults, quantifying model sensitivity, e.g. to rheology, with inverse approaches [*192*].

P1.d. Quantify stress heterogeneity on faults at different spatial scales, correlate the stress concentrations with asperities and geometric complexities, and model their influence on rupture initiation, propagation, and arrest.

P1.e. Evaluate how the stress transfer among fault segments depends on time, at which levels it can be approximated by quasi-static and dynamic elastic mechanisms, and to what degree inelastic processes contribute to stress evolution.

Q2. What is the role of off-fault inelastic deformation on strain accumulation, dynamic rupture, and radiated seismic energy?

Problem Statement: In the brittle upper crust, observations of low-velocity zones associated with active seismogenic faults [*193*], together with time-dependent evolution of seismic velocities following stress perturbations [*194*] suggest intrinsic relationships between damage, healing, and effective elastic moduli of rocks in a fault zone. Such relationships are only poorly understood, but they can elucidate the development and evolution of fault zones in space and time [*195*], as well as the interplay between damage accumulated over multiple earthquake cycles and rupture dynamics. Current dynamic rupture models show that the assumption of elastic deformation of the host rocks is often violated; e.g., in regions of high stress concentration near the propagating rupture front, particularly when stress is further concentrated by geometrically complex fault surfaces [*196*]. This raises important questions about the effect of nonlinearity and damage on the nucleation, propagation, and arrest of rupture. Neglecting inelastic response may systematically bias inversions of seismic and geodetic data for slip distribution and rupture geometry [*197*], affect measurements of coseismic slip at the surface [*198*], and inferences of long-term slip rates from the geologic record [*199*].

The SCEC community is at the forefront of research on inelastic material response associated with earthquake faulting and its effects on dynamic rupture propagation and seismic ground motion. The SCEC focus on extreme ground motion for the Yucca Mountain Project drew attention to the physical limits that realistic, inelastic material response places on strong shaking [*200*]. Recent simulations of earthquakes in the Los Angeles region have demonstrated how yielding near the fault and in sedimentary basins substantially reduces predicted ground motions relative to purely elastic simulations. Accounting for inelasticity brings the model predictions more in line with empirical constraints on strong shaking [*201*].

Research Priorities:

P2.a. Determining how much off fault plasticity contributes to geodetic estimates of strain accumulation and what fraction of seismic-moment accumulation is relaxed by aseismic processes.

P2.b. Explore approaches to represent the effects of non-linearity that would allow the continued use of linear wave propagation as an effective approximation.

P2.c Constrain the form of fault-zone and distributed non-linearity, as well as the factors, such as cohesion and pore fluid pressure, that are likely to influence it.

P2.d. Understand how inelastic strain associated with fault roughness and discontinuities influences rupture propagation, seismic radiation, and scaling of earthquake source parameters.

P2.e Describe how fault complexity and inelastic deformation interact to determine the probability of rupture propagation through structural complexities, and determine how model-based hypotheses about these interactions can be tested by the observations of accumulated slip and paleoseismic chronologies.

Q3. How do the evolving structure, composition and physical properties of fault zones and surrounding rock affect shear resistance to seismic and aseismic slip?

Problem Statement: Fault systems show complexities that range from the macroscales of plate tectonics to the microscales of highly damaged rocks that are fluid-filled and chemically reactive. Many questions about the evolving dynamics of these complex systems remain unanswered. The inferred values of heat outflow from mature faults, such as the San Andreas [*202*], Taiwan's Chelungpu Fault [*203*], and the Japan Trench megathrust [*204*], imply that shear stress acting during sliding is an order of magnitude lower than estimates from Byerlee's law [*205*] and typical static friction measurements—an inconsistency famously known as the "heat-flow paradox." Low values for shear stress acting on major faults are also supported by the steep angles between the principal stress direction and fault trace [*206*], slip-vector rake rotations during faulting [*207*], and significant rotations of principal stresses after large earthquakes [*208*]. In addition, multi-fault earthquake simulations show that observed propagation onto unfavorably oriented structures appears to be more likely to occur if the faults are subject to low tectonic stress [*209*].

These and other observations motivate the continued investigation of the structure, composition, and physical properties of fault zones that host earthquake sources. One important question is which faults are susceptible to coseismic weakening mechanisms, such as flash heating [*210*], thermal pressurization of pore fluids [*211*], partial or full melting of the shearing zone, silica-gel formation [*212*], and thermal decomposition of sheared materials into friction-reducing byproducts [*213*]. Co-seismic weakening may lead to large unexpected slip in creeping fault regions [*214*], including deeper fault extensions below the seismogenic layer [*215*], a phenomenon compatible with a range of observations [*216*]. Fluids play a key role in several of the weakening processes, potentially dominating co-seismic resistance to slip. In fact, fluids can lead to extreme localization of the shearing layer, promoting co-seismic weakening [*217*]. Fluids can also provide a stabilizing factor, for example due to inelastic shear-induced dilatancy of the pore space, and the resulting reduction of pore pressure and hence increase of the effective normal stress [*218*].

Research Priorities:

P3.a. Refine the geometry of active faults across the full range of seismogenic depths, including structures that link and transfer deformation between faults.

P3.b. Constrain the active geometry and rheology of the ductile roots of fault zones.

P3.c. Assess how shear resistance and energy dissipation depend on the maturity of the fault system, and how these are expressed geologically.

P3.d. Determine how damage zones, crack healing and cementation, fault zone mineralogy, and off-fault plasticity govern strain localization, the stability of slip (creeping vs. locked), interseismic strength recovery, and rupture propagation.

P3.e Constrain the extent of permanent, off-fault deformation, and its contribution to geologic and geodetic fault slip-rate estimates.

P3.f. Study the mechanical and chemical effects of fluid flows, both natural and anthropogenic, on faulting and earthquake occurrence, and how they vary throughout the earthquake cycle.

P3.g. Assess the importance of the mechanical properties of the near-surface in the commensurability of geodetic and seismological images of fault slip at depth with fault offset expressed at the surface.

Q4. How do strong ground motions depend on the complexities and nonlinearities of dynamic earthquake systems?

Problem Statement: Physics-based predictions of strong ground motions are "the proof of the pudding"; comparing them with data is essential to testing our understanding of source and wave dynamics, and they connect the basic science of earthquakes to the practical applications of seismic hazard analysis. Ground-motion simulations have become useful in performance-based engineering and nonlinear building response analysis [*219*], operational earthquake forecasting [*220*], and earthquake early warning [*221*]. The use of validated numerical simulations can yield predictions adapted to local geologic conditions such as sedimentary basins [*222*], structural boundaries, and steep topography [*223*], and they provide meaningful ground-motion estimates for conditions poorly represented in the empirical database.

An appropriate baseline for measuring future progress in ground-motion modeling is the recent CyberShake 15.4 study [*224*], which produced hazard curves for the Los Angeles region from a stochastically complete set of UCERF2 ruptures using the CVM-S4.26 crustal structure. The resulting hazard model has several notable limitations: (i) the sources were prescribed by a pseudo-dynamic (kinematic), rather than fully dynamic, rupture model; (ii) the wavefield calculations were computed to an upper cutoff frequency of 1 Hz, compared to engineering needs that can exceed 10 Hz; and (iii) the principle of seismic reciprocity [*225*] was used to compute the requisite ensemble of seismograms. To preserve reciprocity, which strictly applies only to perfectly elastic media, near-fault inelasticity would have to be built into the rupture model *a priori* as a source effect, whereas near-surface inelasticity would have to be incorporated *a posteriori* as a site effect.

We seek to replace the classical treatment of source, path, and site effects as decoupled processes by a new paradigm in which the surface ground motions are modeled as the nonlinear response of a self-excited dynamical system with a rheology that properly represents the most salient aspects of inelastic behavior. As the CyberShake example indicates, this will be a major challenge for SCEC5. Our plan will be guided by four priorities that recognize the practical potential of this paradigm shift.

Research Priorities:

P4.a. Determine the relative roles of fault geometry, heterogeneous frictional resistance, wavefield scattering, intrinsic attenuation, and near-surface nonlinearities in controlling ground motions.

P4.b. Construct methods for validating ground-motion predictions that account for the paucity of recordings in the near-field, where the motions are strong and inelastic effects may be large.

P4.c. Develop ground-motion simulations for anticipated large events that are suitable for probabilistic seismic hazard and risk analysis.

P4.d. Communicate improvements in physics-based seismic hazard analysis to the earthquake engineers, emergency responders, and general public.

Q5. In what ways can system-specific studies enhance the general understanding of earthquake predictability?

Problem Statement: Earthquake prediction is one of the great unsolved problems of physical science. We distinguish intrinsic *predictability* (the degree to which a future earthquake behavior is encoded in the precursory behavior of an active fault system) from a specific *prediction* (a testable hypothesis, usually stated in probabilistic terms, of the location, time, and magnitude of an earthquake). A key objective of the SCEC5 core program is to improve our understanding of earthquake predictability as the basis for advancing useful forecasting models. We propose to take a broad view of the earthquake predictability problem. For example, many interesting problems of conditional predictability can be posed as physics questions in a system-specific context. What will be the shaking intensity in the Los Angeles basin from a magnitude 7.8 earthquake on the southern San Andreas Fault? By how much will the strong shaking be amplified by the coupling of source directivity to basin effects? Will deep injection of waste fluids cause felt earthquakes near a newly drilled well in the San Joaquin Valley? How intense will the shaking be during the next minute of an ongoing earthquake in Los Angeles?

Earthquake system science offers a “brick-by-brick” approach to improving our understanding earthquake predictability. In SCEC5, we propose to build system-specific models of rupture recurrence, stress evolution, and triggering within a probabilistic framework that can assimilate a wide variety of geologic, geodetic, and seismic observations. Five research priorities will guide this plan.

Research Priorities:

P5.a. Develop earthquake simulators that encode the current understanding of earthquake predictability.

P5.b. Place useful geologic bounds on the character and frequency of multi-segment and multi-fault ruptures of extreme magnitude.

P5.c. Assess the limitations of long-term earthquake rupture forecasts by combining patterns of earthquake occurrence and strain accumulation with neotectonic and paleoseismic observations of the last millennium.

P5.d. Test the hypothesis that “seismic supercycles’’ seen in earthquake simulators (e.g., **Fig. 1.4**) actually exist in nature and explore the implications for earthquake predictability.

P5.e. Exploit anthropogenic (induced) seismicity as experiments in earthquake predictability.

2. SCEC5 Thematic Areas and Topical Elements

The basic science questions of **Box 1.2** reflect the core issues currently driving earthquake research. SCEC5 will address these questions through an interdisciplinary program comprising 14 topics in four main thematic areas. While these are by no means the only research activities to be undertaken in SCEC5, they constitute a cogent plan for making progress on the core scientific issues.

a. Modeling the Fault System

The scientific goal of the SCEC5 core program is to obtain new capabilities for improving the predictability of earthquake system models, new data for testing those models, and a better understanding of model uncertainties. We seek to know more about the geometry of the San Andreas system as a fractal network of faults, how stresses acting within this network drive the deformation that leads to fault rupture, and how this system evolves on time scales ranging from milliseconds to millions of years.

Topic 1: Stress and Deformation Over Time

A primary focus for SCEC5 research will be Stress and Deformation Over Time (SDOT, which suggests $\dot{\sigma}$, the time-derivative of stress), with the primary objective of addressing Questions 1 and 5. Within the CSM, we will build alternative models of the stress state for comparative testing and assessment of uncertainties. These models will be used to evaluate and refine estimates of stress and rheology from geodetic analyses of post-seismic deformation, as well as analyses of fault constitutive laws based on correlated changes in microseismicity and fault creep rate. The magnitude of the long-term shear stresses along active faults will provide critical constraints on competing physical models of fault rheology, dynamic weakening during rupture, earthquake recurrence, and fault-system evolution. Knowledge of the time-averaged stress orientation will reduce uncertainties in models of Coulomb stress transfer from earthquake ruptures onto adjacent faults, a process long studied by SCEC scientists [226], which is now being used to improve the physics of fault-based earthquake forecasting (Topic 10).

Time-dependent stresses arise from the slow changes during secular deformation, as well as the rapid coseismic transfer during earthquakes. The comprehensive GPS and InSAR datasets now being merged into the CGM will improve maps of interseismic strain rates at the surface [227]. The UCERF3 deformation-modeling effort [2] reached the surprising conclusion that as much as one-third of the long-term strain rate in California may go into permanent strain not described by purely elastic behavior (**Fig. 3.2**). Some of this “off-fault plasticity” may be due to localized slip on a multitude of minor faults and fractures. Can viscoelastic or viscoplastic rheologies account for this permanent strain? In comparing simple continuum models against discrete-element descriptions, we will combine the geodetic and geologic data on strain rates with laboratory measurements and other types of field observations, such as seismic anisotropy, post-seismic relaxation, and the deformation signatures seen in xenoliths. Our objective will be to understand bulk-rock and fault constitutive laws and their implications for strain localization, fault-zone evolution, the brittle-ductile transition, and coupling of crustal deformation to mantle convection. The need to venture “beyond elasticity” (Topic 5) motivates a SCEC5 initiative to develop a *Community Rheology Model* (Topic 3). The CRM will support the mechanical modeling of a visco-elasto-plastic plate-boundary deformation zone that is permeated by faults, edge-loaded by rigid plate interiors, and basal-loaded by mantle convection, connecting CGM kinematics with CSM dynamics.

Earthquake geology will play a key role in illuminating stress evolution at the largest scales. SCEC4 studies have shown that the San Jacinto and southernmost San Andreas faults have had fairly constant slip rates since mid-Quaternary [228]. In contrast, the Garlock fault and faults in the Los Angeles basin and Eastern California Shear Zone exhibit large, long-term variations in moment release [229,230,231,232]. We will explore the unloading history of major faults using well-constrained piercing points and precise dating methods made possible by previous SCEC research, such as the pairing of U-series with CRN dating [233] and luminescence with ^{14}C dating [234]. Special efforts will be made to understand the stress complexities in selected areas of fault complexities that we call “earthquake gates.”

Topic 2: Special Fault Study Areas – Focus on Earthquake Gates

SCEC4 established Special Fault Study Areas (SFSAs) to focus interdisciplinary research on geographically targeted problems of fault-system behavior. We propose to evolve the SFSA concept in SCEC5 by establishing an *Earthquake Gates* initiative, which will address multiple aspects of Questions 2, 3 & 5. An “earthquake gate” describes a region of fault complexity that can halt earthquake ruptures conditional on proximal fault geometry, rupture direction, and prior earthquake history [235,236,237,238]. These as well as other factors, such as near-fault rheology, may determine whether and how often an earthquake gate is open or closed to a propagating rupture. For example, rupture termination at fault complexities can store significant strain energy, suggesting that loading by prior ruptures can increase the probability of a future event breaking through in a larger earthquake. However, this effect is sensitive to the dynamics of the rupture process [*236*] and cumulative elastic deformation [*239*]. Therefore, these fault subsystems must be modeled dynamically over multiple cycles to assess the relative importance of competing forces and to calibrate them with geologic and geophysical observations. Our working hypothesis is that, within the San Andreas fault system, the dynamics of earthquake gates control the time-dependent probability of large, multi-segment (and multi-fault) ruptures.

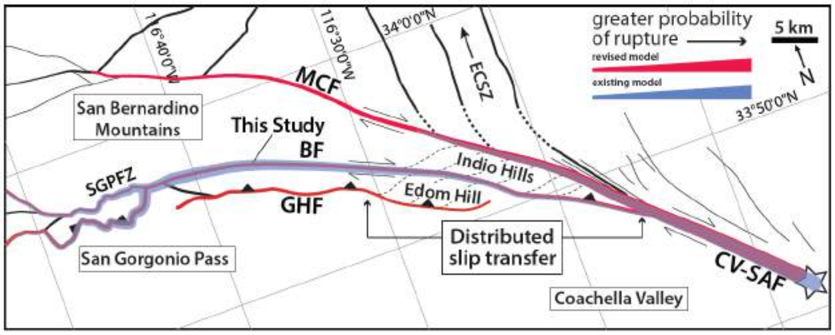


Figure 3.3. Prior to SCEC4, rupture models for slip partitioning among complex strands of the southern San Andreas Fault (sSAF) through the northern Coachella Valley designated the Banning fault as the primary structure entering San Gorgonio Pass, with little to no slip on the Garnet Hill or Mission Creek strands at that latitude. New observations from SCEC4 indicate that the Holocene displacement of the Banning fault represents only 20-30% of the sSAF total, suggesting significant rates of slip on the Garnet Hill and Mission Creek faults. Modified from Gold et al. (2015).

An interdisciplinary approach that combines field studies and structural modeling with dynamic rupture modeling has proven to be very successful in our two initial SFSAs. The choice of San Gorgonio Pass as an SCEC4 SFSA was motivated by the importance of southern San Andreas ruptures to seismic hazards in Southern California (**Fig. 3.3**) [*240*,*241*]. We focused both field-based and model-based research on the region, leading to a consensus that the region's fault complexity impedes, but does not prohibit, through-going ruptures [*242*,*243*,*244*,*245*,*246*,*247*]. Similar interdisciplinary studies within the Ventura SFSA indicated that the thrust systems bounding the northern Ventura Basin tend to link together, generating very large (M > 7.5) ruptures [*248*], and they may produce tsunamis and subsidence events in the heavily populated footwall [*249*,*250*]. The distinct outcomes of the two SCEC4 SFSAs highlight how interdisciplinary research that is geographically focused on fault complexities can significantly revise our understanding of seismic hazards.

The SFSA program in SCEC5 will prioritize earthquake gates according to (a) prospects for reducing seismic hazard uncertainties and (b) the opportunities for obtaining new hazard information from field-based and model-based studies. One guide will be the time-dependent hazards projected by UCERF3 relative to its predecessor, UCERF2. The former reduced the latter's discrepancy in intermediate-size earthquake rates (the M6.5-7.0 "bulge") by including multi-fault ruptures that were not modeled in UCERF2; the 30-year probability of M ≥ 8 ruptures consequently increased from 4.7% to 7.0% [*240*]. By combining the UCERF differences with the epistemic uncertainties from the UCERF3 logic tree, we will identify fault complexities where better constraints on the probabilities of through-going ruptures can most improve the hazard model.

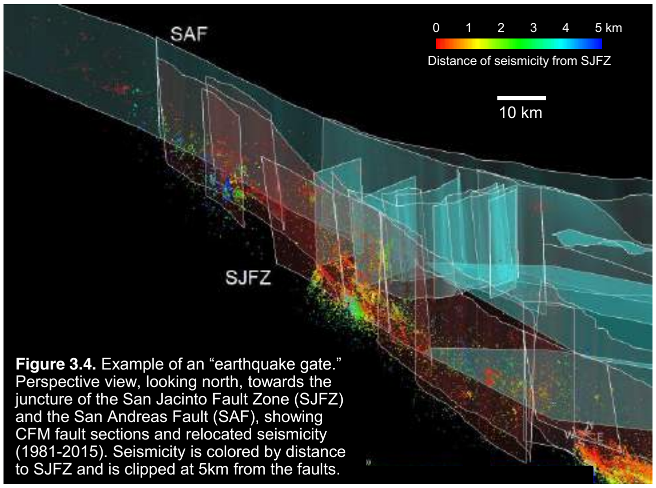


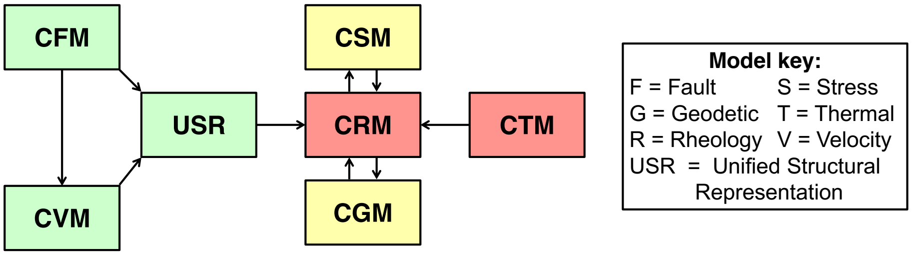
Figure 3.4. Example of an "earthquake gate." Perspective view, looking north, towards the juncture of the San Jacinto Fault Zone (SJFZ) and the San Andreas Fault (SAF), showing CFM fault sections and relocated seismicity (1981-2015). Seismicity is colored by distance to SJFZ and is clipped at 5km from the faults.

The second consideration is the availability of data. The historic and paleoseismic records for the San Andreas system are woefully inadequate for directly assessing how each of its many fault complexities have acted as earthquake gates. We will therefore apply our SFSA approach to areas of structural complexity where it is feasible to obtain enough data from multiple disciplines to improve significantly on previous studies. Along the San Jacinto Fault, for example, collaborations between geologists and modelers are refining our understanding of fault linkages [*251*] and imaging the near-surface fault architecture with dense seismic arrays [*252*]. Other potential SFSAs include the highly vulnerable Cajon Pass, where rupture transmissivity between the San Andreas, San Jacinto, and Cucamunga faults is uncertain (**Fig. 3.4**), the enigmatic Brawley fault zone, and the fault junctures directly beneath downtown Los Angeles.

Topic 3: Community Models

Taken together, the SCEC Community Models provide a unique and robust cyberinfrastructure for the collaborative encoding of our cumulative knowledge of the San Andreas system, including the observational and modeling uncertainties. The original "CXMs" were structural representations of seismic velocities (CVM) and active faults (CFM), which have been iteratively combined into a Unified Structural Representation (USR) [*17*]. In SCEC4, we have undertaken an ambitious (and unfinished) effort to develop community geodetic and stress models that can represent the kinematic (CGM) and dynamic (CSM) states of the fault system consistent with the USR (**Fig. 3.5**). SCEC5 research will further expand and improve the CXMs, adding thermal and rheological models. A priority will be the proper representation of model uncertainties for all CXMs. These representations will provide the knowledge base for addressing all five basic science questions, and their refinement will lead to a better understanding of earthquake processes (Theme B), more predictive models of seismic hazards (Theme C), and more effective partnerships with earthquake engineers and emergency managers aimed at reducing seismic risk (Theme D).

Figure 3.5. Schema of the SCEC Community Models, showing the main directions of information flow among the models. The colors indicate the development status: mature (green), youthful (yellow), in utero (red).



Unified Structural Representation. The USR project is a mature effort with the goal of refining mutually consistent representations of the 2D fault geometry and 3D seismic velocity structure [*17*]. A USR comprises multiple model components constructed from different data sets, including (i) a thin "geotechnical layer" (GTL), representing the near-surface (~300 m thick) low-velocity zone of unlithified sediments and weathered crystalline rocks, geologically mapped and calibrated by local measurements, such as cone penetrometer tests; (ii) fault and basin structures of the upper crust, defined by well control and extensive grids of seismic reflection profiles, primarily from the energy industry (with whom we maintain productive partnerships); and (iii) large-scale crustal and upper-mantle structure, derived primarily by regional tomography (**Fig. 1.6**). In addition to multiple releases of both the CFMs and CVMs, the SCEC4 phase of this project has produced the Unified Community Velocity Model (UCVM) platform, which is a computational framework for comparing and synthesizing Earth models, delivering model products, and quickly building meshes for earthquake simulations [*253*].

In SCEC5, we will accelerate the USR lifecycle through the refinement of CVMs using the F3DT techniques developed in SCEC4, as well as incorporating additional well-log and reflection data in undersampled regions. An objective will be the assimilation of data from earthquake seismograms and ambient-field correlagrams at frequencies higher than the current limit of 0.2 Hz, which should improve the prediction of high-frequency strong ground motions (Question 4). A key problem, not yet solved, is how to preserve the other types of constraints on the GTL and basin/fault structures during the F3DT inversions. We propose to represent these constraints as data functionals with appropriate metadata that can be carried along in the inversions. Another issue is the extension of the CVMs to include frequency-dependent attenuation and small-scale, near-surface heterogeneities that will be needed for high-frequency ground-motion predictions.

Community Geodetic Model. The CGM is built on the complementary strengths of temporally dense GPS data and spatially dense InSAR data [*254*] (**Fig. 3.6**). The SCEC4 focus has been on secular motions. In

SCEC5, we will work on representing variable motions as time series to gain insights into postseismic processes, environmental (e.g., hydrological) contributions to deformation, and other transient phenomena. A key objective is increased vertical precision, which can distinguish among alternative models of secular deformation, slip-partitioning, and post-seismic deformation. Others are finer temporal sampling (daily when possible), spatial densification (especially near faults), and extended (decadal) time series. With the latter, we seek to distinguish background tectonic loading from long-term postseismic effects, which requires accurate preseismic velocity estimates. Such estimates are not available for some GPS sites affected by Southern California earthquakes in recent decades, but future data collection will be targeted to ensure usable observations following future earthquakes.

To facilitate noise reduction and model cross-validation, the enhanced geodetic model will comprise three components, CGM-GPS, CGM-InSAR, and CGM-combined. The two data-specific models will provide raw position time series (3 components for GPS; line-of-sight for InSAR) as well as derived quantities such as quasi-3D displacements from multiple InSAR offsets, velocities, coseismic displacement models, postseismic decay models, noise parameters, common-mode errors, and seasonal signals.

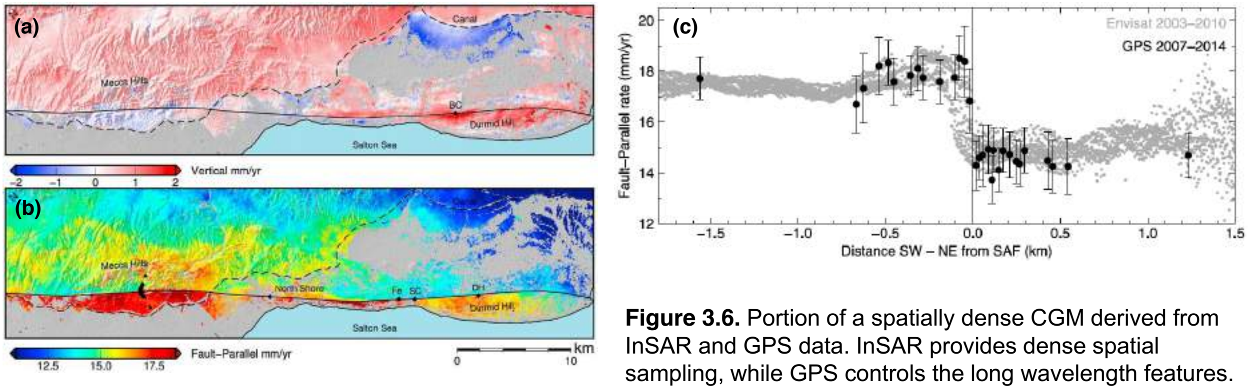


Figure 3.6. Portion of a spatially dense CGM derived from InSAR and GPS data. InSAR provides dense spatial sampling, while GPS controls the long wavelength features. (a) Vertical velocity. (b) Fault-parallel velocity. Transpressional areas show localized creep in a narrow zone while transtensional areas show distributed deformation across a broader zone. Solid line is San Andreas Fault trace along the Salton Sea and Coachella Valley. Triangles are GPS monuments at Painted Canyon. (c) Comparison of fault-parallel velocities along the Painted Canyon transect, derived from InSAR (grey) and GPS (black). From Lindsey et al. (2014).

Community Stress Model. The CSM was initiated in SCEC4 to support the modeling of tectonic loading, rupture-mediated stress interactions, dynamic earthquake rupture propagation, and physics-based earthquake simulators. Models of the orientations of stress and stressing rate in the upper crust, which are now relatively well constrained, have been released to the SCEC community. Estimates of stress and stressing-rate orientations below the upper crust are more poorly known, as are the amplitudes of the deviatoric stress in the crust. In SCEC5, we propose to focus on physics-based models of stress and stressing rate in the Southern California lithosphere. Modeling will allow us to extend the CSM deeper and will facilitate work on difficult, long-standing problems of deviatoric stress amplitude, the scale dependence of stress heterogeneity, and the relationship of stress heterogeneity to fault structure and earthquake kinematics. The physics-based models will be grounded in data, including the CSM stress orientations, the CGM surface kinematics, and the rheological constraints of the proposed Community Rheology Model.

Community Rheology Model. We propose an ambitious new project to develop a CRM that describes how crustal materials deform when subjected to stress, providing the constitutive properties essential for understanding active tectonics and the cyclical deformation of tectonic stress accumulation and earthquake stress release. The non-elastic rheologies needed to explain deformation are determined by material properties (mineralogy, grain size, and fluid content) and conditions (temperature, stress, and fluid pressure) that vary in space and time. We propose to combine into the CRM the constraints from geology on rock composition and structure, from seismic imaging on 3D elastic structure, from heat-flow measurements on temperature structure, from geodesy on surface deformation, and from seismicity and rupture imaging on stress and fault constitutive properties. The CRM will thus build upon the other community models, particularly the linear, anelastic rheology of the CVM, and it will connect the CSM (stress and stress rate) to the CGM (strain and strain rate), as schematized in **Fig. 3.5**.

Our phased plan to develop the CRM will focus efforts on two temporal scales: long-term tectonic stress accumulation and short-term earthquake stress release; and two spatial scales: narrow zones of damage around major faults and the extended volumes of rock between major faults. The first phase, already begun, is to create a Community Thermal Model, which will estimate the temperature structure of the Southern California lithosphere. The CTM will be derived from heat-flow, radiogenic heat-production, and thermal conductivity measurements, as well as thermobarymetric data on rock samples (e.g., xenoliths). The initial version, which should be available in the first year of SCEC5, will ignore horizontal heat flow and reduce hydrothermal effects by simple culling of the heat-flow data. Future versions may include shear heating, extension in the Salton Trough, fluid advection, and heterogeneous (possibly anisotropic) thermal properties. Estimates of the stress state variables will come from the CSM, and strain rates (needed for power-law flow) will come from the CGM.

The second phase, initiated in 2017, will annotate the CVM with lithologic composition that are consistent with geologic mapping, structural cross-sections, and the seismic velocities of the CVM. This effort will leverage on recent F3DT inversions that provide much better estimates of the $\mathrm{v_P}/\mathrm{v_S}$ ratio. Plots of $\mathrm{v_P}/\mathrm{v_S}$ versus $\mathrm{v_P}$ will be corrected for temperature variations and compared with laboratory and well-log measurements to constrain composition [*255*]. This research will directly benefit efforts to model ground motions, e.g., by improving 3D density and attenuation estimates, and to understand fault-zone structure, e.g., by improving knowledge of material contrasts across major faults. Also in the second phase, we will compile rheological data from experimental rock mechanics and studies of exhumed rocks. Microstructural and petrologic analyses on naturally deformed samples indicate that experimental flow laws provide good estimates of the effective viscosities of common minerals at geologic conditions [*256*]. These flow laws will be combined into the CRM with the seismic, thermal, and compositional constraints, as well as state-of-the-art information of the role of grain size evolution and rock fabric, to predict the loading response of narrow fault zones and extended rock volumes.

In the third phase, overlapping with the second, we will evaluate the CRM through mechanical modeling of tectonic and seismic processes. In particular, observations of the lithospheric response to changes in stress from earthquakes and surface loads [*257*] will be used to validate the CRM. Such efforts are hampered by limits in model resolution and tradeoffs between competing processes contributing to observed surface deformation transients from such loads. A successful rheology model should be able to explain crustal deformation throughout the earthquake cycle, as well as from the response of the Earth to hydrological or other surface-load changes, and milestones to chart this success will be developed prior to the start of SCEC5.

Topic 4: Data-Intensive Computing

Dramatically improved sensor technology and inexpensive storage are leading to rapidly increasing data volumes in the Earth sciences, a trend that will continue during SCEC5. LiDAR and InSAR observations often form large datasets, but seismic observations provide the clearest example of how quickly data sets are growing. It is increasingly common to deploy 1000s of sensors for months to record continuously at high sample rates. Such observations open important new scientific opportunities that we plan to pursue in SCEC5, but also demand new approaches. Ambient-field correlation techniques provide new constraints on Earth structure and its effect on ground-motion amplitude and variability, but the number of inter-station correlations scales quadratically with the station count [*258*] and increases further for studying time-dependent processes [*259*]. Current data management and processing techniques will not scale to data volumes of the near future. Signal detection and identification can be applied to continuous, many-channel time series to create micro-earthquake catalogs of unprecedented resolution and completeness [*260*]. These techniques for detecting and imaging earthquakes must also be improved to keep pace with larger data volumes. “Big Data” approaches refer to novel computing techniques developed to deal with datasets so massive that they overwhelm traditional approaches [*261*]. Challenges include analysis, capture, data curation, search, sharing, storage, transfer, visualization, and information privacy.

Big Data computing differs from traditional high performance computing (HPC) in a numbers of ways. For example, HPC processing requires a high-performance cluster, while Big Data processing techniques can be implemented on almost any collection of compute nodes, including commercial cloud infrastructures. HPC and Big Data software stacks can be significantly different, with HPC codes often written in C, Fortran, or CUDA, while Big Data programming is often done in Java, Python, and R. An HPC software stack often includes MPI, OpenMP, and OpenACC, while a data-intensive computing software stack might include Hadoop, Hive, or Spark.

Several actions will help establish data-intensive computing capabilities within SCEC5. We will identify one or two promising research goals, such as creating micro-earthquake catalogs or large-scale ambient-wavefield analysis that are suited to Big Data processing techniques and could serve as prototypes for broader implementation. For prototypes ready to be scaled-up, SCEC will identify NSF computing resources suitable for supporting data-intensive processing (e.g., at TACC and SDSC) and, if needed, augment them with commercial cloud computing resources. Efforts in this direction would fall naturally under SCEC's computational science focus group. We elaborate further on this topic in the SCEC5 Data Management Plan.

b. Understanding Earthquake Processes

Navier's elastic wave equation, Reid's elastic rebound theory, and Elsasser's elastic stress-guide model of the lithosphere have been enormously fruitful concepts in the study of earthquakes. Many of SCEC's most important achievements in understanding fault-system stresses, fault ruptures, and seismic waves have been based on the elastic approximation. However, new problems motivate us to move beyond elasticity in the investigation of these earthquake processes. Three key hypotheses have been framed by SCEC4 research results: (i) up to 30% of the permanent strain in the plate-boundary deformation zone occurs aseismically off major faults; (ii) substantial energy released during rupture is absorbed inelastically within the wall-rock volume, reducing the radiated energy; and (iii) the amplitude of strongest ground motions are substantially attenuated by the inelastic behavior of near-surface materials. In SCEC5, we will test these hypotheses against geologic, geodetic, and seismic data, refine them through dynamic modeling across a wide range of spatiotemporal scales, and assess their implications for seismic hazard analysis.

Topic 5: Beyond Elasticity

"Beyond elasticity" is a unifying theme of the SCEC5 Science Plan. SCEC4 research has improved the quality and quantity of data relevant to earthquake processes, developed new insights into rheological properties of rocks from field observations and laboratory experiments, and advanced computational capabilities to the point where it is now feasible to incorporate more complete descriptions of nonlinear rock behavior into the modeling of tectonic stress deformation, earthquake faulting, and seismic wave propagation. These problems are tightly coupled. For example, we propose to use dynamic rupture models accounting for inelastic off-fault response (Question 2; Topic 6) to address how fault damage zones are created by, and influence, rupture propagation [*262*,*263*] (Question 3; Topic 6); how energy is radiated into the far-field (Question 4; Topic 7); and how ruptures navigate fault complexities such as step-overs and branching [*264*,*265*] (Question 5; Topic 2). The key to success in these endeavors will be constraints on initial stress conditions (Question 1; Topic 1), which strongly influence how ruptures propagate. Those initial stresses are determined by the past history of slip [*266*], motivating further paleoseismic studies of fault slip histories and detailed geologic characterization of fault-zone structures and material properties.

Simulations that span multiple events with realistic loading conditions, spontaneous nucleation, and inelastic material response will benefit from better observational constraints on time-dependent damage and healing, including the role of fluids and diagenesis. Much can be learned about fault-zone structure at seismogeneic depths from high-resolution earthquake catalogs [*267*]. Geologic observations that can be brought to bear on the model predictions include high-resolution topographic and surface imaging and differencing techniques (e.g., LiDAR, SfM, COSICORR, ICP) that can better define the along-strike variability in fault slip, the width of the deformation zone, and the relative contributions of distributed versus localized deformation at the surface [*268*,*269*] and also at depth, as expressed in exhumed fault zones.

Development of state-of-the-art models of earthquake sequences will also require more realistic approaches to loading the system, including a better understanding of ductile deformation in the lower crust and upper mantle [*270*]. A new generation of models will incorporate physical and geological constraints on the mechanisms of strain localization in the ductile substrate, such as dynamic recrystallization [*271*], foliation [*272*], thermo-mechanical coupling [*273*], and mineral alteration [*274*]. This may ultimately lead to an improved understanding of why certain faults have higher slip rates than others, as well as how fault systems develop and evolve over thousands to millions of years.

Topic 6: Modeling Earthquake Source Processes

Dynamic rupture models aim to reproduce details of a spontaneous single rupture, fully resolving wave-mediated stress transfer as the rupture advances along the fault, radiating seismic energy. Realistic simulations require the consideration of off-fault plasticity and damage, co-seismic fault weakening due to shear heating and pore pressure evolution, fault roughness, and large-scale complexities. Such simulations are invaluable for understanding earthquake dynamics and providing input for large-ensemble wave-propagation simulations, such as CyberShake, that enable the probabilistic study of ground motions [*275*] (Question 4; Topic 7).

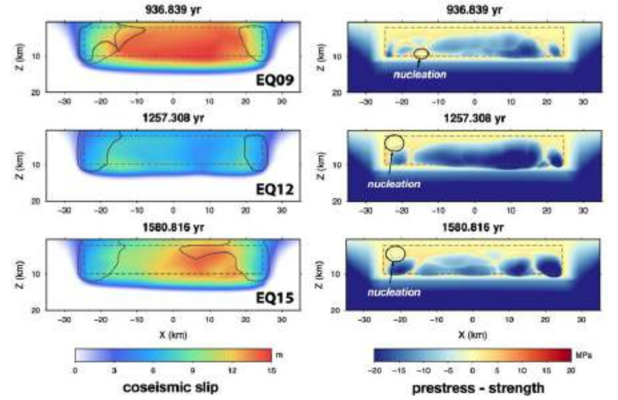


Figure 3.7. The importance of prestress of prior slip on subsequent rupture features of large earthquakes. Spatial distributions of coseismic slip (left) and prestress minus representative quasi-static strength (right) are shown for three consecutive earthquakes simulated in a rate-and-state fault model. The spatial extent of smaller earthquakes that occur between the larger events is indicated by black lines. The fault properties are the same throughout the simulation. The different slip patterns and nucleation locations for these events are due to different prestress established by prior history of fault slip. From Jiang and Lapusta (2015).

On the other end of the spectrum, earthquake simulators, such as RSQSim [*276*], focus on long histories and realistic fault networks, incorporating static stress interactions, back-slip loading, and quasi-dynamic fault slip based on rate-and-state friction. Such simulations are ingeniously efficient in producing long sequences of earthquakes and hence indispensable for examining how complex fault networks interact through static stress changes, a key aspect of earthquake predictability (Question 5). They can also be used for understanding the effects of additional factors such as injected fluids (Topic 8).

In SCEC5, we will fuse these complementary approaches into simulation capabilities that can account for slip history, inertial effects, complexity of fault zone resistance, realistic fault geometry, and realistic loading. Existing dynamic rupture simulations are limited by using initial conditions that do not account for prior fault slip history and by starting rupture through an artificial nucleation process; yet, initial conditions informed by the history of prior slip play a significant role in determining earthquake features (**Fig. 3.7**). The results of earthquake simulators can be affected by the simplified treatment of the rupture process, especially by the absence of dynamic stress interactions through waves, which can change the nature of earthquake sequences [*277*] (**Fig. 3.8**). Intermediate approaches [*278*] account for inertial effects in simulating sequences, which are useful for exploring interactions between slow slip, dynamic rupturing, and source complexities such as heterogeneities in fault properties and co-seismic fault weakening due to shear heating and pore-pressure evolution [*279*]. Yet such approaches are currently limited to planar faults embedded in a homogeneous elastic solid and loaded by back-slip. Long-term simulations need to include more realistic fault geometries and loading models that take into account inelastic block motions and the inelastic response of lower crust and upper mantle [*280*].

Progress in simulating self-consistent earthquake sources will be pursued through several complimentary threads. First, dynamic rupture simulations will be coupled to quasi-static simulations of earthquake-mediated stress evolution, as pioneered in recent studies [*281*] but with even more realistic ingredients. Such simulations will enable investigation of largely unexplored phenomena such as off-fault damage on rough faults, interseismic healing, and stress exchange between the shallower elastic and deeper inelastic bulk response. SCEC's long-standing and highly successful collaboration to verify dynamic rupture simulation methods [*282*] will be extended to such coupled approaches. The initial efforts will be limited by numerical tractability. Hence, a second thread will be to develop better integration of the

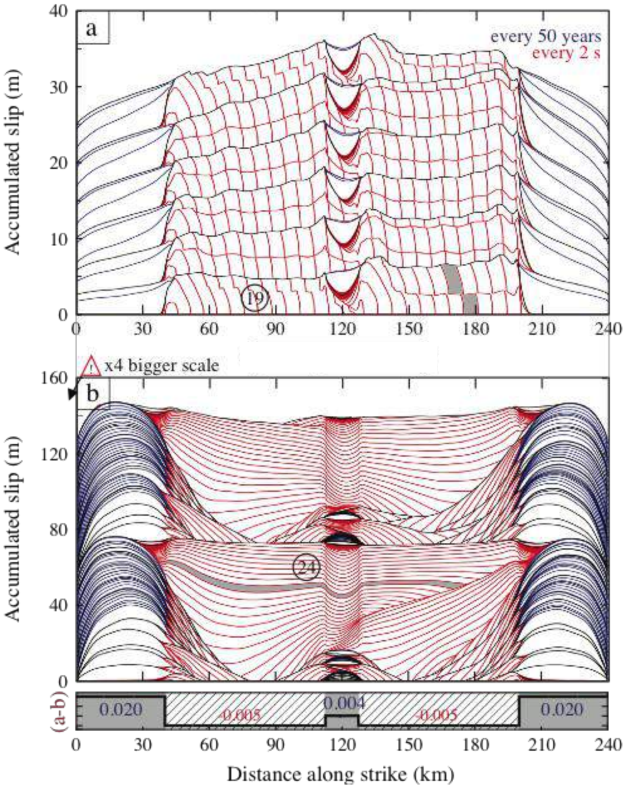


Figure 3.8. Importance of incorporating full wave-mediated inertial effects during simulated earthquake sequences and long-term slip. Fully dynamic (top) and quasi-dynamic (bottom) simulations of earthquakes sequences produce qualitatively different results in models with enhanced co-seismic weakening. Red/blue lines indicate slip accumulation with seismic/aseismic slip rates, respectively. The fully dynamic simulation generates pulse-like ruptures, while the quasi-dynamic approximation is incapable of reproducing this result, generating instead much larger crack-like events combined with many smaller events. From Thomas et al. (2014).

existing simulation approaches to leverage their salient capabilities. For example, long-term, quasi-static simulations can provide prestress conditions for dynamic rupture simulations that account for prior seismic and aseismic fault slip.

A third thrust will be to develop further earthquake source models that satisfy a broad range of observational constraints from the field and laboratory, thus improving our understanding of the operative physical mechanisms during faulting. Simulations that incorporate various weakening mechanisms will explore their potential for explaining the heat-flow paradox, their role in establishing the absolute level of stress on faults, their interaction with fault roughness and evolving off-fault damage, and their implications for the frequency dependence of ground motion. A new objective is to pursue these investigations not only for single spontaneous ruptures but also in a much more challenging setting of earthquake sequences within complex fault systems. Improved simulation capabilities of SCEC5 will also enable a comprehensive investigation of the effects of fluids on the earthquake source processes, including evolving off-fault permeability due to evolving damage and the competition between thermal pressurization and dilatancy in the context of realistic fault roughness.

Topic 7: Ground Motion Simulation

SCEC5 initiatives will include new approaches to the validation of simulations, improvement of their accuracy by incorporating nonlinear rock response into ground-motion simulations, and the integration of complex dynamic rupture models and advanced models for scattering and anelastic attenuation into simulations covering the full frequency range of engineering interest. SCEC4 research has demonstrated the feasibility of computing the full wavefield from complex sources and Earth structures in 3D to frequencies up to 8-10 Hz and out to distances large enough (> 100 km) to facilitate extensive comparisons with seismic recordings [*283*]. Substantial further work will be needed to improve the accuracy and efficiency of deterministic simulations beyond the 1-Hz barrier to make them useable for seismic hazard analysis:

- Source complexity. We will link the random nature of high-frequency ground motion to the small-scale complexity of natural faults. Synthetic seismograms from dynamic ruptures on rough (self-affine) faults are remarkably consistent with observed ground motions to frequencies in excess of 10 Hz [*284*]. These results suggest that high-frequency ground motion may be affected in predictable ways by fault-zone maturity, including surface roughness, the number and size of stepovers, splay faults, and the presence of other structural complexities. Ensembles of rough fault simulations can help quantify expected rupture styles (e.g., sub-Rayleigh vs. supershear, slip pulse vs. crack) and ground motion (both median and variance). They open the door to new, more physically consistent pseudo-dynamic rupture characterizations [*285*] that will be useful in seismic hazard research and may reduce uncertainties in ground-motion predictions for EEW, rapid disaster response, and induced earthquakes.

- Frequency-dependent attenuation. At low frequencies, attenuation structure can be represented in terms of a spatially variable but frequency-independent quality factor Q for pure shear. At higher frequencies, anelastic attenuation must be modeled as a frequency-dependent power law. Such models have been incorporated into several SCEC simulation codes via Day's [*286*] coarse-grained formulation [*287*]. We propose to incorporate the frequency and spatial variations of Q into the CVMs and bring new observations to bear on some poorly understood issues; e.g., the apparent decrease of Q_P relative to Q_S at frequencies above 1 Hz [*288*].
- Small-scale, near-surface heterogeneities. Scattering by small-scale heterogeneities contributes significantly to the apparent attenuation of high-frequency pulses and leads to incoherence in the wavefield important to ground-motion predictions [*289*]. Using data from well-logs, seismic reflection surveys, and dense seismic arrays, we will formulate stochastic representations of small-scale velocity variations of the crust that appear to dominate wavefield scattering at high frequencies and assess what wavefield metrics are predictable from the resulting statistical models.

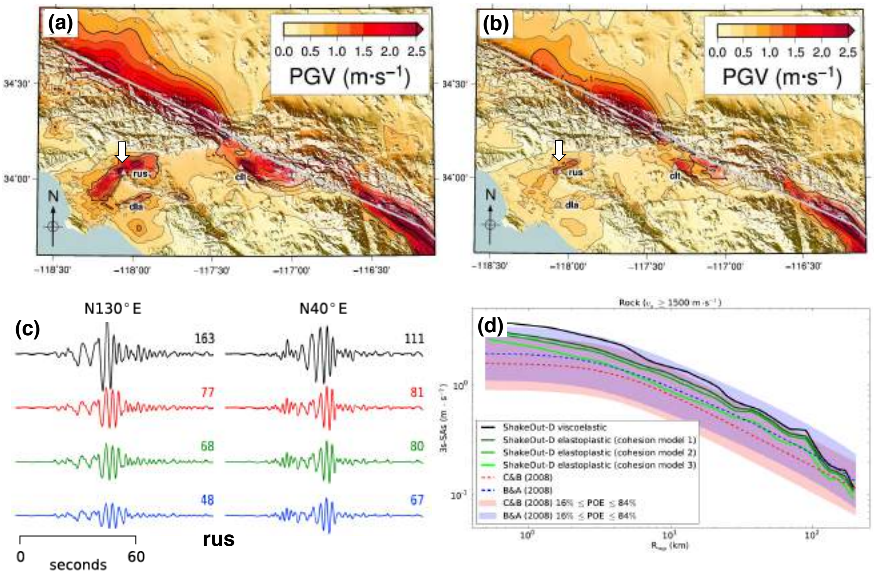


Figure 3.9. Comparison of peak ground velocity (PGV) for the M7.8 ShakeOut scenario earthquake, as modeled by (a) viscoelastic rheology and (b) elastoplastic (Drucker-Prager) rheology. The strong wave-guide amplification in the LA basin seen in (a) is reduced in (b) by up to 50%. PGV reductions in the LA basin appear robust, as shown in (c), which compares horizontal-motion seismograms at rus (arrow) from the viscoelastic model (black) with those from elastoplastic models for end member (red and blue) and average (green) cohesion models. (d) Plot of 3s spectral acceleration vs. distance show that the elastoplastic results agree better with the NGA GMPEs. From Roten et al. (2014).

- Inelastic rheology. Recent simulations have shown that nonlinear rock deformation may significantly modify ground motions from large earthquakes in ways that differ from the traditional engineering understanding of nonlinearity as the site response of a thin geotechnical layer [*290*] (**Fig. 3.9**). The incorporation of nonlinearity into simulation-based ground motion estimation has the potential to provide new insights into ground motion scaling at large magnitude and may impose natural limits on amplification effects such as forward directivity. The research challenges are formidable, because inelastic rheologies depend on the initial stress state and require knowledge of poorly constrained parameters, such as rock cohesion. We will thus coordinate the estimation of stress and rheology with the CSM and CRM activities. Multi-cycle earthquake simulations are likely to provide a means for estimating stress variability at spatial scales smaller than those directly available from other CSM methods. Large simulation ensembles will be used to assess the stress state and rheological uncertainties.

Nonlinear materials do not obey superposition, and nonlinear response can transfer energy between frequency bands. Therefore current approaches that use superposition to combine separately simulated low-frequency and high-frequency ground motions will have to be reexamined. Likewise, methodologies such as CyberShake that gain efficiency by exploiting the linear principle of seismic reciprocity may require modification. In SCEC5, we will accommodate nonlinearity without sacrificing the efficiencies of the reciprocal approach by disaggregating reciprocity-based CyberShake calculations to identify a reduced set of controlling sources [*291*] and then perform fully dynamic, nonlinear forward ground-motion simulations of those sources to adjust any bias in the CyberShake hazard estimates.

Ground Motion Validation Studies. From a practical perspective, unvalidated simulations are essentially useless, but the paucity of near-fault recordings of large events is a severe limitation. In SCEC4, we have made significant progress in the validation of simulation methods through coordinated validation efforts that combined tests based on data from individual earthquakes with tests based on statistical relationships from aggregated data, as encoded in GMPEs. In particular, SCEC's Broadband platform (BBP) was successfully validated during the Southwest U.S. Ground Motion Characterization (SWUS) project, sponsored by the western U.S. electric power companies in response to requirements of the Nuclear Regulatory Commission [*292*]. We have also set up new types of validation gauntlets that compare the nonlinear spectral response of earthquake simulations with those from well-recorded earthquakes [*293*]. Validation of the low-frequency CyberShake models is underway by SCEC's Committee on the Utilization of Ground Motion Simulations, which is evaluating the use of CyberShake in developing the seismic provisions of building codes, as part of the Building Seismic Safety Council's *Project 17* [*294*]. However, more extensive and systematic validations will be necessary to qualify SCEC simulations for specific engineering applications, especially at higher frequencies.

SCEC simulations have revealed potential ground-motion amplification effects that are not purely local in origin, but are path specific and involve complex interactions between path and source, such as the waveguide effects seen in **Fig. 3.9** [*295*]. Observational testing is especially challenging because such effects depend upon the seismic velocity model over an extended region, as well as upon rupture location, extent, and propagation direction. SCEC researchers have therefore developed a novel methodology that uses ambient noise recordings from fault-aligned seismic arrays to synthesize "virtual earthquakes", which can be used to test scenario-specific predictions from numerical simulations [*296*]. We plan to apply this technique extensively in Southern California and other regions, such as Japan, where dense networks are available.

The SCEC4 validation studies have focused exclusively on median predictions [*297*], which does not address the consistency of simulations with measures of inter- and intra-event variability. The former are critical to hazard estimates at low probabilities. Moreover, measures of ground-motion variability provide important tests of the simulation physics. For example, anelastic attenuation and scattering may affect median amplitude similarly, but have distinguishable effects on intra-event standard deviations. Other statistical criteria that may be useful in validation of simulation methods include spatial correlations of spectral accelerations [*298*], correlation coefficients between spectral ordinates at different periods [*299*], and partitioning of variance into intra- and inter-site components [*300*].

Topic 8: Induced Seismicity

Human-triggered earthquakes are important and growing aspect of the U.S. seismic hazard [*301*]. Anthropogenic seismicity presents one of the more tractable aspects of the earthquake problem. From the mitigation perspective, human-generated earthquakes should also be human-preventable. From the physics perspective, fluid injections that produce proximate earthquakes, if properly understood, provide rare controlled experiments on the Earth's seismic response to a known forcing [*302*].

Interpreting induced seismicity episodes has proven far from trivial, however, because the tradeoffs among the potential triggering processes are insufficiently understood. Pore pressure diffusion, poroelastic loading, and thermal stresses are all thought to play a role, but the circumstances under which any one of the processes is dominant are unclear [*303*]. Apparently identical operations in different regions elicit differing seismic responses [*304*]. The controls on magnitude are controversial with conflicting evidence on whether human-induced earthquakes are necessarily confined to small magnitudes [*305*]. Time-dependent nucleation may be a significant aspect [*306*]. Agreement even on a metric for attribution of triggering remains elusive.

SCEC is uniquely positioned to make progress on these issues. We have a well-instrumented and well-characterized natural laboratory that includes well-documented cases of anthropogenic seismicity [*307*]. We have extensive expertise in fault and rock mechanics and also the computational infrastructure, provided by CSEP, for the long-term evaluation of earthquake statistics and predictability [*308*].

The geothermal fields in Southern California provide a clear case study of anthropogenic forcing. During SCEC4, we showed that the net extraction from the Salton Sea geothermal field is well-correlated with seismicity (**Fig. 3.10**). This connection between human and earthquake activity invites a combined effort of geodetic, geologic and mechanical studies. The goal is to develop a physical model that accurately predicts the expected earthquake rate and magnitudes in restricted, well-characterized environments. Similar approaches may be applicable to the Cerro Prieto geothermal area in northern Baja California, where InSAR data show a very high subsidence rate (~10 cm/yr). A simple Coulomb model of the volume change due to the extraction results in a stress rate of 15 kPa/yr, which exceeds the tectonic stressing rate [*309*]. In addition, oil and gas extraction can lead to induced seismicity both directly, through changing the stress field, and indirectly, through disposal of produced wastewater. Hints of oil and gas-related seismicity exist in our study area but are difficult to interpret, in part due to the complex exploitation history and high level of natural seismicity [*310*]. Isolating the human-related earthquake component has become particularly important regionally as the hydrocarbon extraction from the Monterey shale is being vigorously debated in the legislature and press (**Fig. 3.11**). Finally, we note that temporal variations in groundwater loading [*311*] and changing lake level of the Salton Sea [*312*] can cause large perturbations to the normal stress on faults (200 to 400 kPa) due to plate flexure. While these processes occur on relatively long time scales, they may nevertheless modulate seismicity.

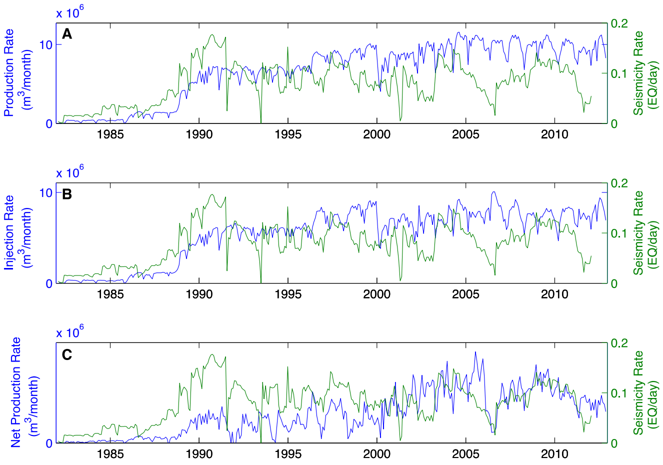


Figure 3.10. Background seismicity rate (μ) vs. year compared to injected fluid volumes at the Salton Sea Geothermal Field. The seismicity rate curve is identical for each panel (right axis, green curve); the operational rate (left axis, blue curve) in each case is (A) production rate, (B) injection rate and (C) net production rate. Seismicity rates are on 2-year overlapping intervals centered on each month for which there is operational data. From…

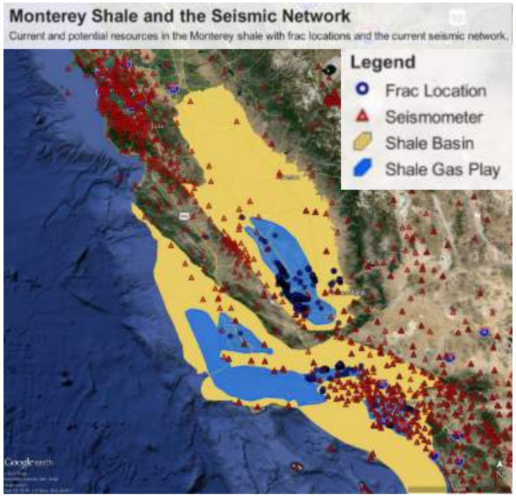


Figure 3.11. Network seismometer locations and hydraulic fracturing locations as recorded by the state of California. Hydraulic fracturing locations are used as a proxy for active oilfield enhancement.

Detection of potentially induced seismicity and discrimination from tectonic earthquakes is inhibited by low seismometer density in the Central Valley, where fluid injection and extraction activity is currently most vigorous (**Fig. 3.11**). Attribution assessment depends critically on permanent, publically managed data with sufficient detection capability to establish background activity on the timescales relevant to hydraulic fracturing, wastewater disposal, and other industrial activities. Previous SCEC work also points to the important role of small earthquakes in cascades that are the most observable manifestation of triggering. For both reasons, we will employ waveform-based detection techniques to lower earthquake detection thresholds and probability-based magnitude of completeness to assess detection improvements.

Pore fluid pressure is the most commonly cited cause of anthropogenic seismicity; therefore, prediction of fluid migration through an understanding of fault-zone hydrology is critical to any mitigation strategy. In order to address this problem, we plan to participate in the assembly of a hydrological framework to accompany our induced seismicity studies in key areas, such as southern Kern County. Both conventional and exploratory hydrological methods can be used to constrain appropriate models [*313*]. SCEC will work within organizational partnerships that include the expertise from regional water boards and reservoir engineers needed to build such hydrological models.

The mechanistic understanding of induced seismicity is intimately linked to the study of fluid transport along fault zones. Fractured damage zones provide potential high-permeability conduits along fault zones. Recent SCEC work has shown that the formation and evolution of these damage zones is linked to the earthquake cycle. Damage zones open during fault rupture and then heal interseismically [*314*]. That time-dependence may be particularly important in understanding injection effects on long-dormant faults in bedrock, whose partially healed (and thus reduced-permeability) damage zones may be renewed by the first seismic events, enabling pore pressurization and seismic activity to spread.

Key tasks for SCEC5 studies of induced seismicity include: (i) developing detection methods for low magnitude earthquakes; (ii) participating in the building of an observationally founded hydrological model for special study sites; and (iii) developing and testing mechanistic and empirical models of anthropogenic earthquakes within Southern California, capitalizing on the geodetic, seismic, hydrologic and geological datasets.

c. Characterizing Seismic Hazards

Characterization of seismic hazards across a wide spectrum of forecasting and response times, including a proper assessment of model uncertainties, is the foundation on which most risk-reduction strategies are built (**Fig. 2.1**). In this section we propose SCEC5 applied research in probabilistic seismic hazard analysis, operational earthquake forecasting, earthquake early warning, and rapid earthquake response. This research will be coordinated with the USGS and CGS, which have statutory responsibilities for providing this information.

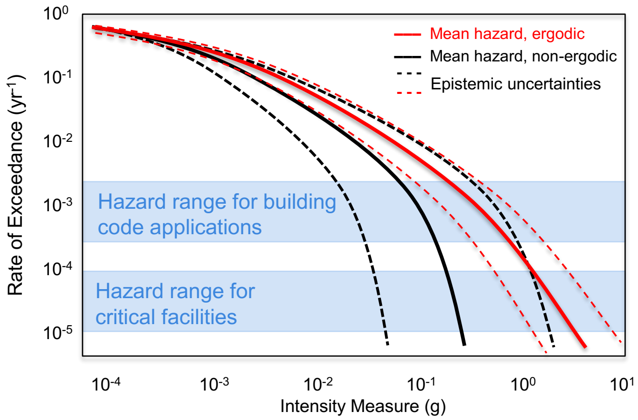


Figure 3.12. Schematic hazard curves, showing the mean value under the ergodic assumption (red solid line) and its reduction due to a reduction in σ_T from a non-ergodic (e.g., path- and site-specific) treatment (black solid line). Owing to uncertainties in the non-ergodic parameters (e.g., in the 3D velocity structure used for simulations), the epistemic uncertainty may be larger for the non-ergodic model (black dashed lines) than for the ergodic model (red dashed lines). However, this epistemic uncertainty can, in principle, be reduced by new knowledge that leads to model improvements.

Topic 9: Probabilistic Seismic Hazard Analysis

Among the technologies used to reduce risk, probabilistic seismic hazard analysis (PSHA) is the most effective, because it guides the long-term construction of a seismically safe built environment. PSHA contains two main components, an earthquake rupture forecast (ERF) and a ground-motion prediction (GMP) model. SCEC5 will provide a strong focus on the basic earthquake science that is foundational to all aspects of PSHA. It also will contribute directly to the main PSHA components through the continuing development of fault-based ERF models, such as the Uniform California Earthquake Rupture Forecast, and physics-based GMP models, such as CyberShake.

The goal of SCEC5 research on this topic will be to characterize and reduce the uncertainties in PSHA predictions by incorporating more and better physics into ERF and GMP models. The empirical ground-motion prediction equations (GMPEs) in common use, such as those developed by PEER's Next Generation Attenuation (NGA) project [*315*], 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 σ_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 for common intensity measures. Reducing this residual or "aleatory" variability is a high priority for seismic hazard analysis, because the probabilities of exceedance at high shaking intensities go up rapidly with σ_T, e.g., adding costs to the seismic design of critical facilities to account for the prediction uncertainty (**Fig. 3.12**); however, attempts to decrease σ_T by incorporating more explanatory variables into the GMPEs have been largely unsuccessful [*316*]. Substantial work in engineering seismology is now directed at "non-ergodic" models that explicitly account for effects that are specific to the region, the path, and the site [*317*].

As an alternative to empirical models, SCEC is developing physics-based earthquake simulations that properly account for source complexity and directivity, basin effects, directivity-basin coupling, and other 3D effects. The theoretical limits of this approach can be estimated through an analysis of simulations that have been generated for the Los Angeles region by the CyberShake project (**Fig. 2.19**). The residual variance obtained by applying the NGA-2008 [*318*] GMPEs to the CyberShake dataset matches the frequency-dependence of σ_T^2 obtained for the GMPE calibration dataset, indicating that the variability of the simulated ground motions is comparable to the observed. Using the new tool of averaging-based factorization (ABF) [*319*], we can partition this variance into uncorrelated components representing source effects (directivity, magnitude, source complexity) and propagation effects (path, site).

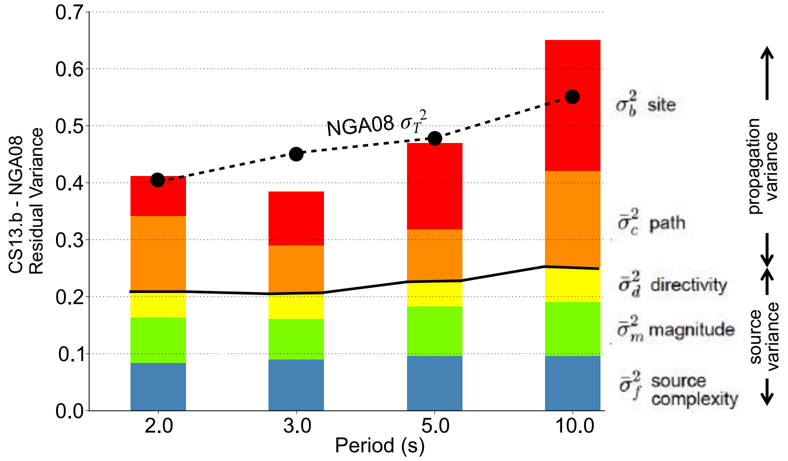


Figure 3.13. Histograms of the residual variance in spectral acceleration at periods 2-10 s, computed for CyberShake 13.b relative to the mean of the NGA (2008) GMPEs, using averaging-based factorization (ABF). The total residual variance (bar height) agrees with the NGA σ_T^2 (black points), indicating that the CyberShake ground-motion variability is similar to that of the global dataset used to calibrate the GMPEs. Colors show the independent contributions of the various ABF factors; black line separates the source variance (directivity, magnitude, complexity) from the propagation variance (site, path). From Jordan et al. (2015).

At the long periods shown in **Fig. 3.13** (2-10 s), about half of the variability not captured in the GMPEs is due to 3D path and site effects that potentially can be modeled using physics-based simulations. Therefore, accurate ground-motion simulations (Topic 7) can potentially reduce σ_T by about one-third. At favorable sites, this decrease in uncertainty would lower the exceedance probabilities at high intensity levels by orders of magnitude, as sketched in **Fig. 3.12**, while at unfavorable sites the probabilities would go up [*320*]. Realizing this forecasting gain would have a broad impact on risk-reduction strategies, especially for critical facilities such as large dams, nuclear power plants, and energy transportation networks. In SCEC5, we will also attempt to reduce the magnitude variability associated with magnitudes (stress-drop variations) and possibly even directivity through better source modeling (Topic 6).

Topic 10: Operational Earthquake Forecasting

Operational earthquake forecasting (OEF) is the dissemination of authoritative information about time-dependent earthquake probabilities to help communities prepare for potentially destructive earthquakes [*321*]. SCEC5 will support the USGS OEF program [*322*] through its core program and special projects:

(i) Fundamental research on earthquake predictability, including the modeling of earthquake source processes (Topic 6) and strong ground motions (Topic 7), as well as the organization of a rapid scientific response to earthquake crises in Southern California (Topic 12).

(ii) Development of physics-based forecasting models in its Collaboratory for Interseismic Simulation and Modeling (CISM). OEF is feasible with existing short-term statistical models, but there are many areas where improvements are possible, especially through the incorporation of physics-based nucleation and stress-transfer models (**Fig. 3.16**) [*323*].

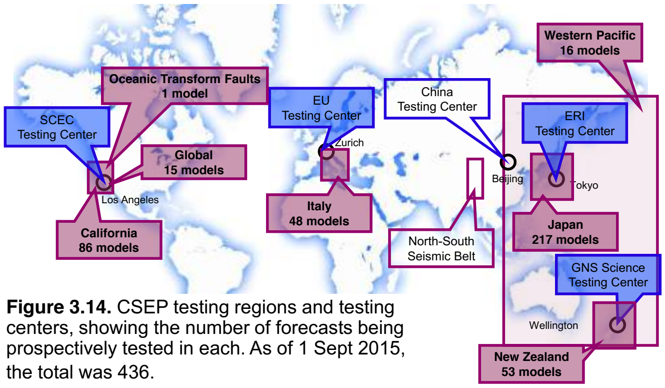


Figure 3.14. CSEP testing regions and testing centers, showing the number of forecasts being prospectively tested in each. As of 1 Sept 2015, the total was 436.

(iii) Coordination of the Working Group on California Earthquake Probabilities (WGCEP), which is developing UCERF3-ETAS as a candidate model for OEF implementation. SCEC will continue to support WGCEP through funding received from the California Earthquake Authority and other agencies and with its HPC resources.

(iv) Testing of short- and medium-term forecasting models, including UCERF3 and other USGS models, within the Collaboratory for the Study of Earthquake Predictability (CSEP).

CSEP is a critical infrastructure for the retrospective calibration and prospective testing of the OEF systems; its global scope allows forecasting models to be evaluated in a variety of well-instrumented tectonic regions, reducing the time needed for forecast validation (**Fig. 3.14**). We request specific funding for CSEP activities in the USGS part of the SCEC5 core budget. The CEO program will work with the USGS in developing plans to educate the public and other end-users on OEF capabilities and uncertainties.

Topic 11: Earthquake Early Warning

An earthquake early warning (EEW) system is under development for the U.S. west coast that can provide the public with automated warnings up to tens of seconds before strong seismic shaking [*324*]. Several topics of SCEC5 research will address scientific issues of major importance to EEW:

(i) Determine how quickly the magnitudes, fault mechanism, and other source parameters of very large (M > 7) earthquakes can be determined after the origin time [*325*]. Improve techniques for inferring fault rupture parameters from time-limited seismic and geodetic data [*326*]. (Topic 6)

(ii) Provide more accurate ground-motion predictions that account for directivity, basin, and other 3D effects. Develop more realistic earthquake simulations for testing the seismic and geodetic components of EEW system performance [*327*]. (Topic 7)

(iii) Obtain better long-term and short-term earthquake rupture forecasts for prior conditioning Bayesian EEW algorithms, such as the Virtual Seismologist [*328*]. (Topics 9,10)

Priority will be given to EEW-related research that can potentially reduce the size of the region where no warning is issued by providing more accurate information sooner [*329*]. SCEC will continue to foster international partnerships with Japanese, European, and other foreign research programs in EEW that will include the data sharing, joint algorithm development and testing, and exchange of lessons learned from public response to alerts. Education and outreach activities that can help the public understand and more effectively utilize EEW will be incorporated into the SCEC5 CEO program (see §III.C).

Topic 12: Post-Earthquake Rapid Response

Rapid scientific response to strong earthquakes, especially in Southern California, is central to SCEC's mission. Mobilizing the core geoscience disciplines of seismology, geodesy, and geology to gather and preserve ephemeral earthquake data must occur as quickly as possible, while aftershocks, transient motions, and surface rupture are strongest and best expressed. Thus, earthquake response demands experimental design in real time, with information shared freely and efficiently among disciplines and guided by cutting-edge scientific hypotheses. SCEC serves three roles that guide a more effective rapid scientific response to earthquakes: (i) *intellectual leadership* spanning the breadth of earthquake system science, (ii) *coordination* of the response of the academic science community, and (iii) c*ommunication* of knowledge to the world at large. SCEC's role in fostering scientific inquiry thus differs from, and complements, the statutory responsibilities of federal and state agencies, such as the USGS and CGS.

SCEC has developed an infrastructure to coordinate a rapid scientific response through its working groups and a special website, http://response.scec.org, in concert with the California Earthquake Clearinghouse [*330*]. If a major earthquake occurs in Southern California during SCEC5, the Center will coordinate the scientific response with the USGS, CGS, and other relevant agencies in the following areas:

Aftershock monitoring. Because aftershocks illuminate many aspects of fault-zone structure and its post-seismic evolution, it is critical to enhance aftershock monitoring with portable instrumentation as soon as possible. Quick instrument deployment (<1 day) also increases the chances of capturing the nucleation process of a large aftershock and feeds data into operational earthquake forecasting.

Geodetic monitoring. Rapid geodetic measurements, especially within the near field, are needed to separate post-seismic afterslip from coseismic displacement. Where permanent station coverage is sparse, significant effort and equipment will be needed to survey campaign benchmarks around the rupture.

Surface rupture mapping. Rapid observations of any surface rupture are crucial. Mapping of coseismic displacement, afterslip, and distributed deformation are needed to understand the event and interpret paleoseismic data. High-resolution fault-zone imaging with LiDAR, airborne InSAR, and structure-from-motion techniques should commence immediately, before fragile rupture features disappear.

Post-seismic deformation observations. Deformations near the end points of a rupture are particularly useful in discriminating post-seismic deformation mechanisms. The sooner the endpoints are identified from field observations, the sooner instruments can be deployed to measure subsequent deformation.

Operational earthquake forecasting. Post-event OEF requires rapid information about the mainshock rupture. Timely aftershock locations and focal mechanisms are also critical, ideally with magnitude completeness to M0 or lower, as are observations of time-dependent post-seismic phenomena.

Strong ground motion characterization. Early deployment of additional strong-motion instrumentation, while aftershock productivity is high, provides the data needed to disentangle path and site effects on strong motions, and better informs which ground-motion metrics are most correlated with damage.

Fault-zone drilling**.** Rapid-response drilling into a fault after a major earthquake provides insights into the rupture conditions, the stresses on the fault during and after the earthquake, the process by which the fault heals and rebuilds stress, and how the fault zone is affected by other earthquakes. Drilling across the fault slip zone at >1 km depth should commence within ~1-2 years of a large surface rupture.

The SCEC management structure, as expressed in its working groups, is able to respond quickly in coordinating field programs with the USGS and CGS to capture perishable data and conduct post-earthquake studies. Through its cooperative agreements with the NSF and USGS and its contractual arrangements with core and participating institutions, SCEC will provide a well-organized conduit for the funding of scientific investigations in the critical period immediately following a major event.

d. Reducing Seismic Risk

The ultimate goal of seismic hazard analysis, and a central aspect of SCEC's mission, is to provide earthquake information useful in motivating civic actions to reduce risk and increase resilience. In working towards this goal, SCEC has developed an effective network of partnerships with engineering and emergency management organizations through both its core research program and its CEO program (see §III.C). The SCEC5 core research program will continue to engage earthquake engineers through joint projects with the PEER Center, the California Earthquake Authority, the NHERI DesignSafe-CI Center, the Building Seismic Safety Council's *Project 17*, and the Pacific Gas & Electric Company. These "ruptures-to-rafters" activities will be managed through SCEC's Earthquake Engineering Implementation Interface (EEII). In SCEC5, the EEII will engage research and practicing engineers on two main topics.

Topic 13: Risk to Distributed Infrastructure

As emphasized in Mayor Garcetti's plan *Resilience by Design* [*331*], seismic damage to vulnerable infrastructure is a major threat to the functioning of cities like Los Angeles. Urban infrastructures are spread over wide regions; hence, improving the resilience of these systems requires predicting spatial variations and correlations in ground motions. SCEC4's achievements in ground-motion prediction include progress in quantifying the effects of sedimentary basins on patterns of ground motion and in understanding the impacts of rupture complexity and structural heterogeneity on the spatial coherence of ground motions. A focused EEII activity on infrastructure risk will serve to validate simulated ground motions at regional scales, providing insights about seismic risk to infrastructure owners, operators, and regulators.

Buried infrastructure is often damaged by large ground deformations and failures caused by surface faulting, soil liquefaction, and landslides [*332*]. For example, most of LA's drinking water and energy supply is carried in conduits that cross the San Andreas Fault, and its massive port facilities are subject to liquefaction. These phenomena are amenable to study via ground-motion simulations but require further refinements to rupture models (Topic 6) and ground-motion models (Topic 7). In particular, ground failures are associated with highly nonlinear material behavior during strong shaking—prime examples of phenomena that are Beyond Elasticity (Topic 5). Validation of ground-failure models will be achieved in part via comparisons with CGS's liquefaction and landslide hazard maps, and new insights from ground-failure simulations will supplement and perhaps contribute to those maps.

We will work with engineers to develop measures of distributed infrastructure impacts; e.g., by combining pipeline fragility functions into network flow models to estimate the impact of various earthquake scenarios on water supply (see Los Angeles Department of Water & Power letter of commitment). We will apply these measures in assessing to what degree specific physical effects, such as high frequency scattering and the impedance at basin boundaries, contribute to the damage. The main goal will be to compare the predictions of correlated damage from physics-based ground-motion simulations with empirical GMPE-based correlation models [*333*].

Topic 14: Earthquake Physics of the Geotechnical Layer

The built environment is anchored in a near-surface complex of highly inelastic rock and soil. Understanding the earthquake physics of this "geotechnical layer" is important to information-based risk reduction strategies. SCEC recently convened two workshops to explore how 3D ground-motion simulations could be applied to the characterization of nonlinear site effects [*334*] and soil-structure interactions [*335*]; the workshops concluded that engaging earthquake engineers on these topics would benefit both communities. The 3D constitutive soil models developed by geotechnical engineers can be used to predict plastic ground deformation and secondary ground failure; research on the response of clays [*336*] and sands [*337*] has enabled high-fidelity simulations on local (facility-specific) scales. However, the models require many input parameters that are difficult to constrain on the scale of regional ground motion simulations. Simplified (1D) nonlinear response models offer computationally efficient alternatives to complex 3D constitutive models, particularly when geotechnical input is limited [*338*, *339*]. But full-3D models are needed to account for nonlinear strains from topography, basin edge effects, and caustic phenomena.

As part of the proposed Community Rheology Model effort, we will develop simplified 3D soil plasticity models that can predict inelastic ground deformation with a small number of input parameters, and we will take a multi-scale approach to integrating 3D nonlinear site response into regional-scale ground motion simulations. For example, simplified models using Iwan's [*340*] elastoplastic springs can be extended to 3D [*341*]. The geotechnical layer model will be designed to have the computational efficiency and scalability required for implementation in regional-scale earthquake simulations, and it will be deployed on the UCVM platform to facilitate user-specified HPC mesh generation. Recent work [*342*] suggests that PGV/Vs30 (the ratio of peak ground velocity to near-surface shear velocity) is a reliable proxy for ground surface strain. We will examine the use of this parameter, among others, to identify the conditions in regional 3D simulations where the ground strains are sufficiently large to warrant a nonlinear treatment.

Soil-structure interaction (SSI) describes the altering of seismic shaking by structural vibrations and the subsequent effects of the altered shaking on the building response [*343*]. For a single building, SSI effects can change significantly the characteristics of ground motion compared to free-field conditions [*344*]. Site-city interaction (SCI) describes the SSI effects that come from the dynamic interaction of multiple structures [*345*]. SCI simulations have been run at various scales [*346*], and recent studies have begun to investigate SCI models that more fully couple SSI effects to 3D wavefields [*347*]. Still lacking are realistic SCI simulations that allow for large deformations of the geotechnical layer, which often drive the vulnerability of distributed and critical infrastructure systems [*348*]. SCEC/EEII will encourage collaborations with engineers to investigate SSI and SCI effects using SCEC5 earthquake simulations.

3. Special Projects

Since SCEC became a free-standing center in 2002, its core funding has remained essentially flat in as-spent dollars and has decreased by about one-third in inflation-adjusted dollars, while participation in SCEC-coordinated research has more than doubled (**Fig. 1.5**). Two main factors account for this growth: the high value researchers place on participating in SCEC collaborative activities, even at very low funding levels, and the research support they obtain from SCEC special projects. The special projects are research partnerships in targeted earthquake research that heavily leverage the core program. Here we briefly describe the major special projects that are likely to be active at the beginning of SCEC5 and comment on the synergy we expect to realize through research interactions with the core program. Synergy is ensured by a central SCEC policy, instituted by the Board of Directors in 2005: *the science objectives of all SCEC special projects must be aligned with those of the SCEC core program and explicitly included as objectives in the SCEC Annual Science Plan*. Under this policy, any SCEC participant can propose core-program research pertinent to a special project, enabling them to participate in that project.

Community Modeling Environment (CME). The CME is SCEC's high-performance computing collaboratory for large-scale earthquake simulations. 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 (**Fig. 3.15**). These resources have enabled SCEC to sustain its HPC usage at an average rate of ~1 million CPU-hours per day. CME resources support five major SCEC computational platforms:

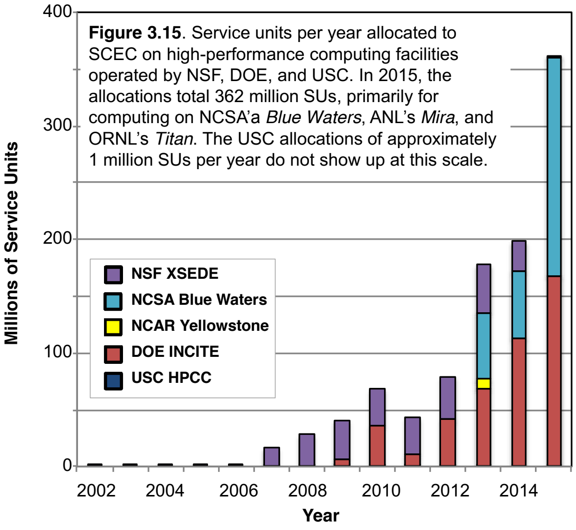


Figure 3.15. Service units per year allocated to SCEC on high-performance computing facilities operated by NSF, DOE, and USC. In 2015, the allocations total 362 million SUs, primarily for computing on NCSA'a *Blue Waters*, ANL's *Mira*, and ORNL's *Titan*. The USC allocations of approximately 1 million SUs per year do not show up at this scale.

High-F Platform: The High-F platform comprises the AWP-OCD and Hercules codes that SCEC researchers are using to push earthquake simulations to higher frequencies (> 1 Hz). Software under development will be capable of modeling the effects of fault roughness, near-fault plasticity, frequency-dependent attenuation, topography, small-scale near-surface heterogeneities, and near-surface nonlinearities (e.g., **Fig. 3.9**). The High-F Platform will support dynamic-rupture and ground-motion studies as part of the SCEC5 plans to move simulations Beyond Elasticity.

CyberShake Platform: The CyberShake Platform uses seismic reciprocity to generate large ensembles of simulations (> 10^8) that Monte-Carlo sample earthquake rupture forecasts and multiple crustal-structure models. Implementation of physics-based probabilistic seismic hazard modeling requires this capability. The platform is being developed using the Los Angeles region as a test bed, and it has already produced PSHA models as candidates for the USGS Urban Seismic Hazard Mapping Project (**Fig. 2.18**). In SCEC5, CyberShake PSHA models will be developed for other regions; e.g., in Central California as part of the Central California Seismic Project (see below). Because reciprocity derives from linear elasticity, a SCEC5 challenge will be the reengineering of CyberShake to enable the efficient, large-ensemble simulation of nonlinear wave phenomena that lie Beyond Elasticity.

Broadband Platform: The open-source Broadband Platform (BBP) provides a verified, validated, and user-friendly computational environment for generating broadband (0-100Hz) ground motions. In its validation mode, the BBP computes goodness-of-fit measures that quantify how well the synthetics match the observations (**Fig. 2.19**). In its scenario mode, it calculates suites of synthetic seismograms from user-specified rupture sets, structural models, and station sets. In SCEC5, the BBP will be extended from 1D to 3D structural models, and it will support the development and validation of physics-based ground-motion models in projects and partnerships managed under the EEII.

F3DT Platform: This platform integrates the software needed for full-3D waveform tomography using the adjoint-wavefield and scattering-integral formulations of the structural inverse problem [*349*]. F3DT can invert both earthquake waveforms and ambient-field correlagrams for high-resolution crustal models, and it can refine the centroid moment tensors of earthquakes by matching observed waveforms with 3D synthetics. These capabilities have been used to produce CVM-S4.26 (**Fig. 2.17**) and will be employed in the SCEC5 CVM studies.

Unified Community Velocity Model Platform. The UCVM platform provides an easy-to-use software framework for comparing and synthesizing 3D Earth models and delivering model products to users [*350*]. This community software is an important component of the CME cyberinfrastructure: a standardized, high-speed query interface enables users to build very large simulation meshes very quickly, and its file utilities can export meshes in both eTree and NetCDF formats.

Uniform California Earthquake Rupture Forecast. UCERF is a joint project of SCEC, USGS, and CGS to build a California-wide, time-dependent, fault-based earthquake rupture forecast, funded in part by the

California Earthquake Authority and managed through the Working Group on California Earthquake Probabilities. The latest (third) version (**Fig. 1.1**) comprises a time-independent model used in the 2014 release of the National Seismic Hazard Mapping Project (UCERF3-TI), a time-dependent model based on long-term Reid renewal statistics (UCERF3-TD), and a time-dependent model based on short-term ETAS statistics (UCERF3-ETAS). The latter is being developed as a candidate model for use in operational earthquake forecasting [*351*]. CSEP testing of UCERF3-ETAS will commence in 2016. A major SCEC5 initiative is to incorporate more physics into UCERF models through the use of physics-based earthquake simulators developed by SCEC-sponsored researchers [*352*] participating in the Earthquake Simulators Technical Activity Group [*353*] (**Fig 1.4**).

Collaboratory for the Study of Earthquake Predictability*.* CSEP provides an international cyberinfrastructure that sustains the prospective, blind testing of short- and medium-term earthquake forecasts on regional and global scales. CSEP testing centers (except Japan and China) run a common software stack that is developed and released quarterly by SCEC software engineer Maria Liukis. CSEP operations at SCEC include the testing of California and global forecasting models in addition to the development and maintenance of the collaboratory software. SCEC is responsible for the registration of new models and the coding of new testing procedures; many of these innovations, such as the testing of geodetic anomaly detectors [*354*], have come from the SCEC core program. Over 400 earthquake-forecasting models and their variations are currently under prospective CSEP testing (**Fig. 3.14**). The registration and testing of external forecasting models (e.g., M8 and QuakeFinder forecasts) is underway and may eventually include USGS operational models (Task 10). A SCEC partnership with GEM through GFZ/Potsdam has begun the testing of ground-motion models against observed intensity data. CSEP and its new sister collaboratory, CISM (see below), will be critical SCEC5 infrastructures for the development and evaluation of comprehensive earthquake forecasting models (Tasks 6, 7 & 10). The proposed earthquake-simulator effort under Task 6 is supported by the recent results of the CSEP Canterbury Retrospective Experiment. This SCEC collaboration with GNS/New Zealand and the European REAKT project has demonstrated that models incorporating the physics of rate-state nucleation and Coulomb stress transfer can outperform purely statistical models such as ETAS (**Fig. 3.16**) [*355*].

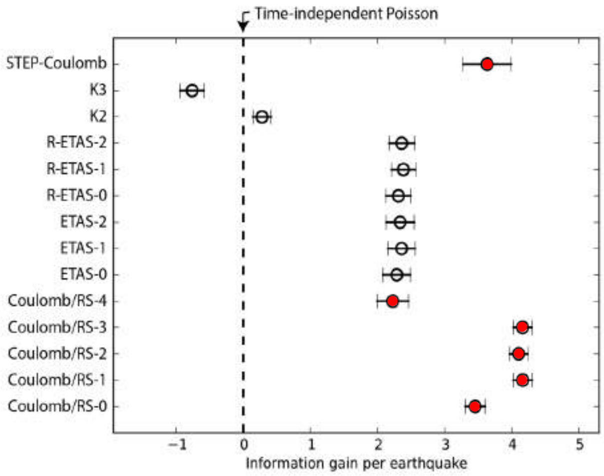


Figure 3.16. Preliminary results from the retrospective Canterbury experiment recently conducted in CSEP. The circles with error bars show the average information gain (natural log of the probability gain) per earthquake relative to a time-independent reference model (dashed line). The 14 forecasts in this experiment are listed on the left axis. 394 earthquakes with M > 3.95 were observed during the 18-month forecasting interval. This experiment is the first CSEP demonstration that physics-based models (red dots) can outperform statistical models (open circles) in short-term forecasting. From Werner et al. (2015).

CSEP was initiated in 2006 with support from the W. M. Keck Foundation and has been subsequently funded under grants and contracts from the USGS and Department of Homeland Security. Owing to CSEP's importance to SCEC core research, this proposal requests USGS funding of $200K/year to support collaboratory operations in California and USGS-relevant software development. Allocation of CSEP resources to specific projects would be guided as part of the core budgeting process by the Joint SCEC/USGS Planning Committee. As part of the SCEC-USGS Cooperative Agreement, SCEC will continue to provide USGS/EHP personnel with full access to all CSEP resources and will do its best to leverage USGS support with other SCEC partners. More information supporting this request is in the Budget Justification.

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 in 2015 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 physics-based ground-motion forecasting models. 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 (**Fig. 3.12**). 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. The CCSP will provide SCEC researchers with new data in both location and type. Its objectives are well aligned with the SCEC5 Basic Questions of Earthquake Science, especially Q4 and Q5.

C. Communication, Education & Outreach Plan

SCEC's Communication, Education, and Outreach (CEO) program addresses the final element of SCEC's mission: *Communicate understanding to end-users and society at large as useful knowledge for reducing earthquake risk and improving community resilience*. In particular, the SCEC5 CEO program will investigate the fifth problem identified in SCEC's Vision Statement (§III.A): *social dynamics of communicating earthquake knowledge*. This understanding will be pursued through interconnected focus areas with four long-term intended outcomes, which are listed in **Table 3.1**: (O1) improved application of earthquake science in policy and practice; (O2) reduced loss of life, property, and recovery time; (O3) increased science literacy; and (O4) increased diversity, retention, and career success in the scientific workforce. Combined, these outcomes address not only what and how to communicate, but expand the diversity of those involved in providing and receiving earthquake knowledge. They also fulfill each of NSF's Broader Impacts Review Criteria, as concluded in the 2015 CEO Program Evaluation [*356*].

The theme of the CEO program in SCEC5 is *Partner Globally, Prepare Locally.* The letters of collaboration from many of our partners (see Supplementary Documents) portray strong and effective regional, national and global collaborations that anticipate many years of joint activity. These partnerships foster new research opportunities and ensure the delivery of research and educational products that improve the preparedness of the general public, government agencies, businesses, research and practicing engineers, educators, students, and the media—locally in California as well as in other states and countries. *Prepare Locally* not only refers to improved resiliency to local hazards, but also to preparing students and the public for the future with the enhanced science literacy to make informed decisions to reduce their risk, and to preparing future scientists via research opportunities and support through career transitions.

The innovative CEO program has evolved and expanded considerably during SCEC4. For example, CEO is now involved in tsunami awareness and preparedness (TsunamiZone.org, with support from NOAA) and also in multi-hazard preparedness (America's PrepareAthon, with support from FEMA). In SCEC5, these and other CEO activities will align in an evidence-based program solidly founded in social science research, with strong synergies across disciplines. This program will be regularly evaluated, and its results and best practices will be published as models for other education and outreach efforts. In SCEC5, additional funding from government, corporate, and foundation partnerships, international organizations, and other sources will provide support for program implementation as well as for evaluation.

Table 3.1. Long-term Outcomes of the SCEC5 CEO Program and Related Basic Questions

Long-term Outcomes	SCEC CEO Focus Areas	Basic Questions of Earthquake Education and Outreach
O1. Improved application of earthquake science in policy and practice	KI, ELCA	Q1. What knowledge is most important to be communicated to technical end-users? Q2. What activities best transfer research into policy and practice?
O2. Reduced loss of life, property, and recovery time	KI, PEP	Q3. What are effective ways to improve preparedness and resiliency? Q4. How can potential reduction of likely losses be assessed prior to earthquakes?
O3. Increased science literacy	K14, PEP	Q5. Which approaches and content are most effective in educating students for living in earthquake country? Q6. What approaches and earthquake-related content most contribute to overall increases in science literacy?
O4. Increased diversity, retention, and career success in the scientific workforce	ELCA, K14	Q7. What are the best strategies for increasing diversity? Q8. How can retention of students and early career researchers be improved? Q9. What are effective ways to support career success of early career researchers?

* KI (Knowledge Implementation); PEP (Public Education and Preparedness); K14 (K-14 Education Initiative); ELCA (Experiential Learning and Career Advancement)

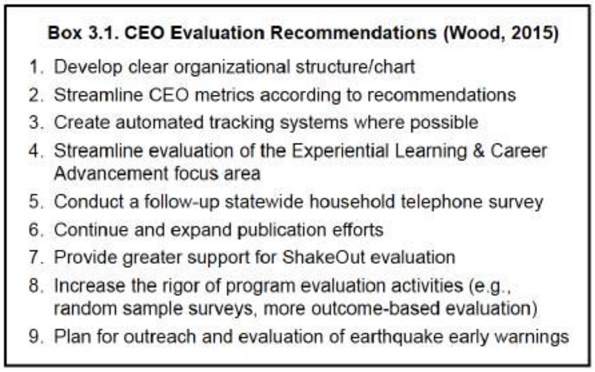
1. SCEC5 CEO Approach

The CEO program for SCEC5 has been designed based on the conclusions and recommendations resulting from the 2015 SCEC CEO evaluation [*357*]. The report highlights where SCEC has already incorporated strategies based on social science research evidence, and offers a set of recommendations for incorporating outcome-based evaluation as a key structure for implementing the program.

a. Evidence-Based Program Design

During SCEC4, the involvement of social scientists in SCEC CEO activities has resulted in increased application of social science theory in general [*358*], and on disaster preparedness theory in particular [*359*]. The 2015 CEO evaluation showed that SCEC programs also adhere to a variety of established best practices informed by social science research. In SCEC5, CEO will increase the rigor of its program development based on theory and best practice. Moreover, SCEC CEO will leverage its multi-disciplinary network to facilitate knowledge implementation of SCEC research to meet the needs of multiple end-users.

In SCEC5, CEO programs will continue to incorporate program features associated with increased program impact [*360*]. Strategies for motivating particular actions will be adapted from successful efforts in community building, education, marketing, environmental change, organizational culture change, and other disciplines. Programs will have high multiplicity (number of different components) to increase potential impact above-and-beyond what each component might produce alone [*361*], as well as provide opportunities for people to participate in a given activity multiple times and in multiple ways for greater exposure and depth of experience. SCEC CEO will continue to extend program reach to maximize the proportion of intended populations that have an opportunity to participate, and target multiple levels of influence [*362*]; i.e., individual, small group, and organizational/community. Public preparedness activities will be based on the theory of communicating actionable risk [*363*], which has shown that campaigns are more effective when: (i) they emphasize actions people should take to become better prepared (rather than on increasing perceived risk), (ii) their focus is shifted from representatives of government and nongovernmental groups to members of the public who have already taken steps to become prepared, and (iii) they distribute information that is *dense* (i.e., from multiple sources across multiple channels over time).



Box 3.1. CEO Evaluation Recommendations (Wood, 2015)

1. Develop clear organizational structure/chart
2. Streamline CEO metrics according to recommendations
3. Create automated tracking systems where possible
4. Streamline evaluation of the Experiential Learning & Career Advancement focus area
5. Conduct a follow-up statewide household telephone survey
6. Continue and expand publication efforts
7. Provide greater support for ShakeOut evaluation
8. Increase the rigor of program evaluation activities (e.g., random sample surveys, more outcome-based evaluation)
9. Plan for outreach and evaluation of earthquake early warnings

b. Outcome-Based Program Evaluation

Recommendations for SCEC CEO were developed as part of a recent external evaluation [*364*] and include a variety of suggestions for streamlining program design and evaluation to maximize program efficiency and impact (**Box 3.1**). In SCEC5, program evaluation will be focused on outcomes and will link to theory. A logic model, developed in the CEO evaluation process [*365*], will provide a visual roadmap of the theoretical framework and rationale of program activities, as well as their impact on human behavior and knowledge. This logic model will guide reviews of the CEO program by the CEO Planning Committee and SCEC's Advisory Council. It will also be the theoretical basis for identifying appropriate milestones and metrics and will guide the development of post-ShakeOut surveys, teacher workshop evaluations, post-internship discussions, and other assessments. A listing of CEO activities and available data will be promoted to graduate students and early-career researchers in sociology, public health, education, communications, marketing, and other fields for potential class or thesis projects or as the basis of research grants. The goal is to expand the level of ongoing assessment of the CEO program as well as provide evaluation research opportunities.

CEO's range of activities are designed to achieve four long-term outcomes identified in the SCEC5 CEO Logic Model, each the result of activities within interconnected CEO Focus Areas, described below. These outcomes inspire a set of basic questions of earthquake education and outreach, as shown in **Table 3.1**, which we intend to answer via implementation and evaluation of CEO activities in SCEC5.

2. SCEC5 CEO Focus Areas

In SCEC5, the CEO program will manage and expand activities within four CEO focus areas. *Knowledge Implementation* will connect SCEC scientists and research results with practicing engineers, government officials, business risk managers, and other professionals active in the application of earthquake science. The *Public Education and Preparedness* focus area will educate people of all ages about earthquakes, tsunamis, and other hazards, and motivate them to become prepared. The *K-14 Earthquake Education Initiative* will improve Earth science education in multiple learning environments, overall science literacy, and earthquake safety in schools and museums. The *Experiential Learning and Career Advancement* program will provide research opportunities, networking, and other resources to encourage and sustain careers in STEM fields. Each of these areas will build on improved earthquake science understanding. In particular, we will prepare individuals and organizations for making decisions (split-second through long-term) about how to respond appropriately to changing seismic hazards, including new technologies such as operational earthquake forecasting and earthquake early warning.

a. Knowledge Implementation

Long-term intended outcomes of this focus area are O1 (improved application of earthquake science in policy and practice) and O2 (reduced loss of life, property, and recovery time). The implementation of SCEC research for practical purposes depends on effective interactions with engineering researchers and organizations (via SCEC's Earthquake Engineering Implementation Interface, see §III.B.2.d) as well as knowledge transfer between earthquake researchers and those that make decisions based on understanding of earthquake hazards and risk (practicing engineers, geotechnical consultants, building officials, insurers, utilities, emergency managers, and other technical users)

These interactions are most effective as partnerships towards common objectives. In SCEC5 we will partner with professional organizations including the Structural Engineers Association of California (SEAOC) to develop training sessions and seminars for practicing engineers and building officials to introduce new technologies (including 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. A critically needed product to be developed in SCEC5 are improved earthquake scenarios for use in emergency planning, similar to the 2008 ShakeOut Scenario but likely much simpler with a common template that can be readily reproduced for likely earthquake sources nationwide. To understand SCEC's effectiveness in this area, we will document the use of SCEC research within practice and policy.

Knowledge Implementation efforts in SCEC5 will include expansion of the Earthquake Country Alliance (see next section) to include members focused on planning, mitigation, building codes, and other technical issues, perhaps organized as Technical Advisory Groups for each of ECA's Regional Alliances

(So. Cal., Bay Area, Redwood Coast). These groups will provide a research implementation focus in parallel with ECA's public education efforts.

b. Public Education and Preparedness

Long-term intended outcomes of this focus area are O2 (reduced loss of life, property, and recovery time) and O3 (increased science literacy). This 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.

Starting at home, CEO in SCEC5 will increase awareness of SCEC, its resources, and its researchers and specialists (across multiple institutions) among the news media and with the general public. The SCEC.org website will be a primary source of current information about SCEC, its innovative research, and its resources. Members of the SCEC Community will create summaries on SCEC.org about their research, supplemented with videos and other materials developed with the assistance of CEO staff. Press briefings will be held to announce new results, and webinars will be offered for the media and other key audiences. CEO will work with media relations personnel from SCEC institutions to coordinate media and risk communication training at the SCEC Annual Meeting and via webinars, and to offer programs that educate the media on how to report earthquake science. SCEC's risk communication goal will be to provide essential risk information at (1) critical times (post-earthquake in CA and elsewhere), in (2) appropriate ways (developed via media trainings) and (3) to key recipients (news media, elected officials, business owners, and others who need essential risk information for making decisions).

Social media capabilities have been expanded in SCEC4 and will be further developed during SCEC5. SCEC's accounts (facebook.com/scec, twitter.com/scec, youtube.com/scecmovies) are regularly updated with new content developed by SCEC and its partners, which are also increasing the availability of multi-lingual resources (materials, news releases, experts, etc.) to more effectively engage all media.

Continuing statewide, SCEC CEO is the home of the *Earthquake Country Alliance* (ECA, §II.B.2.b), which in SCEC5 will lead and develop earthquake and tsunami education and preparedness efforts in partnership with three regional alliances and hundreds of organizations, supported by FEMA, CalOES, CEA, and expanded private sector support. SCEC manages ECA's online resources (earthquakecountry.org, terremotos.org, facebook.com/earthquakecountryalliance, twitter.com/eca, etc.), vital resources that are continually updated to reach new audiences, and promote key ECA resources. These include the *Seven Steps to Earthquake Safety, Putting Down Roots in Earthquake Country,* instructional videos, regional risk information, and audience-specific materials (developed by ECA's Sector-Based Committees). More of these resources will be translated into Spanish and other languages during SCEC5 as recommended in the 2015 SCEC CEO Evaluation.

ECA also has developed resources and activities used nationwide (and beyond). This includes the Earthquake Education and Public Information center (EPIcenter) Network (§II.B.2.b), which will expand to more states in SCEC5, connecting us with their communities as providers of reliable information (and distributing materials developed by SCEC, ECA, and our partner organizations such as IRIS). EPIcenter locations also in SCEC5 will be prepared to quickly implement programs based on elevated forecasts and will educate visitors about how to respond to earthquake early warnings.

ECA also created the first Great ShakeOut Earthquake Drill in 2008. The mission of ShakeOut is now to encourage everyone, everywhere to know how to protect themselves during earthquakes (at home, work, and where they may travel). Beyond earthquake safety, SCEC engages ShakeOut participants in understanding earthquake science, learning about their particular earthquake hazards, and taking actions to reduce their risk. These aspects are integrated with other activities across all CEO focus areas, including the Quake Catcher and EPIcenter Networks, our internship programs, and interactions with practicing engineers and government officials. In SCEC5, ShakeOut drills will include new scenarios developed for use nationwide, and ShakeOut will play a key role in educating the public about operational earthquake forecasting and earthquake early warning, including annual tests on ShakeOut day. CEO will continue its leadership role in expanding participation worldwide (§II.B.2.a) with new Official ShakeOut Region websites managed by SCEC, complemented by simpler webpages for additional countries or organizations (e.g., ShakeOut.org/akdn). ShakeOut will also be used as a global digital infrastructure for sharing earthquake preparedness and mitigation best practices developed by countries, multi-national organizations, and local advocates.

Finally, SCEC's role in tsunami awareness and preparedness will be further expanded via its partnerships in ECA and its management of TsunamiZone.org as a global resource based on the ShakeOut model. Similarly, ShakeOut is also the model for FEMA's "America's PrepareAthon!" national campaign, designed to assess preparedness activities as directed by Presidential Policy Directive 8 [*366*]. ShakeOut registration totals are included in this assessment, and we will provide contracted support to FEMA for the expansion of ShakeOut, to advise FEMA on the development of PrepareAthon (including advice for activities related to other hazards), and to assist in recruitment.

c. K-14 Earthquake Education Initiative

Long-term intended outcomes of this focus area are O3 (increased science literacy) and O4 (increased diversity, career success, and retention in the scientific workforce). Achieving these outcomes must begin early, when attitudes towards science are formed and basic science and mathematics skills can be fostered. SCEC's position is that knowledge of science content and its application may be best achieved through an event-based (teachable-moment) approach, connected to standards-based curricula. While most earthquake content is in California's middle school curriculum, earthquake science and preparedness education can be encouraged in all grades when real-world events increase interest (tied to geography, math, history, and other curricula). Educational materials must also be supplemented to provide better information about local earthquake hazards, to increase relevance (place-based education). ShakeOut drills provide teachers an additional opportunity for teaching earthquake science, useful for explaining why certain preparedness actions are recommended.

SCEC's leadership in the Quake Catcher Network (QCN) during SCEC4 has expanded (see §II.B.2.c) via installation of sensors nationwide and inclusion of IRIS as a major partner. QCN bridges both event-based and place-based modes, with local earthquakes recorded on sensors within classrooms and local EPIcenter partners (museums, etc., see §II.B.2.b). In SCEC5 a partnership with IRIS will result in the integration of QCN and Seismographs in the Schools program enabling learners to engage local and global events. This provides tremendous opportunities to engage students, educators, and the community in citizen science and will improve understanding of earthquake early warnings.

SCEC will continue to offer summer high-school educator research experiences as a continuation of the NASA-sponsored InSight Vital Signs of the Planet (VSP) Professional Development Program or similar programs with future funding. The concept exposes participants to real-world research and trains them to develop Next Generation Science Standards aligned lesson plans. High school student participants can be encouraged to apply for SCEC internships in college. High-school educators have become vital members of the SCEC partnership by creating lessons distributed via SCEC, such as in educational kits for the "Quake Heroes" documentary under development. Educator workshops will introduce these and other resources (including SCEC's Plate Tectonics Puzzlemap, SCEC-VDO animations, and earthquake simulations) to educators at all levels. Workshops will include follow-up activities to help implement the content and evaluate long-term outcomes. SCEC's annual participation in educational conferences will continue as a venue for sharing resources, encouraging participation in ShakeOut, and recruiting new partners.

d. Experiential Learning and Career Advancement (ELCA)

Long-term intended outcomes of this focus area are O4 (increased diversity, career success, and retention in the scientific workforce) and O1 (improved application of earthquake science in policy and practice). The ECLA program engages scientists at the early stages of their academic careers, providing them with research experiences, exposure to the SCEC community, and leadership opportunities, and it supports them across key career transitions (e.g., undergraduate to graduate school, post-PhD, etc.).

The ELCA program in SCEC5 will be built on the foundation of our long-established successful USEIT and SURE internship programs (§II.B) that, since 1994, have challenged more than 540 undergraduates with difficult, real-world problems that require collaborative, interdisciplinary solutions. Special education and outreach internships will involve students from communications, marketing, policy, and other disciplines with the CEO program. In total, more then 40 students (including students at minority-serving colleges and universities and local community colleges) will participate each summer. The interns will experience how their skills can be applied to societal issues, and benefit from interactions with practicing professionals in earth science, engineering, computer science, and policy. Enhanced longitudinal tracking of intern alumni will continue to support evaluation of the program.

These internship programs will be the centerpiece of a high school to graduate school career pathway for recruiting the best students, providing them with high-quality research and education experiences, and supporting career advancement. Challenges often experienced as young researchers advance through educational levels will be mitigated through a new *SCEC Transitions Program*, a component of SCEC's Diversity Plan, described in the next section.

D. Diversity Plan

Figure 3.17. Some of the women participants at the 2015 Annual Meeting, photographed following banquet honoring Dr. Lucy Jones (near center with hands clasped). Lucy tweeted a picture of this group with the caption "Women @SCEC. In 25 years, so many more women in earthquake science!"

The SCEC leadership is committed to the growth of a diverse scientific workforce as articulated by the NSF's *Diversity and Inclusion Strategic Plan* [*367*]. Although SCEC has no direct say in the hiring and promotion decisions of its member institutions, it is a high-visibility arena for aspiring scientists and a forum for organizational leaders who seek workforce diversity (**Fig. 3.17**). We propose to pursue our diversity goals by combining the diversity-promoting mechanisms developed in SCEC4 with a new *Transitions Program*, which will provide junior members of the SCEC community with resources and mentoring at major steps in their careers. The goal is to promote diversity within the SCEC community that more closely reflects the population we serve.

1. Measuring Diversity

According to national surveys, the geosciences rank as the least ethnically diverse major STEM field; only about 6% of bachelor's degrees are awarded to underrepresented ethnic minority students [*368*]. A major objective of the SCEC4 Diversity Plan has been to increase the diversity of undergraduates that choose geoscience careers. The UseIT and SURE intern programs have been very effective in this regard (§II.B.2.d). A second SCEC4 objective has been to promote diversity in its leadership ranks, again with good results. A third has been longer term: to sharpen our knowledge of the composition of the SCEC community and the career trajectories of its junior members, so that we can better formulate programs to increase diversity. As part of this effort, we have been collecting demographic information during the Annual Meeting registration that allows us to track the diversity of career cohorts (**Fig. 3.18**).

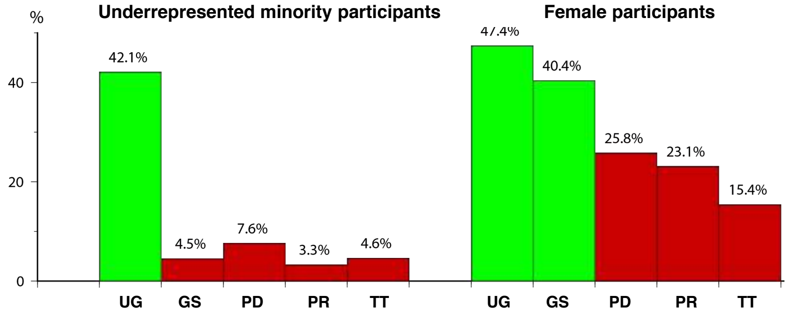


Figure 3.18. Self-reported ethnic and gender diversity of SCEC Annual Meeting participants in 2014 by cohort:
UG: undergraduate.
GS: graduate student.
PD: postdoc and instructors.
PR: professional researcher.
TT: tenure-track faculty.

These data confirm that SCEC has been successful at attracting diverse undergraduate participants, primarily through its internship programs: 42% from underrepresented minority ethnic backgrounds, 47% female participants in the 2014 Annual Meeting. But the data also show how quickly this diversity drops in the more senior ranks. Only about 15% of our tenure-track faculty are women, and less than 5% are underrepresented minorities. The largest drop in ethnic diversity is at the "post-UG" career transition, following the bachelor's degree, while the largest drop in gender diversity is at the "post-GS" transition. These critical transitions are marked by green-to-red in Fig. 3.18. The SCEC Transitions Program

2. The SCEC Transitions Program

To improve the diversity of senior participants in SCEC and earthquake science as a whole, we must retain the diversity of the professional cohort as it progresses through a series of career transitions. Moving towards this goal will require a sustained program that carefully targets its human and financial resources [*369*]. We propose to focus new resources on promoting diversity by helping students through their post-UG and post-GS transitions. The SCEC5 Transitions Program will comprise five basic activities:

a. Post-UG mentoring and networking. SCEC will sponsor workshops at SCEC Annual Meetings and fall webinars to guide students through the graduate applications process, provide them with information about research careers in industry and government, as well as academia. The main goal will be to connect interested undergrads with graduate students and professional scientists at SCEC institutions.

b. Facilitating the transition to graduate school. SCEC will support first-year graduate students through research assistantships at SCEC institutions for a three-month interval prior to graduate school; e.g., bridging the summer between college and graduate school. The SCEC institutions proposing to participate in this program will provide equivalent student financial support, faculty supervision, and an appropriate locus of study. These resources will act as an attractant for outstanding students of all ethnicities and genders, an incentive for schools to admit them, and a means of fostering student success [*370*]. The program will encourage and facilitate students to apply for NSF Graduate Research Fellowships.

c. Building community among graduate students. Alienation from the wider research community often leads underrepresented students to abandon science [*371*]. SCEC will build a culture of inclusivity and community by pairing first-time attendees at SCEC meetings with senior mentors, and by bringing cohorts together face-to-face at the Annual Meeting and on social media throughout the year. The Center will also support travel grants to SCEC workshops that can increase the participation of underrepresented groups.

d. Post-GS transition to academic jobs. SCEC will support early-career scientists through post-doctoral research fellowships at SCEC institutions for up to one-half year of a 2-year postdoctoral appointment. We will encourage social scientists as well as geoscientists to apply for these resources.

e. Post-GS transition to non-academic jobs. SCEC recognizes the need to help students and young professionals make career transitions not just within academia but also into tech-savvy careers in industry, commerce, and government. SCEC will solicit industry and private-sector partnerships to sponsor SCEC pre-professional interns who will be dually mentored by SCEC and industry experts.

The SCEC Transitions Program will be supervised by the Board Subcommittee on Diversity and managed by Dr. Bob de Groot through the SCEC Experiential Learning and Career Advancement office that he leads, and it will be coordinated with IRIS's early-career investigator working group [*372*] (see letter of collaboration). Longitudinal data on participants' careers and retention, including surveys of student and mentor satisfaction, will be collected for quantifying program success. Regular evaluations of the program will be solicited from the SCEC Advisory Council.

E. Information Technology Plan

Advanced information technology (IT) will be designed and deployed to support the Center's mission of gathering, integrating, and communicating seismic hazard information. A goal will be to maintain SCEC's access to high-performance computing and the development of the HPC-enabled simulation codes required for earthquake system science. We will use advanced IT to enhance SCEC research productivity, sustain its community models, and provide for education, training, and lifelong learning [*373*].

Types of Information Technology. SCEC5 IT capabilities will be separated into three broad categories—*Administration*, *Collaboration*, *and Research Computing*—mirroring IT areas often treated separately within universities and research organizations. There is enough overlap among these IT categories to motivate integrated approaches, but we recognize that each area has unique technical requirements warranting special consideration.

- *Administration IT* will provide computing support for SCEC human resources, SCEC contracts with funding sources, and sub-contracts with researchers, and will be integrated with University of Southern California (USC) accounting systems. As in SCEC4, SCEC5 will utilize University of Southern California IT tools to support SCEC5 administrative IT.
- *Collaboration IT* will provide support for the SCEC collaboratories, enabling local and remote participants to collaborate on research. SCEC5 collaboration IT will leverage existing USC collaboration tools that provide networking and telecommunications capabilities, including video conference calls, shared desktops, email lists, shared documents, and other routine collaborative tasks. Use of these collaboration tools has become an essential part of many SCEC4 collaborative research projects, and SCEC5 will widen access to these capabilities to the broader SCEC community. SCEC5 will also use a modern (Drupal-based) content management system (CMS) as a key information exchange mechanism. The SCEC5-CMS will provide a consolidated source of information about SCEC research. The SCEC5-CMS will be developed and maintained by a Community Information System Manager, supported half-time by the core program. The SCEC5-CMS will be used to manage the annual SCEC scientific collaboration cycle that includes development of the Science Plan, submission of research proposals, development and approval of the Collaboration Plan, award notifications, and project reporting. CMS application programs will also be developed to support workshop registration, participation, and reporting.
- *Research Computing IT* capabilities will include scientific computing, HPC, data-intensive computing, scientific software development, simulation data management, and software integration. Scientific software development capabilities will be a strategic priority for SCEC5. These will enable SCEC5 to produce important new results in physics-based modeling, high-performance computing, data-intensive computing, data assimilation, and forecast testing. Our SCEC5 efforts will build on successful SCEC scientific software projects, which include OpenSHA, CVM-H, SCEC-VDO, UCVM, Broadband Platform, AWP-ODC, Hercules, CyberShake, and CSEP.

IT Support for SCEC5 Core Research. Most SCEC software engineering is supported by special projects rather than through the core program. Requests from SCEC researchers for software and data management support from the SCEC IT group have been growing, and they now often go unmet because all SCEC software personnel are committed to existing special projects. Therefore, the proposed SCEC5 budget includes an additional full-time software developer to support the IT needs of SCEC core research and collaboration. This developer will support scientific data management, with a particular focus on the SCEC Community Models. Software resources within core SCEC5 will also enable SCEC to evaluate and apply new computing models, such as distributed near-real-time HPC needed for OEF and EEW, or big-data signal processing of continuous seismograms to produce high-resolution earthquake catalogs. SCEC5 data management priority will be to systematize the management of the SCEC Community Models, open-source software distributions, and seismic hazard data products, as discussed in the Data Management Plan. In SCEC5, we plan to continue the scientific software collaborations with the major NSF and DOE supercomputing centers that have been so productive in SCEC4.

Computing Collaborations and Resources. SCEC obtains computing time through competitive open-science allocation processes operated by DOE and NSF. Our allocation requests emphasize that SCEC is a multi-disciplinary research consortium currently using petascale scientific software to solve difficult computational problems of societal importance. As SCEC5 computing continues to grow, we will work to stay qualified on the largest available open-science supercomputers. This may require new, or re-written, versions of our high-performance codes. In July 2014, President Obama issued an executive order establishing a multi-agency National Strategic Computing Initiative (NSCI) that aims to develop an exascale computer for scientific use in the next 10 years. Achieving this national priority will require a co-design approach, in which next generation hardware and software are developed together. We will pursue opportunities in SCEC5 to collaborate with the supercomputer facilities in extreme-scale co-design activities.

IV. SCEC5 Management Plan

SCEC has developed an effective management structure for coordinating earthquake research and educational activities. The Center's ability to facilitate collaborative, investigator-driven research has been repeatedly proven by its diverse accomplishments. Participation in SCEC is rising despite flat funding (**Fig. 1.5**), and its national and international partnerships are flourishing. In its annual reports, the SCEC External Advisory Council has repeatedly documented the enthusiasm among SCEC participants and endorsed their high levels of satisfaction with the Center's leadership and administration. SCEC5 will continue to operate under its lean, well-tested management structure, which is described in detail below.

In preparing this proposal, the SCEC Board of Directors voted unanimously to operate SCEC5 under a similar set of by-laws as SCEC4. The University of Southern California (USC) will continue as the managing institution, and Tom Jordan, the proposal PI, will continue as the Center Director. The by-laws now designate the responsibilities of a Center Co-Director, Greg Beroza of Stanford University, who is Co-PI on this proposal. Establishment of a co-directorship and several other augmentations to the SCEC leadership structure have been designed to facilitate the SCEC leadership transition, as described in §IV.C.

A. Organization of the Center

Institutional Membership and Board of Directors. The Center will retain its structure as an institutionally based organization governed by a Board of Directors. It will recognize both core institutions, which make a major, sustained commitment to SCEC objectives, and a larger number of participating institutions, which are self-nominated and confirmed by the Board. The 17 core and 52 participating institutions that were enrolled as of October 1, 2015, are listed in **Table 1.1**. One participating institution, Texas A&M University, has requested core status, and the Board has approved this request. The institutional membership is expected to evolve, because SCEC will remain an open consortium, available to any individuals and institutions seeking to collaborate on earthquake science in Southern California.

Each core institution will appoint one member to the Board of Directors, which will be chaired by the Center Director. The Board will elect two nominees from the participating institutions to serve two-year terms as members-at-large. The Board will be the primary decision-making body of SCEC; it will meet three times per year (typically in Feb, June & Sept) to approve the Annual Collaboration Plan and budget and deal with major business items. The by-laws allow the Board to conduct business via email. Based on current projections, the SCEC5 Board will comprise 17 voting members. The USGS members will serve in non-voting liaison capacity. *Ex officio* members will include the Co-Director; the Associate Director for Administration (serving as Executive Secretary); the Associate Director for CEO; the IT Architect; and the Executive Science Director for Special Projects.

An Executive Committee will handle daily decision-making responsibilities, mainly through email. It will comprise five voting members, the Center Director, who will act as Chair, the Co-Director, the Board Vice-Chair, and two Board members elected for 3-year terms, plus three non-voting members: the Executive Director for Special Projects, the AD for CEO, and the AD for Administration.

Administration. The Center Director will be the Chief Executive Officer and bear ultimate responsibility for all of the Center's programs and budget. The Director will serve as PI on the SCEC core grants; ensure that funds are properly allocated for various Center activities; chair the Board of Directors, presiding at Board meetings and, insofar as resources permit, overseeing that Board decisions are properly executed; and appoint committees to carry out Center business. The Center Co-Director (G. Beroza, Stanford) will serve as Co-PI of the SCEC core grants, chair of the Planning Committee, and chair of the Annual Meeting. The Co-Director will oversee the development of the Annual Science Plan, lead the review process, and submit an Annual Collaboration Plan for approval by the Board. Either the Director or Co-Director will be the PI on all proposals submitted by the Center.

The Vice-Chair of the Board of Directors, elected by the Board, will call and conduct Board meetings in the absence of the Chair, and will perform duties and exercise powers as assigned by the Center Director and Board. The Vice-Chair of the Planning Committee (J. Chester, Texas A&M) will assist the Co-Director in the development of the Annual Collaboration Plan, the proposal review process, and the Annual Meeting planning. The Associate Director for Administration will assist the Center Director in the daily operations of the Center and be responsible for managing the budget as approved by the Board, filing reports as required by the funding agencies, and keeping the Board, funding agencies, and Center participants current on all Center activities. J. McRaney of USC has agreed to continue to serve in this capacity through the first two years of SCEC5.

Advisory Council. An Advisory Council (AC) will serve as an experienced advisory body to the Center. The AC will comprise a diverse membership representing all aspects of SCEC, including earthquake science and related disciplines, formal and informal education, and public outreach. Members of the AC will be drawn from academia, government, and the private sector; they will be elected by the Board for 3-year terms and may be re-elected. The AC will meet annually to review Center programs and will prepare an Annual AC Report, which will be made available to the NSF, USGS, and other funding agencies.

Management of Center Research Activities. The SCEC4 organization chart (**Fig. 4.1**) shows the current set of standing disciplinary committees (green boxes); interdisciplinary focus groups (yellow boxes); the Earthquake Engineering Implementation Interface (EEII, orange box), and special projects (pink boxes). Each of these working groups has a leader and co-leader who share organization and management responsibilities, act as spokespersons for the group, and serve on the SCEC PC. The working-group structure and PC membership will be reorganized when the proposed SCEC5 Plan has been accepted under the NSF and USGS cooperative agreements and the scope of the SCEC5 budget is known.

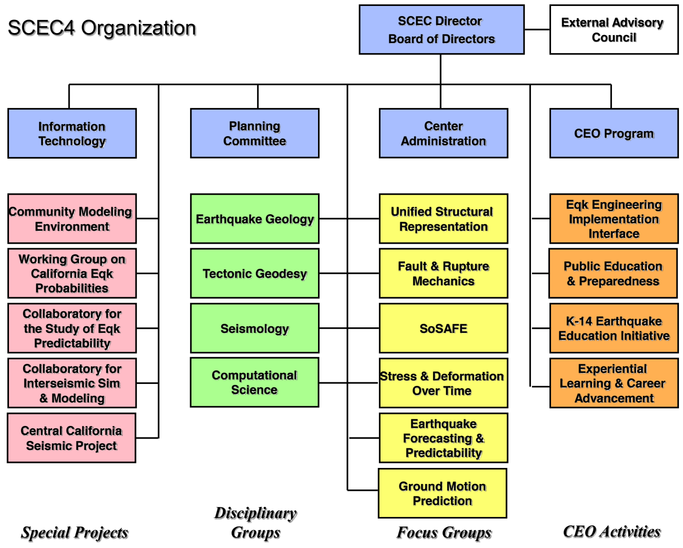


Figure 4.1. SCEC4 organization chart, showing Disciplinary Groups (green boxes), interdisciplinary Focus Groups (yellow boxes), CEO Focus Areas (orange boxes), Special Projects (pink boxes), and administrative units (blue boxes).

The SCEC Planning Committee (PC) will be responsible for developing the Annual Science Plan, which describes the Center's research interests and priorities, and the Annual Collaboration Plan, which details how resources will be allocated to projects. The PC will be chaired by the SCEC Co-Director, who will be assisted by a PC Vice-Chair. It will comprise representatives from each of the working groups plus the SCEC IT Architect and the Executive Director for Special Projects. The Center Director and the Associate Directors for Administration and CEO will serve *ex officio*.

Management of Communication, Education, and Outreach (CEO) Activities. Public outreach, knowledge implementation, education, and experiential learning/career advancement will be managed by the Associate Director for CEO, who will supervise highly experienced staff and consultants, supported by USC student workers. The Associate Director and CEO staff will act as liaison between SCEC and its partners in education, the business community, and earthquake preparedness and risk management. The SCEC CEO program will continue to manage the Great ShakeOut Earthquake Drills both nationally and internationally, the SCEC internship programs, the proposed "Transitions" diversity program to facilitate career transitions (§III.D), and other related activities. M. Benthien, the current SCEC AD for CEO, has agreed to continue in his leadership role in SCEC5. Regular advice will be provided by a CEO Planning Committee of stakeholders representing the main CEO focus areas; this CEO-PC is currently chaired by Dr. Tim Sellnow (U. Central Florida).

Management of Special Projects and Cyberinfrastructure. A key to SCEC's success has been the Center's growing expertise in scientific software engineering and its capability in HPC-enabled cyberinfrastructure. The oversight of SCEC Information Technology, including the software standards for data structures and model interfaces, will be the responsibility of the Associate Director for Information Technology, who will serve as the SCEC IT Architect. The IT Architect will report to the Center Director and will coordinate the Community Modeling Environment (CME), supervise the software engineering staff, and support SCEC research. P. Maechling has agreed to continue to serve in this leadership position in SCEC5.

SCEC recently recruited Christine Goulet, an engineering seismologist, into the new position of Executive Director of Special Projects (ED-SP); she will continue to serve full-time in SCEC5. The duties of the EDSP are to manage science activities in the externally funded SCEC Special Projects and to coordinate these activities with the SCEC IT Architect and Planning Committee. She will report to the Center Director, serve as a voting member of the PC, and serve *ex officio* on the SCEC Executive Committee.

SCEC Content Management System. SCEC is a virtual organization that coordinates interdisciplinary, multi-institutional earthquake system science on a global as well as regional scale. To enhance this coordination, the Center is developing a flexible and secure web-based Content Management System (SCEC-CMS) that can be used to gather information, synthesize knowledge, and communicate our understanding within and beyond the extended SCEC community. The SCEC-CMS will simplify the way diverse groups can contribute, update, and publish information online, allowing researchers to share scientific results with colleagues more rapidly and to communicate directly with end-users and the public. The first version of SCEC-CMS was released just prior to the 2015 SCEC Annual Meeting, and it will support development of the Science and Collaboration Plans, proposal submission, proposal review, and project reporting. In SCEC5, the website will also serve as curated archive of Center knowledge and resources, as well as a virtual meeting place for researchers and other users to discover experts, research results, and useful knowledge for promoting community preparedness and resilience. The SCEC-CMS development will leverage the widespread adoption of distance learning and collaboration tools by academic institutions. This portal will also enable publishing to different social media channels.

Post-Event Scientific Response, Major Southern California earthquakes have been important events for focusing SCEC research and stimulating collaboration. The Center's management structure, as expressed in its working groups, has been able to respond quickly in coordinating field programs with the USGS and other organizations to capture perishable data and conduct post-earthquake studies. The SCEC leadership recognizes the need to be constantly prepared to fulfill its scientific responsibilities following a major earthquake in Southern California. To improve this capability, we have included Post-Earthquake Rapid Response as a research focus (Topic 12) in the SCEC5 Science Plan (see §III.C).

B. Collaboration Planning Process

The annual budget cycle will begin with a SCEC Leadership Meeting in early June, where the Board, PC, and agency representatives will discuss SCEC research priorities. Based on these discussions, the PC will draft an Annual Science Plan, which will be presented to the SCEC community at the Annual Meeting in early September. Based on feedback received at the meeting, the PC will finalize the Annual Science Plan and present it to the Board for approval. This plan will form the basis for a project solicitation, released in October. SCEC participants will submit proposals in response to this solicitation in November. All proposals will be independently reviewed by the Director, the Co-Director, Vice-Chair of the PC, and the leaders of at least 3 relevant working groups. Review assignments will avoid conflicts of interest.

The PC will meet in January to review all proposals and construct an Annual Collaboration Plan. The plan's objective will be a coherent science program, consistent with SCEC's basic mission, institutional composition, and budget that achieves the Center's short-term objectives and long-term goals, as expressed in its Annual Science Plan. The Co-Director will submit the recommended Annual Science Collaboration Plan to the Board of Directors for approval. The annual budget approved by the Board and the Center Director will be submitted to the sponsoring agencies for final approval and funding.

Evaluation Criteria. In constructing the Annual Collaboration Plan, proposals submitted in response to the annual solicitation will be evaluated based on: (a) scientific merit of the proposed research; (b) competence, diversity, career level, and performance of the investigators; (c) priority of the proposed project for short-term SCEC objectives; (d) promise of the proposed project for contributing to long-term SCEC goals; (e) commitment of the PI and institution to the SCEC mission; (f) value of the proposed research relative to its cost; and (g) the need to achieve a balanced budget while maintaining a reasonable level of scientific continuity given funding limitations. With respect to criterion (b), we note that improving the diversity of the SCEC community and supporting early-career scientists is a major goal of the Center.

Joint SCEC/USGS Planning Committee. SCEC will maintain close alignment with the USGS Earthquake Hazards Program through three mechanisms: (a) reporting and accountability required by USGS funding of SCEC, (b) liaison memberships on the Board of Directors by the three USGS offices now enrolled as SCEC core institutions, and (c) a Joint SCEC/USGS Planning Committee (JPC). The JPC will augment the SCEC Planning Committee with a group of program leaders designated by the USGS, who will participate in the construction of the Annual Collaboration Plan. If requested, the PC chair will continue to sit on the Southern California Proposal Review Panel for the USGS External Research Program.

C. SCEC Leadership Transition

Tom Jordan is willing to continue as Center Director as long as necessary into SCEC5, but he is planning to step down as soon as a successor is ready to take on his responsibilities. John McRaney will continue in his position of Associate Director for Administration into SCEC5, but he is planning to retire by the end of 2018. To facilitate these two major leadership transitions, the Center has reconfigured its management structure and accelerated its staff development.

Jordan has been prepared to step down since the end of SCEC3, but two previous searches for a new SCEC Director, in 2009 and 2014, did not reach successful conclusions. In both searches, the directorship transition was timed to coincide with the start of a new five-year program; i.e., SCEC4 in 2012 and SCEC5 in 2017. Both were predicated on a job description adopted at the beginning of SCEC2 (2002): the Director is a tenured faculty member at USC who acts as PI on all SCEC grants and contracts, including all special projects. The expansion of SCEC special projects has raised the question of whether this “super-PI-ship” model can be sustained.

After closure of the search in 2014, several changes in the SCEC management structure were recommended by the Director and approved by the Board to redistribute the leadership 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. Two new science leadership positions have been created: a PC Vice-Chair (PC-VC), filled by Judi Chester (Texas A&M); and an Executive Director of Special Projects (ED-SP), filled by Christine Goulet (USC). USC has agreed to half-time salary support for the ED-SP and also for another new leadership position, the CEO Assistant Director for Strategic Partnership, filled by Sharon Sandow (USC).

Appropriate changes have been made to the SCEC administrative structure and by-laws to recognize the expanded role of the Co-Director and the new roles of the PC-VC and ED-SP. In particular, 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 with Jordan as a Co-PI. This redistribution of leadership responsibilities and workload is expected to facilitate the search for a new Director. The pressure on a new Director will be further reduced by effecting a “mid-term” transition; i.e., in the first few years of SCEC5.

USC has agreed to restart the senior faculty search after a brief strategic pause during the writing and evaluation of this proposal; as the host institution for SCEC, it is fully committed to a successful search process. If necessary, alternative models will also be considered, such as the appointment of a research faculty member as SCEC Director, as well as a more distributed directorship. Both funding agencies will be informed of key steps in the Director selection process and will approve any PI changes.

The AD for Administration McRaney—the first SCEC employee (1991)—will be difficult to replace, owing to his exceptional abilities and experience in Center organizational issues and financial management. The Center Director, working with the USC administration, has already started an internal transition process anticipating his departure prior to December, 2018. The existing Center staff includes three other experienced administrators, Tran Huynh, Karen Young, and Deborah Gormley, who will form the core of the new Center administrative structure. All three are recognized by USC as exceptional, and all three have earned degrees in geoscience; their technical knowledge of SCEC research and its participating disciplinary communities has been, and will continue to be, a boon to the Center. It is expected that one or two new staff members will be hired to support Center operations.

References (alphabetized)

For references numbered in the Project Plan, see References (endnotes) on pp. 24-48 of this document. The alphabetized list below also includes all endnote references.

Aagaard, B. T., M. G. Knepley, and C. A. Williams (2013). A domain decomposition approach to implementing fault slip in finite-element models of quasi-static and dynamic crustal deformation, *J. Geophys. Res.*, **118**, doi:10.1002/jgrb.50217.

Abrahamson, N., Atkinson, G., Boore, D., Bozorgnia, Y., Campbell, K., Chiou, B., Idriss, I. M., Silva, W., and Youngs, R. (2008). Comparisons of the NGA Ground-Motion Relations, *Earthquake Spectra*, **24**(1), 45–66.

Addair, T. G., D. A. Dodge, W. R. Walter, and S. D. Ruppert (2014). Large-scale seismic signal analysis with Hadoop, *Comput. Geosci.*, **66**, 145-154.

Ader, T. J., N. Lapusta, J.-P. Avouac, and J.-P. Ampuero (2014). Response of rate-and-state seismogenic faults to harmonic shear-stress perturbations, *Geophys. J. Int.*, **198**, 385-413 doi:10.1093/gji/ggu144.

al Atik, L., N. Abrahamson, J.J. Bommer, F. Scherbaum, F. Cotton, and N. Kuehn (2010). The variability of ground-motion prediction models and its components, *Seismol. Res. Lett.*, **81**, 794-801.

Allam, A.A., Y. Ben-Zion, I. Kurzon, and F. Vernon (2014). Seismic velocity structure in the Hot Springs and trifurcation seismicity cluster areas of the San Jacinto Fault Zone from double-difference tomography, *Geophys. J. Int.*, **198**, 978–999.

Allen, R. M., and H. Kanamori (2003). The potential for earthquake early warning in Southern California, *Science*, **300**, 786-789.

Allen, R. M., and A. Ziv (2011). Application of real-time GPS to earthquake early warning, *Geophys. Res. Lett.*, **38**, L16310, doi:10.1029/ 2011GL047947.

Amos, C. B., P. Audet, W. C. Hammond, R. Burgmann, I. A. Johanson, and G. Blewitt (2014). Uplift and seismicity driven groundwater depletion in central California, *Nature*, **509**, 483-486, doi:10.1038/nature13275.

Anderson, J. G., and J. N. Brune (1999). Probabilistic seismic hazard analysis without the ergodic assumption, *Seismol. Res. Lett.*, **70**, 19-28.

Andrews, D. J. (2002). A fault constitutive relation accounting for thermal pressurization of pore fluid, *J. Geophys. Res.*, **107**, B2363.

Andrews, D. J. (2005). Rupture dynamics with energy loss outside the slip zone, *J. Geophys. Res.*, **110**, B01307, doi 10.1029/2004JB003191.

Andrews, D. J., T. C. Hanks, and J. W. Whitney (2007). Physical limits on ground motion at Yucca Mountain, *Bull. Seismol. Soc. Am.*, **97**, 1,771-1,792; doi:10.1785/0120070014.

Asimaki, D., and J. Shi (2014). Site response validation studies using KIK-net strong motion recordings, *Proc. Southern California Earthquake Center* (SCEC) Annual Meeting 2014, Palm Springs, CA, September 2014.

Asimaki, D., R. Taborda, J. Anderson, and J. Stewart (2015). SCEC Site Effects Workshop (workshop report), Southern California Earthquake Center, May 5, 2015, 14 pp., available at *http://www.scec.org/workshops/*.

Ajzen, **I**. (1991). The theory of planned behavior, *Organizational Behavior and Human Decision Processes*, **50**, 179-211.

Atkinson, G.M., and D. M. Boore (2006). Earthquake ground-motion prediction equations for Eastern North America, *Bull. Seismol. Soc. Am.*, **96**, 2181-2205.

Auzende, A.-L., J. Escartin. N. P. Walte, S. Guillot, G. Hirth, and D. J. Frost (2015). Deformation mechanisms of antigorite serpentinite at subduction zone conditions determined from experimentally and naturally deformed roc*ks,* **Earth Planet Sci. Lett.**, **411**, 229-240.

Baker, J.W., and N. Jayaram (2008). *Effects of spatial correlation of ground motion parameters for multi-site seismic risk assessment: Collaborative research with Stanford University and AIR*, Final Technical Report for U.S. Geological Survey National Earthquake Hazards Reduction Program (NEHRP) External Research Program Award 07HQGR0031, 69 pp.

Baker, J. W., N. Luco, N. A. Abrahamson, R. W. Graves, P. J. Maechling, and K. B. Olsen (2014). Engineering uses of physics-based ground motion simulations, *Proc. Tenth U.S. National Conference on Earthquake Engineering*.

Balco, G. (2014). Quaternary fault slip behavior of the Mission Creek fault of the southern San Andreas fault zone in the San Gorgonio Pass, CA, *SCEC Annual Report*, Award 14103, 3 pp.

Bandura, A. (2004). Health promotion by social cognitive means, *Health Education and Behavior*, **31**, 143-164.

Barall, M., and R. A. Harris (2014). Metrics for comparing dynamic earthquake rupture simulations, *Seismol. Res. Lett.*, **86**, 1-13, doi: 10.1785/0220140122.

Baumann, T., B. J. Kaus, and A. Popov (2014). Constraining effective rheology through parallel joint geodynamic inversion, *Tectonophysics*, **631**, 197-211.

Beeler, N. M., T. E. Tullis, and D. L. Goldsby (2008). Constitutive relationships and physical basis of fault strength due to flash heating, *J. Geophys. Res*. **113**, B01401, doi 10.1029/2007JB004988.

Behr, Y., J. Clinton, P. Kästli, C. Cauzzi, R. Racine, and M.-A. Meier (2015). Anatomy of an earthquake early warning (EEW) alert: Predicting Time Delays for an End-to-End EEW system, *Seismol. Res. Lett.*, **86**, doi:10.1785/0220140179.

Ben-Zion,Y., F. L. Vernon, Y. Ozakin, D. Zigone, Z. E. Ross, H. Meng, M. White, J. Reyes, D. Hollis, and M. Barklage (2015). Basic data features and results from a spatially dense seismic array on the San Jacinto fault zone, *Geophys. J. Int.*, **202,** 370-380 doi:10.1093/gji/ggv142.

Beroza, G. C., and M. D. Zoback (1993). Mechanism diversity of the Loma Prieta aftershocks and the mechanics of mainshock-aftershock interaction, *Science*, **259**, 210-213.

Bettinelli, P., J.-P. Avouac' , M. Flouzat, L. Bollinger, G. Ramillien, S. Rajaure, NS S. Sapkota (2008). Seasonal variations of seismicity and geodetic strain in the Hamalya induced by surface hydrology, *Earth Planet. Sci. Lett.,* **266**, 332-344, doi:10.1016/j.epsl.2007.11.021.

Bielak, J., C.B. Crouse, and T. H. Jordan (2015). *SCEC Workshop on Soil-Structure Interaction of Complex Systems* (workshop report), Southern California Earthquake Center, January 29, 2015, 7 pp., available at *http://www.scec.org/workshops/*.

Bijelic, N., T. Lin, and G. Deierlein (2014). Seismic response of a tall building to recorded and simulated ground motions, *Proceedings of the Tenth National Conference on Earthquake Engineering*, in press.

Biasi, G. P., T. Parsons, R. J. Weldon II, and T. E. Dawson (2013). Appendix J: Fault-to-fault rupture probabilities, *U.S. Geol. Surv. Open-File Rept. 2013-1165-J*, and *California Geol. Surv. Special Rept. 228-J*.

Bird, P. (1999). Thin-plate and thin-shell finite element programsfor forward dynamic modeling of plate deformation and faulting, *Computers & Geosc.*, 25, 383-394.

Bird, P. (2009). Long-term fault slip rates, distributed deformation rates, and forecast of seismicity in the western United States from joint fitting of community geologic, geodetic, and stress direction data sets, *J. Geophys. Res.*, **114**, B11403, doi:10.1029/2009JB006317.

Bird, P. (2014). Stress field models from Maxwell stress functions, *SCEC Annual Report*, Award 12053, March 2014, 12 pp.; submitted to *Geophys. J. Int.*

Blisniuk, K., M. Oskin, K. Fletcher, T. Rockwell, and W. Sharp (2012). Assessing the reliability of U-series and 10Be dating techniques on alluvial fans in the Anza Borrego Desert, California, *Quaternary Geochronology*, **13**, 26-41.

Blisniuk, K., M. Oskin, A. Mériaux, T. Rockwell, R. Finkel, and F. Ryerson (2013). Stable, rapid rate of slip since inception of the San Jacinto Fault, California, *Geophys. Res. Lett.,* **40**, 1-5, doi: 10.1002/grl.50819.

Blisniuk, K., K. Scharer, W. Sharp, R. Burgmann, M. Rymer, and P. Williams (2013). New geological slip rate estimates for the Mission Creek strand of the San Andreas Fault Zone, *2013 SCEC Annual Meeting*.

Bonilla, L. F., R. J. Archuleta, and D. Lavallée (2005). Hysteretic and dilatant behavior of cohesionless soils and their effects on nonlinear site response: Field data observations and modeling, *Bull. Seismol. Soc. Am.*, **95**, 2373-2395.

Borsa, A. A., D. C. Agnew, and D. R. Cayan (2014). Ongoing drought-induced uplift in the western United States, *Science*, **345**, 1587-1590, doi:10.1126/ science.1260279.

Boulanger, R. W. (2010). A sand plasticity model for earthquake engineering applications, *Report UCD/CGM-10-01*, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA, 77 pp.

Bozorgnia, Y., N. A. Abrahamson, L. Al Atik, T. D. Ancheta, G. M. Atkinson, J. W. Baker, A. Baltay, D. M. Boore, K. W. Campbell, B. S.-J. Chiou, R. Darragh, S. Day, J. Donahue, R. W. Graves, N. Gregor, T. Hanks, I. M. Idriss, R. Kamai, T. Kishida, A. Kottke, S. A. Mahin, S. Rezaeian, B. Rowshandel, E. Seyhan, S. Shahi, T. Shantz, W. Silva, P. Spudich, J. P. Stewart, J. Watson-Lamprey, K. Wooddell, and R Youngs (2014). NGA-West2 research project, *Earthquake Spectra*, **30**, 973-987, doi: 10.1193/072113EQS209M.

Böse, M., R. Allen, H. Brown, G. Gua, M. Fischer, E. Hauksson, T. Heaten, M. Hellweg, M. Liukis, D. Neuhauser, P. Maechling, K. Solanki, M. Vinci, I. Henson, O. Khainovski, S. Kuyuk, M. Carpio, M.-A. Meier, and T. Jordan (2014). CISN ShakeAlert: An earthquake early warning demonstration system for California, *Early Warning for Geological Disasters*, ed. F. Wenzel and J. Zschau, Springer-Verlag, Berlin, pp. 49-69, doi:10.1007/978-3-642-12233-0_3.

Brantut, N., A. Schubnel, J.-N. Rouzaud, F. Brunet, and T. Shimamoto (2008). High-velocity frictional properties of a clay-bearing fault gouge and implications for earthquake mechanics, *J. Geophys. Res.*, **113**, B10401, doi:10.1029/2007JB005551.

Brantut, N., A. Schubnel, J. Corvisier, and J. Sarout (2010). Thermo-chemical pressurization of faults during coseismic slip, *J. Geophys. Res.*, **115**, B05314, doi:10.1029/2009JB006533.

Brenguier, F., M. Campillo, C. Hadziioannou, N.M. Shapiro, R.M. Nadeau, and E. Larose (2008). Postseismic relaxation along the San Andreas Fault at Parkfield from continuous seismological observations, *Science*, **321**, 1478-1481, doi:10.1126/science.1160943.

Brocher, T. (2005). Empirical relations between elastic wavespeeds and density in the Earth's crust, *Bull. Seismol. Soc. Am.*, **95**, 2081-2092.

Brodsky, E. E., and L. J. Lajoie (2013). Anthropogenic seismicity rates and operational parameters at the Salton Sea Geothermal Field, *Science*, **341**(6), 543–546, doi:10.1126/science.1239213.

Bronfenbrenner, U. (1989). Ecological systems theory, in R. Vasta (Ed.), *Annals of Child Development*, **6**, 187-249, JAI Press, Greenwich, CT.

Brothers, D. S., N. W. Driscoll, G. M. Kent, A. J. Harding, J. M. Babcock, R. L. Baskin (2009). Tectonic evolution of the Salton Sea inferred from seismic reflection data, *Nature Geoscience*, **2**, 581-584.

Bruhat, L., Z. Fang, and E. M. Dunham (2015). Rupture complexity and the supershear transition on rough faults, *J. Geophys. Res.*,submitted.

Brune, J. N., T. L. Henyey, and R. F. Roy (1969). Heat flow, stress, and rate of slip along the San Andreas fault, California, *J. Geophys. Res.*, **74**, 3821–3827.

Building Seismic Safety Council (2015). *Project 17*, *http://www.nibs.org/events/event_details.asp?id=645728*.

Burks, L. S., and J. W. Baker (2014). Validation of ground motion simulations through simple proxies for the response of engineered systems, *Bull. Seismol. Soc. Am.*, **105**, doi:10.1785/0120130276.

Byerlee, J. (1978). Friction of rocks, *Pure Appl. Geophys.*, **116**, 615-626.

Byrne, P. M., S. S. Park, M. Beaty, M. Sharp, L. Gonzalez, and T. Abdoun (2004). Numerical modeling of liquefaction and comparison with centrifuge tests, *Canadian Geotechnical Journal*, **41**, 193-211.

Building Seismic Safety Council, Project 17, *http://www.nibs.org/?page=bssc.*

California Earthquake Clearinghouse (2015). Website: *http://californiaeqclearinghouse.org*.

Callaghan, S., P. Maechling, K. Vahi, G., Juve, E. Deelman, Y. Cui, E. Poyraz, T. H. Jordan (2013). Running A Seismic Workflow Application on Distributed Resources*, SC13*, poster, Denver, Nov 17-22.

Candela, T., F. Renard, Y. Klinger, K. Mair, J. Schmittbuhl, and E. E. Brodsky (2012). Roughness of fault surfaces over nine decades of length scales, *J. Geophys. Res.*, **117**, B08409, doi:10.1029/2011JB009041.

CESMD: Center for Engineering Strong Motion Data (CESMD) available at *https://www.strongmotioncenter.org.*

Chaljub, E., Moczo, P., Tsuno, S., Bard, P. Y., Kristek, J., Käser, M. & Kristekova, M. (2010). Quantitative comparison of four numerical predictions of 3D ground motion in the Grenoble Valley, France. *Bull. Seismol. Soc. Am.*, **100**, 1427-1455.

Charlevoix, D. J, and A. R. Morris (2014). Increasing diversity in geoscience through research internships, *Eos*, **95**, 69-70.

Chen, P., L. Zhao, and T. H. Jordan (2007a). Full 3D Tomography for Crustal Structure of the Los Angeles Region, *Bull. Seismol. Soc. Am.*, **97**, 1094-1120, doi: 10.1785/0120060222.

Chen, P., L. Zhao, and T. H. Jordan (2007b). Full 3D Waveform Tomography: A Comparison Between the Scattering-Integral and Adjoint-Wavefield Methods. *Geophys. J. Int.*, 175-181, doi:10.1111/j.1365-246X.2007.03429.x.

Chen, X., and P. M. Shearer (2013). California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett*., **40**, doi:10.1002/grl.50444.

Chen, X. and P. M. Shearer (2011). Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, **116**, doi: 10.1029/2011JB008263.

Chen, X., P. M. Shearer, and R. E. Abercrombie (2102). Spatial migration of earthquakes within seismic clusters in Southern California: Evidence for fluid diffusion, *J. Geophys. Res.*, **117**, B04301, doi: 10.1029/2011JB008973.

Chen Y-H., and C.-C. P.Tsai (2002). A new method for estimation of the attenuation relationship with variance components, *Bull. Seismol. Soc. Am.*, **92**, 1984−1991.

Chester, F. M., Chester, J. S ., Kirschner, D. L., Schulz, S. E., Evans, J. P. (2004). Structure of large-displacement strike-slip fault zones in the brittle continental crust, in: Karner, Gary D., Taylor, Brian, Driscoll, Neal W., Kohlstedt, David L. (eds.), *Rheology and Deformation in the Lithosphere at Continental Margins*, Columbia University Press, New York, *MARGINS Theoretical and Experimental Earth Science Series 1*, 223-260.

Cochran, E., Y.-G. Li, P. Shearer, S. Barbot, Y. Fialko, and J. Vidale (2009). Seismic and geodetic evidence for extensive, long-lived fault damage zones, *Geology*, 37, 315-318, doi:10.1130/G25306A.

COGNOS: Available at *http://www-01.ibm.com/software/analytics/cognos/.*

Cole, J., B. Hacker, L. Ratschbacher, J. Dolan, G. Seward, E. Frost, and W. Frank (2007). Localized ductile shear below the seismogenic zone: Structural analysis of an exhumed strike-slip fault, Austrian Alps, *J. Geophys. Res.,* **112**, B12304, doi:10.1029/2007JB004975.

Colella, H. V., D. L. Schutt, D. F. Sumy, and A. M. Frassetto (2015). Helping early-career researchers succeed, *Eos*, **96**, doi:10.1029/2015EO034965. Published on 8 September 2015.

Cooke, M. (2014). Impact of Fault Geometry within the San Gorgonio Pass on Deformation, *San Gorgonio Pass Special Fault Study Area Workshop,* available at *http://www.scec.org/workshops/*.

ComCat: ANSS Comprehensive Catalog (ComCat), available at *http://earthquake.usgs.gov/earthquakes/map/doc_aboutdata.php.*

CommonCore: Project Open Data Common Core Metadata Specification available at *http://project-open-data.cio.gov.*

CommonData: Common Data Format available at *http://cdf.gsfc.nasa.gov/html/sw_and_docs.html*

Crouse, C. B. (2012). The Role SCEC can play in improving seismic provisions in US codes through ground-motion simulations, *2012 SCEC Annual Meeting.*

Cua, G. B., M. Fischer, T. H. Heaton, and S. Wiemer (2009). Real-time performance of the Virtual Seismologist earthquake early warning algorithm in Southern California, *Seismol. Res. Lett.*, **80**, 740-747, doi:10.1785/gssrl.80.5.740.

Cui, Y., E. Poyraz, S. Callaghan, P. Maechling, P. Chen and T. Jordan (2013). Accelerating CyberShake Calculations on XE6/XK7 Platforms of Blue Waters, *Extreme Scaling Workshop 2013*, August 15-16, Boulder, Colorado.

Cui, Y., E. Poyraz, K. B. Olsen, J. Zhou, K. Withers, S. Callaghan, J. Larkin, C. Guest, D. Choi, A. Chourasia, Z. Shi, S. M. Day, P. J. Maechling, T. H. Jordan (2013). Physics-based seismic hazard analysis on petascale heterogeneous supercomputers, *SC13*, Denver, CO, November 18-21, 2013.

Cummings, J., T. Finholdt, I. Foster, C. Kesselman, and K. A. Lawrence (2008). *Beyond Being There: A Blueprint for Advancing the Design, Development, and Evaluation of Virtual Organizations*, Final Report from Workshops on Building Effective Virtual Organizations, National Science Foundation, May 2008, 58 pp.

Byrne, P. M., S. S. Park, M. Beaty, M. Sharp, L. Gonzalez, and T. Abdoun (2004). Numerical modeling of liquefaction and comparison with centrifuge tests, *Canadian Geotechnical Journal*, **41**, 193-211. Dafalias, Y. F., M. T. Manzari, and A. G. Papadimitriou (2006). SANICLAY: simple anisotropic clay plasticity model, *Int. J. Numerical & Analytical Methods in Geomechanics*, **30**, 1231-1257.

d'Avila, M. P. S., J. F. Semblat, and L. Lenti (2013). Strong ground motion in the 2011 Tohoku Earthquake: A one-directional three-component modeling, *Bull. Seismol. Soc. Am.*, **103**, 1394-1410.

Davis, J. L., Y. Fialko, W. E. Holt, M. M. Miller, S. E. Owen, and M. E. Pritchard (Eds.) (2012), *A Foundation for Innovation: Grand Challenges in Geodesy*, Report from the Long-Range Science Goals for Geodesy Community Workshop, UNAVCO, Boulder, Colorado, 79 pp.

Dawson, T. E., S.F. McGill, and T. K. Rockwell (2003). Irregular recurrence of paleoearthquakes along the central Garlock fault near El Paso Peaks, California, *J. Geophys. Res.*, **108**, doi: 10.1029/2001JB001744.

Day, S. (1998). Effective Simulation of Constant Q Using Coarse-Grained Memory Variables, *Bull. Seismol. Soc. Am.*, 88(4), 1051-1062.

Day, S. M., R. W. Graves, J. Bielak, D. Dreger, S. Larsen, K. B. Olsen, A. Pitarka, and L. Ramirez-Guzman (2008). Model for basin effects on long-period response spectra in southern California, *Earthquake Spectra* **24**, 257-277.

Day, S.M., D. Roten, and K.B. Olsen (2012). Adjoint analysis of the source and path sensitivities of basin-guided waves, *Geophys. J. Int.* , **189**, 1103-1124, doi: 10.1111/j.1365-246X.2012.05416.x.

DeDontney, N., J. R. Rice, and R. Dmowska (2012). Finite element model of branched ruptures including off-fault plasticity, *Bull. Seismol. Soc. Am.*, **102**, 541-562.

Delépine, N., L. Lenti, G. Bonnet, and J. F. Semblat (2009). Nonlinear viscoelastic wave propagation: an extension of Nearly Constant Attenuation models, *J. Eng. Mech.*, **135**, 1305-1314.

Delorey, A. A., A. D. Frankel, P. Liu, and W. J. Stephenson (2014). Modeling the effects of source and path heterogeneity on ground motions of great earthquakes on the Cascadia Subduction Zone using 3D simulations. *Bull. Seismol. Soc. Am.*, **104**, 1430-1446, doi:10.1785/0120130181.

Denolle, M., E. M. Dunham, G. A. Prieto, and G. C. Beroza (2014). Strong ground motion prediction using virtual earthquakes, *Science*, **343**, 399-403, doi:10.1126/science.1245678.

Denolle, M**.**, E. M. Dunham, G. A. Prieto, and G. C. Beroza (2013). Ground motion prediction of realistic earthquake sources using the ambient seismic field, *J. Geophys. Res.*, **118**, 2102-2118, doi:10.1029/2012JB009603.

DeVechio, D. (2013). Precise Fault Slip Rates on the Oak Ridge fault: New age constraints on the Saugus Formation using 36C/10Be isochron burial dating, *SCEC Annual Report*, Award 13105, 10 pp.

Dieterich, J. and D. Smith (2009). Nonplanar faults: mechanics of slip and off-fault damage, *Pure Appl. Geophys.*, **166**, 1799-1815.

Dieterich, J. H., and K. B. Richards-Dinger (2010). Earthquake recurrence in simulated fault systems, *Pure Appl. Geophys.,* **167**, 1087-1104, doi:10.1007/s00024-010-0094-0.

Di Toro, G., D. L. Golbsby, and T. E. Tullis (2004). Friction falls toward zero in quartz rock as slip velocity approaches seismic rates, *Nature*, **427**, 436-439.

Dolan, J.F., Bowman, D.D., and Sammis, C.G. (2007). Long-range and long- term fault interactions in southern California, *Geology*, **35**, 855-858, doi: 10.1130/G23789A.1.

Dolan, J. F., and B. D. Haravitch (2014). How well do surface slip measurements track slip at depth in large strike-slip earthquakes? The importance of fault structural maturity in controlling on-fault slip versus off-fault surface deformation, *Earth Planet. Sci. Lett.*, **388**, 38-47, doi:10.1016/j.epsl.2013.11.043.

Dolan, J. F., L. J. McAuliffe, E. J. Rhodes, S. F. and McGill (2015). Extreme multi-millennial slip rate variations on the Garlock fault, California: Strain super-cycles, time-variable fault strength, and implications for system-level earthquake occurrence, *Earth Planet Sci Lett.,* submitted.

Donnellan, A., J. R. Arrowsmith, and V. Langenheim (2015). Select Airborne Techniques for Mapping and Problem Solving, Applied Geology in California, eds. R. Anderson and H. Ferriz, Association of Engineering Geology, in press.

Doser, D., C. Manduca, D. Rhodes, S. Sempkin, J. Tyburczy, and J. Villalobos (2014). *Broadening Access to the Earth and Environmental Sciences* (workshop report), accessed at *http://serc.carleton.edu/integrate/workshops/broaden_access/report.html*,4/27/2015.

Dreger, D. S., and T. H. Jordan (2015), Introduction to the focus section on validation of the SCEC Broadband Platform V14.3 simulation methods, *Seismol. Res. Lett.,* **86**, 15-16, doi:10.1785/0220140233.

Dreger, D. S., G. C. Beroza, S. M. Day, C. A. Goulet, T. H. Jordan, P. A. Spudich, and J. P. Stewart (2015). Validation of the SCEC broadband platform v14.3 simulation methods using pseudospectral acceleration data. *Seismol. Res. Lett.*, **86**, 39-47, doi:10.1785/0220140118.

Duan, B. C., and D. D. Oglesby (2005). Multicycle dynamics of nonplanar strike-slip faults, *J. Geophys. Res.*, **110**, doi:10.1029/2004JB003298.

Duan, B., and S. M. Day (2008). Inelastic strain distribution and seismic radiation from rupture of a fault kink, *J. Geophys. Res.*, **113**, B12311, doi:10.1029/2008JB005847.

Dunham, E. M., D. Belanger, L. Cong, and J. E. Kozdon (2011). Earthquake ruptures with strongly rate-weakening friction and off-fault plasticity, Part 2: Nonplanar faults, *Bull. Seismol. Soc. Am.*, **101**, 2308-2322, doi:10.1785/0120100076.

Duru, K., and E. M. Dunham (2015). Dynamic earthquake rupture simulations on nonplanar faults embedded in 3D geometrically complex, heterogeneous elastic solids, *J. Comput. Phys.*, in revision.

Ellsworth, W. L. (2013), Injection-induced earthquakes, *Science*, **341**, 581-584, doi:10.1126/science.1225942.

Ely, G., S.M. Day, and J-B. Minster (2010). Dynamic rupture models for the southern San Andreas fault, *Bull. Seismol. Soc. Am.*, **100**, 131-150, doi:10.1785/0120090187.

Erickson, B. A., and E. M. Dunham (2014). An efficient numerical method for earthquake cycles in heterogeneous media: alternating subbasin and surface-rupturing events on faults crossing a sedimentary basin, *J. Geophys. Res.*, **119**, 3290-3316, doi: 10.1002/2013JB010614.

Evans, J. P., M. R. Prante, S. U. Janecke, A. K. Ault, and D. L. Newell (2014). Hot faults: Iridescent slip surfaces with metallic luster document high- temperature ancient seismicity in the Wasatch fault zone, Utah, USA, *Geology*, **42**, 623-626, doi:10.1130/G35617.1.

Fang, Z., and E. M. Dunham (2013). Additional shear resistance from fault roughness and stress levels on geometrically complex faults, *J. Geophys. Res.*, **118**(7), 3642-3654, doi:10.1002/jgrb.50262.

Federal Emergency Management Agency (2008), *HAZUS® MH Estimated Annualized Earthquake Losses for the United States*, FEMA Report 366, Washington, D.C., April, 2008, 53 pp.

FGDC: Federal Geographic Data Committee's "Content Standard for Digital Geospatial Metadata" Version 2 - 1998. (FGDC-STD-001 June 1998) available at *http://www.fgdc.gov/csdgmgraphical/index.html.*

Field, E. H., R. J. Arrowsmith, G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, T. Parsons, P. M. Powers, B.

E. Shaw, W. R. Thatcher, R. J. Weldon, II, and Y. Zeng (2014). Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model, *Bull. Seismol. Soc. Am.*, **104**, 1122-1180, doi:10.1785/0120130164. [Also published in U.S. Geological Survey Open-File Report 2013–1165, 96 p., California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792, *http://pubs.usgs.gov/of/2013/1165/.*]

Field, E. H., G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, Y. Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Y. Zeng (2015). Long-term, time-dependent probabilities for UCERF3, *Bull. Seismol. Soc. Am.*, **105**, 511–543, doi:10.1785/0120140093.

Field, E. H., T. H. Jordan, L. M. Jones, A. J. Michael, and M. L. Blanpied (2015). The potential uses of operational earthquake forecasting (Powell Center workshop report), *Seismol. Res. Lett.*, submitted.

Flesch, L. M., W. E. Holt, A. J. Haines, L. Wen, and B. Shen-Tu (2007). The dynamics of western North America: Stress magnitudes and the relative role of gravitational potential energy, plate interaction at the boundary and basal tractions, *Geophys. J. Int.*, **169**, 866-896.

Frank, W. B., N. M. Shapiro, A. L. Husker, V. Kostoglodov, A. Romanenko, and M. Campillo (2014). Using systematically characterized low-frequency earthquakes as a fault probe in Guerrero, Mexico, *J. Geophys. Res.*, **119**, 7686–7700, doi:10.1002/2014JB011457.

Frankel, A., and J. Vidale (1992). A three-dimensional simulation of seismic waves in the Santa Clara Valley, California, from a Loma Prieta aftershock, *Bull. Seismol. Soc. Am.*, **83**, 1042-1063.

Frohlich, C., and M. Brunt (2013). Earth Planet. Sci. Lett., **379**, 56-63, doi:10.1016/j.epsl.2013.07.025.

Fulton, P. M., E. E. Brodsky, Y. Kano, J. Mori, F. Chester, T. Ishikawa, R. N. Harris, W. Lin, N. Eguchi, S. Toczko, Expedition 343, 343T, and KR13-08 Scientists (2013). Low coseismic friction on the Tohoku-Oki fault determined from temperature measurements, *Science*, **342**, 1214–1217, doi:10.1126/science.1243641.

Gabriel, A. A., J.-P. Ampuero, L. A. Dalguer, and P. M. Mai (2013). Source properties of dynamic rupture pulses with off-fault plasticity, *J. Geophys. Res.*, **118**, 4117-4126.

Gerstenberger, M. C., G. H. McVerry, D. A. Rhoades, M.W. Stirling (2014). Seismic hazard modeling for the recovery of Christchurch, New Zealand, *Earthquake Spectra*, **30**, 17-29.

Getsinger, A. J., G. Hirth, H. Stunitz, and E. T. Goergen (2013). Influence of water on rheology and strain localization in the lower continental crust, *Geophysics, Geochemistry, Geosystems,* **14**, 2247-2264.

Gill, D., P. Small, P. Maechling, T. Jordan, J. Shaw, A. Plesch, P. Chen, E. Lee, R. Taborda, K. Olsen, and S. Callaghan (2014). UCVM: open source framework for 3D seismic velocity models (abstract), *Seismol. Res. Lett.,* **85**, 457.

GITHUB: available at *https://github.com.*

Given, D. D., E. S. Cochran, T. Heaton, E. Hauksson, R. Allen, P. Hellweg, J. Vidale, and P.Bodin (2014). *Technical implementation plan for the ShakeAlert production system: an Earthquake Early Warning system for the West Coast of the United States*. U.S. Geological Survey Open File Report 2014-1097.

Glanz, K., and D. B. Bishop (2010). The role of behavioral science theory in development and implementation of public health interventions. *Annu. Rev. Pub. Health*, **31**, 399-418, doi:10.1146/annurev.publhealth.012809.103604.

Glennie, C., A. Hinojosa, E. Nissen, A. Kusari, M. Oskin, J. R. Arrowsmith, A. Borsa (2014). Optimization of Legacy LiDAR Datasets for Measuring Near-Field Earthquake Displacements, *Geophys. Res. Lett.*, **41**, 3494-3501, doi: 10.1002/2014GL059919.

Global Earthquake Modeling (GEM) Project: *http://www.globalquakemodel.org.*

Glowacka, E., O. Sarychikhina, F. Suarez, F. Alejandro Nava, and R. Mellors (2010). Anthropogenic subsidence in the Mexicali Valley, Baja California, Mexico, and slip on the Saltillo fault, *Environ. Earth Sci.*, **59**, 1515-1524.

Goebel, T. H. W. (2015). Comparing seismicity rates and fluid injection operations in Oklahoma and California: Implications for upper crustal stresses, *The Leading Edge*, Spec. Vol.: *Injection-induced seismicity*, eds. R. Habiger and G. Beroza.

Goebel, T. H. W., T. W. Becker, C. G. Sammis, G. Dresen, and D. Schorlemmer (2014). Off-fault damage and acoustic emission distributions during the evolution of structurally-complex faults over series of stick-slip events, *Geophys. J. Int.*, **197**, 1705-1718.

Goebel, T. H. W., Candela, T., Sammis, C. G., Becker, T. W., Dresen, G., and Schorlemmer, D. (2014). Seismic event distributions and off-fault damage during frictional sliding of saw-cut surfaces with predefined roughness, *Geophys. J. Int.,* **196**, 612-625.

Goebel, T., E. Hauksson, A. Plesch and J. H. Shaw (2014). A comparative study of the seismo-tectonics in the San Gorgonio and Ventura Special Fault Study Areas, *SCEC Annual Meeting*.

Gold, P. O., W. M. Behr, D. Rood, W. D. Sharp, T. K. Rockwell, K. Kendrick, and A. Salin (2015). Holocene geologic slip rate for the Banning strand of the southern San Andreas Fault, southern California. *J. Geophys. Res.*, **120**, doi:10.1002/2015JB012004.

Goldsby, D. L., and T. E. Tullis (2011). Flash heating leads to low frictional strength of crustal rocks at earthquake slip rates. *Science*, **334**, 216–218. doi:10.1126/science.1207902.

Gomberg, J., J. L. Rubinstein, Z. Peng, K. C. Creager, J. E. Vidale, and P. Bodin (2008). Widespread Triggering of Nonvolcanic Tremor in California, *Science,* **319***,* 5860, 10.1126/science.1149164.

Goulet, C. A., N. A. Abrahamson, P. G. Somerville, and K. E. Wooddell (2015). The SCEC Broadband Platform validation exercise: Methodology for code validation in the context of seismic-hazard analyses, *Seismol. Res. Lett.*, **86**, 17-26.

Gover, M., R. Trettevik, G. Hoffman, T. Bachman, S. Dingwall, K. Raines, E. Mattingly, J. Kavetsky, and P. Zheng (2014). GradSuccess 2013-2014 Annual Report, UC Riverside internal report.

Globus: Globus Components for Grid Security available at *http://toolkit.globus.org/grid_software/security/.*

Grant-Ludwig, L., J. N. Brune, A. Anooshehpoor, M. D. Purvance, R. J. Brune, and J. N. Brune (2015). Reconciling precariously balanced rocks (PBRs) with large earthquakes on the San Andreas Fault system, *Seismol. Res. Lett.,* **86**, 1-9, doi: 10.1785/0220140239.

Graves, R.W. (1998). Three-dimensional finite-difference modeling of the San Andreas fault: source parameteriazation and ground-motion levels, *Bull. Seismol. Soc. Am.*, **88**, 881-897.

Graves, R., B. Aagaard, K. Hudnut, L. Star, J. Stewart and T. H. Jordan (2008). Broadband simulations for Mw 7.8 southern San Andreas earthquakes: Ground motion sensitivity to rupture speed, *Geophys. Res. Lett.*, **35**, L22302, doi: 10.1029/2008GL035750.

Graves, R., T. H. Jordan, S. Callaghan, E. Deelman, E. Field, G. Juve, C. Kesselman, P. Maechling, G. Mehta, K. Milner, D. Okaya, P. Small, and K. Vahi (2011). CyberShake: A physics-based probabilistic hazard model for Southern California, *Pure Appl. Geophys.*, **167**, 367-381, doi:10.1007/s00024-010-0161-6.

Gregor, N., N. A. Abrahamson, G. M. Atkinson, D. M. Boore, Y. Bozorgnia, K. W. Campbell, B. S.-J. Chiou, I. M. Idriss, R. Kamai, E. Seyhan, W. Silva, J. P. Stewart, and R. Youngs (2014). Comparison of NGA-West2 GMPEs, *Earthquake Spectra*, **30**(3), 1179–1197.

Guéguen, P., P.-Y. Bard, and J.-F. Semblat (2000). From soil-structure interaction to site-city interaction, *Proc. 12th World Conf. on Earthquake Eng.*, Paper 0555, Auckland, New Zealand.

Guéguen, P., P.-Y. Bard, and F. J. Chávez-García (2002). Site-city seismic interaction in Mexico City-like environments: An analytical study." *Bull. Seismol. Soc. Am.*, **92**, 794-811.

Gueydan, F., Y. M. Leroy, L. Jolivet, P. Agard (2003). Analysis of continental midcrustal strain localization induced by reaction-softening and microfracturing, *J. Geophys. Res.*, 108, 2064-2081, doi:10.1029/2001JB000611.

Hall, J. F., T. H. Heaton, M. W. Halling, and D. J. Wald (1995). Near-source ground motion and its effects on flexible buildings, *Earthquake Spectra*, **11**, 569-605.

Hammond, W. C., G. Blewitt, and C. Kreemer (2011). Block modeling of crustal deformation of the northern Walker Lane and Basin and Range from GPS velocities, *J. Geophys. Res.,* **166**, B04402.

Hammond, W. C., R. Burgette, and K. Johnson (2014). Measuring Ventura Area Uplift: A Four-Technique Geodetic Study of Vertical Tectonics Combining GPS, InSAR, Leveling and Tide Gauges, *SCEC Annual Meeting*, Palm Springs, CA.

Han, R., T. Shimamoto, T. Hirose, J.-H. Ree, and J.-I. Ando (2007). Ultralow friction of carbonate faults caused by thermal decomposition, *Science*, **316**, 878-881, doi:10.1126/science.1139763.

Hardebeck, J. L. (2015). Stress orientation in subduction zones and the strength of subduction megathrust faults, *Science*, **349**, 1213-1216.

Harris, R. A., J. F. Dolan, R. Hartleb, and S.M. Day (2002). The 1999 Izmit, Turkey earthquake - a 3D dynamic stress transfer model of intraearthquake triggering, *Bull. Seismol. Soc. Am.*, **92**, 245-255.

Harris, R. A. and R. J. Archuleta (2004). Seismology: earthquake rupture dynamics: comparing the numerical simulation methods, *Eos*, **85**, 321.

Harris, R. A., M. Barall, D. J. Andrews, B. Duan, S. Ma, E. M. Dunham, A.-A. Gabriel, Y. Kaneko, Y. Kase, B. Aagaard, D. D. Oglesby, J.-P. Ampuero, T. C. Hanks, and N. Abrahamson (2011). Verifying a computational method for predicting extreme ground motion, *Seismol. Res. Lett.*, **82**, 638-644, doi:10.1785/gssrl.82.5.638.

Hartzell, S., A. Leeds, A. Frankel, R. A. Williams, J. Odum, W. Stephenson, and W. Silva(2002). "Simulation of broadband ground motion including nonlinear soil effects for a magnitude 6.5 earthquake on the Seattle fault, Seattle, Washington." *Bull. Seismol. Soc. Am.*, **92**, 831-853.

Hauksson, E., and P. M. Shearer (2006). Attenuation models (Q_P and Q_S) in three dimensions of the Southern California crust: Inferred fluid saturation at seismogenic depths, *J. Geophys. Res.*, **111**, B05302, doi:10.1029/2005JB003947.

Hauksson, E. and W. Yang, and P. M. Shearer (2012). Waveform Relocated Earthquake Catalog for Southern California (1981 to June 2011), *Bull. Seismol. Soc. Am.,* **102**, 5, 2239-2244, doi:10.1785/0120120010.

Hawthorne, J. C. and J.-P. Ampuero (2014). A search for seismic precursors to earthquakes in southern California, *2014 SCEC Annual Meeting*, September, Palm Springs, CA.

HDF5: The HDF Group available at *http://www.hdfgroup.org/HDF5/.*

Hearn, E. H. (2015). Contributions to the SCEC CSM: A finite-element model of the southern California lithosphere, SCEC Annual Report, Award 14023, 8 pp.

Herbert, J. W., and M. L. Cooke (2012). Sensitivity of the southern San Andreas fault system to tectonic boundary conditions, *Bull. Seismol. Soc. Am.*, **105**, 2046-2062, doi: 10.1785/0120110316.

Herbert, J. W., M. L. Cooke, M. Oskin, and O. Difo (2014). How much can off-fault deformation contribute to the slip rate discrepancy within the Eastern California Shear Zone?, *Geology*, **42**, 71-75, doi:10.1130/G34738.1.

Hickman, S. H., and B. Evans (1987). Influence of geometry upon crack healing rate in calcite, *Phys. Chem. Minerals*, **15**, 91-102, doi:10.1007/BF00307614.

Hirose, T., and M. Bystricky (2007). Extreme dynamic weakening of faults [containing serpentine] during dehydration by coseismic shear heating, *Geophys. Res. Lett.*, **34**, L14311, doi:10.1029/2007GL030049.

Holmes, R. R., L. M. Jones, J. C. Eidenshink, J. W.Godt, S. H. Kirby, J. J. Love, C. A. Neal, N. G. Plant, M. L. Plunkett, C. S. Weaver, A. Wein, and S. C. Perry (2012). Natural Hazards Science Strategy—Public Review Release, USGS Open File Report #2012-1088, 75 pp., *http://pubs.usgs.gov/of/2012/1088.*

Huang, Y., J.-P. Ampuero and D. V. Helmberger (2014). Earthquake ruptures modulated by waves in damaged fault zones, *J. Geophys. Res.*, **119**, 3133–3154, doi:10.1002/2013JB010724

Huang, Y. and G. C. Beroza (2015). Temporal variation in the magnitude-frequency distribution during the Guy-Greenbrier earthquake sequence, *Geophys. Res. Lett.*, in press.

Hubbard, J., J. H. Shaw, J. Dolan, T. L. Pratt, L. McAuliffe, and T. K. Rockwell (2014). Structure and seismic hazard of the Ventura Avenue anticline and Ventura fault, California: Prospect for large, multisegment ruptures in the Western Transverse Ranges, *Bull. Seismol. Soc. Am.,* **104**, 1070-1087, doi:10.1785/0120130125.

Huftile, G. J., and R. S. Yeats (1995). Convergence rates across a displacement transfer zone in the western Transverse Ranges, Ventura Basin, California, J*. Geophys. Res*. **100** (B2), 2043–2067.

Humphreys, E. D., and D. Coblentz, D. (2007). North American dynamics and western U.S. Tectonics, *Rev. Geophys.*, **45**, doi:10.1029/2005RG000181.

Huntoon, J. E., and M. J. Lane (2007). Diversity in the geosciences and successful strategies for increasing diversity, *J. Geosci. Educ.*, **55**, 447-457.

Idriss, E. (2011). Use of Vs30 to represent local site conditions, in *Proc. 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion*, August 23-26, 2011, University of Santa Barbara.

IM OSQI 2015-03: U.S. Geological Survey Instructional Memorandum No: IM OSQI 2015-03 Review and Approval of Scientific Data for Release available at *http://www.usgs.gov/usgs-manual/im/IM-OSQI-2015-03.html.*

IM OSQI 2015-01: U.S. Geological Survey Instructional Memorandum No: IM OSQI 2015-01 Scientific Data Management Foundation available at *http://www.usgs.gov/usgs-manual/im/IM-OSQI-2015-01.html.*

IRIS DMC: IRIS DMC Web Services available at *http://service.iris.edu.*

Isbiliroglu, Y. (2013). Coupled Soil-Structure Interaction Effects of Symmetric and Asymmetric Buildings In Urban Regions, *Ph.D., Thesis,* Civil and Environmental Engineering, Carnegie Institute of Technology, Carnegie Mellon University, Pittsburgh, Pennsylvania.

Isbiliroglu, Y., R. Taborda, and J. Bielak (2015). Coupled soil-structure interaction effects of building clusters during earthquakes, *Earthquake Spectra*, **31**, No. 1, 463-500.

Issel, M. L. (2014). *Health Program Planning and Evaluation*, 3rd ed., Jones and Bartlette Publishing, Burlington, MA.

Iwan W. D. (1967). On a class of models for the yielding behaviour of continuous and composite systems, *J. Appl. Mech.*, **34**, 612-617, doi:10.1115/1.3607751.

Jackson, D. (2014). Did someone forget to pay the earthquake bill? (abstract), *Seismol. Res. Lett.*, **85**, 421.

Jeremić, B., G. Jie, M. Preisig, and N. Tafazzoli (2009). Time domain simulation of soil-foundation-structure interaction in non-uniform soils., *Earthquake Eng. Struct. Dyn.* **38**, 699-718.

Jiang, J., and N. Lapusta (2014). Long-term fault behavior at the seismic-aseismic transition: space-time evolution of microseismicity and depth extent of earthquake rupture, *Proc. of the Southern California Earthquake Center (SCEC) Annual Meeting*, Palm Springs, California.

Jiang, J., and N. Lapusta (2015). Variability in earthquake slip and arresting depths in rate-and-state fault models with coseismic weakening, *J. Geophys. Res.*, in preparation.

Johnson, K. M. (2013). Slip rates and off-fault deformation in southern California inferred from GPS data and models, *J. Geophys. Res.*, **118**, 5643–5664.

Johnson, K. M. and J. Fukuda (2010). New methods for estimating the spatial distribution of locked asperities and stress-driven interseismic creep on faults with application to the San Francisco Bay Area, California, *J. Geophys. Res.*, **115**, B12408, doi:10.1029/2010JB007703.

Johnson, K. J., W. C. Hammond, and R. Burgette (2014). Geodetic constraints on shortening, uplift, and fault slip across the Ventura Basin, *SCEC Annual Meeting*, Palm Springs, CA.

Johri, M., E. M. Dunham, M. D. Zoback, and Z. Fang (2014). Predicting fault damage zones by modeling dynamic rupture propagation and comparison with field observations, *J. Geophys. Res.*, **119** 1251-1272, doi:10.1002/2013JB010335.

Jolly, E. J, P. B. Campbell, and L. Perlman (2004). *Engagement, Capacity and Continuity: A Trilogy for Student Success*, Science Museum of Minnesota, St Paul, MN, downloaded from *http://www.smm.org/static/about/ecc_paper.pdf*, 4/24/2015.

Jones, L. M., R. Bernknopf, D. Cox, J. Goltz, K. Hudnut, D. Mileti, S. Perry, D. Ponti, K. Porter, M. Reichle, H. Seligson, K. Shoaf, J. Treiman, and A. Wein (2008). The ShakeOut Scenario: U.S. Geological Survey Open-File Report 2008-1150 and California Geological Survey Preliminary Report 25; *http://pubs.usgs.gov/of/2008/1150/*.

Jordan, T. H. (2014). The prediction problems of earthquake system science, *Seismol. Res. Lett.*, **85**, 767-769, doi:10.1785/0220140088.

Jordan, T. H. (2015). An effective medium theory for three-dimensional elastic heterogeneities, *Geophys. J. Int.*, doi:10.1093/gji/ggv355.

Jordan, T. H., Y.-T. Chen, P. Gasparini, R. Madariaga, I. Main, W. Marzocchi, G. Papadopoulos, G. Sobolev, K. Yamaoka, and J. Zschau (2011). *Operational Earthquake Forecasting: State of Knowledge and Guidelines for Implementation*, Final Report of the International Commission on Earthquake Forecasting for Civil Protection, *Annals Geophys.,* **54**(4), 315-391, doi:10.4401/ag-5350.

Jordan, T. H., and L. M. Jones (2010). Operational earthquake forecasting: some thoughts on why and how, *Seismol. Res. Lett.*, **81**, 571-574, doi:10.1785/gssrl.81.4.571.

Jordan, T. H., W. Marzocchi, A. J. Michael, and M. C. Gerstenberger (2014). Operational earthquake forecasting can enhance earthquake preparedness. *Seismol. Res. Lett.*, **85**, 955-959, doi:10.1785/0220140143.

Jordan, T. H., F. Wang, R. Graves, S. Callaghan, K. B. Olsen, Y. Cui, K. Milner, G. Juve, K. Vahi, J. Yu, E. Deelman, D. Gill, and P. J. Maechling (2015). How much can the total aleatory variability of empirical ground motion prediction equations be reduced using physics-based earthquake simulations? (abstract), *2015 Annual AGU Meeting*.

Kallivokas, L. F., A. Fathi, S. Kucukcoban, K. H. Stokoe, J. Bielak, and O. Ghattas (2013). Site characterization using full waveform inversion, *Soil Dynamics & Earthquake Eng.*, **47**, 62‑82.

Kame, N., J. R. Rice, and R. Dmowska (2003). Effects of prestress state and rupture velocity on dynamic fault branching, *J. Geophys. Res.*, **108**, doi:10.1029/2002JB002189.

Kamerling, M. J., C. C. Sorlien, and C. Nicholson (2003). 3D development of an active, oblique fault system: Northern Santa Barbara Channel, CA (poster), *SSA Annual Meeting*.

Kamerling, M. J. and C. C. Sorlien (1999). Quaternary slip and geometry of the Red Mountain and Pitas Point-North Channel faults, California (abstract), *Eos. Trans. AGU*, **80** 46 (1003).

Kanamori, H., and E. Hauksson (1992). A slow earthquake in the Santa Maria Basin, California, *Bull. Seismol. Soc. Am.*, **82**, 2087-2096.

Kaneko, Y., J.-P. Ampuero, and N. Lapusta (2011). Spectral-element simulations of long-term fault slip: Effect of low-rigidity layers on earthquake-cycle dynamics, *J. Geophys. Res.*, **116**, B10313.

Kaneko, Y. and Y. Fialko (2011). Shallow slip deficit due to large strike-slip earthquakes in dynamic rupture simulations with elasto-plastic off-fault response, *Geophys. J. Int.*, **186**, 1389-1403, 2011.

Kang, J., and B. Duan (2014). Inelastic response of compliant fault zones to nearby earthquaks in three dimensions, *Tectonophysics* , **612-613**, 56-62, doi:10.1016/j.tecton.2013.11.033.

Kano, Y., J. Mori, R. Fujio, H. Ito, T. Yanagidani, S. Nakao, and K. F. Ma (2006). Heat signature on the Chelungpu fault associated with the 1999 Chi-Chi, Taiwan earthquake, *Geophys. Res. Lett.*, **33**, L14306, doi:10.1029/2006GL026733.

Kendrick, K. J., J. C. Matti, and S. A. Mahan (2015). Late Quaternary slip history of the Mill Creek strand of the San Andreas fault in San Gorgonio Pass, Southern California: The role of a subsidiary left-lateral fault in strand switching, *Geol. Soc. Am. Bull.*, **127**, 825-849.

Kham, M., J.-F. Semblat, Pierre-Yves Bard, and P. Dangla (2006). Seismic site–city interaction: main governing phenomena through simplified numerical models, *Bull. Seismol. Soc. Am.*, **96**, 1934-1951.

Kozdon, J. E., and E. M. Dunham (2015). Adaptive mesh refinement for earthquake rupture simulation, *Geophys. Res. Lett.*, in preparation.

Kozdon, J. E., and L. C. Wilcox (2015). Provably stable, general purpose projection operators for high-order finite difference methods, submitted.

King, G. C. P., R. S. Stein, and J. Lin (1994). Static stress changes and the triggering of earthquakes, *Bull. Seismol. Soc. Am.*, **84**, 935-953.

Kramer, S. L., A. J. Hartvigsen, S. S. Sideras, and P. T. Ozener (2011). Site response modeling in liquefiable soil deposits, *Proceedings 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion*, University of California, Santa Barbara, 23-26 August 2011.

Krishnan, S., C. Ji, D. Komatitsch, and J. Tromp (2006a). Performance of two 18-story steel moment-frame buildings in Southern California during two large simulated San Andreas earthquakes, *Earthquake Spectra*, **22**, 1035-1061.

Krishnan, S., C. Ji, D. Komatitsch, and J. Tromp (2006b). Case studies of damage to tall steel moment-frame buildings in Southern California during large San Andreas earthquakes, *Bull. Seismol. Soc. Am.*, **96**, 1523-1537.

Kuyuk, H. S., R. M. Allen, H. Brown, M. Hellweg, I. Henson, and D. Neuhauser (2014). Designing a network-based earthquake early warning algorithm for California: ElarmS-2., *Bull. Seismol. Soc. Am.*,, **104**, 162-173, doi:10.1785/0120130146.

Lachenbruch, A. H. (1980). Frictional heating, fluid pressure, and the resistance to fault motion, *J. Geophys. Res.*, 85, 6097-6122.

Lachenbruch, A.H., and Sass, J.H. (1980). Heat flow and energetics of the San Andreas fault zone, *J. Geophys. Res.*, **85**, 6185–6223.

Lapusta, N., and J. Jiang (2014). Long-Term Fault Slip in Models With Coseismic Weakening: Depth Extent and Spatio-Temporal Complexity of Earthquake Ruptures, *Proc. of the American Geophysical Union Fall Meeting*, San Francisco, California.

Lapusta, N., J. R. Rice, Y. Ben-Zion, and G. Zheng (2000). Elastodynamic analysis for slow tectonic loading with spontaneous rupture episodes on faults with rate- and state-dependent friction, *J. Geophys. Res.*, **105**, 23765-23789.

Lapusta, N, and Y. Liu (2009). Three-dimensional boundary integral modeling of spontaneous earthquake sequences and aseismic slip, *J. Geophys. Res.*, **114**, doi:10.1029/2008JB005934.

Lay, T., ed. (2009). *Seismological Grand Challenges in Understanding Earth's Dynamic Systems*, Report to the National Science Foundation, IRIS Consortium, 76 pp.

Le Pourhiet, L., B. Huet, and N. Traoré (2014). Links between long-term and short-term rheology ofthe lithosphere: Insights from strike-slip fault modelling, *Tectonophysics*, **631**, 146-159.

Lee, E., H. Huang, J. M. Dennis, P. Chen and L. Wang (2013). An optimized parallel LSQR algorithm for seismic tomography, *Computers & Geosciences*, **61**, 184-197.

Lee, E.-J. and P. Chen (2013). Automating seismic waveform analysis for full 3-D waveform inversions, *Geophysical Journal International*, **194**, 572-589, doi: 10.1093/gji/ggt124.

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

Li, Y.-G., G. P. De Pascale, M. C. Quigley, and D. M. Gravley (2014). Fault damage zones of the M7.1 Darfield and M6.3 Christchurch earthquakes characterized by fault-zone trapped waves, *Tectonophysics*, **618**, 79-101.

Lin, P.-S., Chiou B., Abrahamson N.A., Walling M., Lee C.-T., Cheng, C.-T. (2011). Repeatable source, site, and path effects on the standard deviation for empirical ground-motion prediction models, *Bull. Seismol. Soc. Am.*, **101**, 2281-2295.

Lindsey, E. O., Y. Fialko, Y. Bock, D. T. Sandwell, and R. Bilham (2014), Localized and distributed creep along the southern San Andreas Fault, *J. Geophys. Res.*, **119**, 7909-7922, doi:10.1002/2014JB011275.

Lieou, C. K. C., A. E. Elbanna, and J. M. Carlson (2014). Grain fragmentation in sheared granular flow: Weakening effects, energy dissipation, and strain localization, *Phys. Rev. E*, **89**, 022203.

Lindsey, E. O., Y. Fialko, Y. Bock, D. T. Sandwell, and R. Bilham (2014). Localized and distributed creep along the southern San Andreas Fault, *J. Geophys. Res.*, **119**, 7909-7922, doi:10.1002/2014JB011275.

Lindsey, E., V. Sahakian, Y. Fialko, Y. Bock, S. Barbot, and T. Rockwell (2014). Interseismic strain localization in the San Jacinto fault zone, *Pure Appl. Geophys.*, **171**, 2937-2954.

Liu, Z. (2014). *Rupture Dynamics of Strike-Slip Faults with Stepovers: From Conceptually Simplified to Realistically Complex Fault Systems* (Ph.D thesis), Texas A&M University, 107 pp.

Liu, Z., and Z.-K. Shen (2015) Improve and integrate InSAR deformation map with GPS towards improved Community Geodetic Model, *SCEC Annual Report*, Award 14102, 5 pp.

Llenos, A. L. and J. J. McGuire (2011). Detecting aseismic strain transients from seismicity data, *J. Geophys. Res.,* **116**, B06305, doi:10.1029/2010JB007537.

Loth, C., and J. W. Baker (2013). A spatial cross-correlation model of ground motion spectral accelerations at multiple periods, *Earthquake Engineering & Structural Dynamics*, **42**, 397-417.

Lohman, R. B., and J. R. Murray (2013). The SCEC geodetic transient-detection validation exercise, *Seismol. Res. Lett.*, **84**, 419-425.

Loveless, J. P., and B. J. Meade (2011). Stress modulation on the San Andreas fault due to interseismic fault system interactions, *Geology,* **39**, 1035-1038, doi:10.1130/G32215.1.

Lozos, J. C., J. H. Dieterich, and D. D. Oglesby (2014). The effects of d_o on rupture propagation on fault stepovers, *Bull. Seismol. Soc. Am.,* 10.1785/0120130305.

Lozos, J. C., D. D. Oglesby, B. Duan, and S. G. Wesnousky (2011). The effects of double fault bends on rupture propagation: a geometrical parameter study, *Bull. Seismol. Soc. Am.*, **101**, doi:10.1785/0120100029.

Lozos, J. C., D. D. Oglesby, J. N. Brune, and K. B. Olsen (2012). Small intermediate fault segments can either aid or hinder rupture propagation at stepovers, *Geophys. Res. Lett.,* **39**, 10.1029/2012GL053005.

Lozos, J., D.D. Oglesby, J. Brune, and K.B. Olsen (2015). Rupture and ground ‐ motion models on the northern San Jacinto Fault, incorporating realistic complexity, *Bull. Seismol. Soc. Am.*, **105**, 1931-1946, doi:10.1785/0120140327.

Lozos, J., K. B. Olsen, J. Brune, R. Takedatsu, R. Brune, and D. D. Oglesby (2015). Broadband ground motions from dynamic models of rupture on the northern San Jacinto fault, and comparison with precariously balanced rocks, *Bull. Seismol. Soc. Am.*, **105**, 1947-1960, doi:10.1785/0120140328.

Luco, N., T.H. Jordan, and S. Rezaeian (2013). Progress of the Southern California Earthquake Center Technical Activity Group on Ground Motion Simulation Validation (abstract), *Seismol. Res. Lett.*, **84**, 336.

Luttrell, K., D. Sandwell, B. Smith-Konter, B. Bills, and Y. Bock (2007). Modulation of the earthquake cycle at the southern San Andreas fault by lake loading, *J. Geophys. Res.*, **112**, B08411, doi:10.1029/2006JB004752.

Luttrell K., B. Smith-Konter, and D. Sandwell (2012). Investigating absolute stress in southern California: How well do stress models of compensated topography and fault loading match earthquake focal mechanisms?, *2012 SCEC Annual Meeting*, Poster 039.

Lyakhovsky, V. and Y. Ben-Zion (2014). Damage-breakage rheology model and solid-granular transition near brittle instability, *J. Mech. Phys. Solids*, **64**, 184-197.

M-07-16: Safeguarding Against and Responding to the Breach of Personally Identifiable Information, Clay Johnson III, Deputy Director for Management available at *https://www.whitehouse.gov/sites/default/files/omb/memoranda/fy2007/m07-16.pdf.*

M-13-13: OMB Memorandum M-13-13 Open Data Policy-Managing Information as an Asset available at *https://project-open-data.cio.gov/policy-memo.*

Ma, S., R. J. Archuleta, and M. T. Page (2007), Effects of large-scale surface topography on ground motions, as demonstrated by a study of the San Gabriel Mountains, Los Angeles, California, *Bull. Seismol. Soc. Am.*, **97**, 2066-2079, doi:10.1785/0120070040.

Ma, S. (2008), A physical model for widespread near-surface and fault zone damage induced by earthquakes: *Geochem. Geophys. Geosyst.*, **9**, Q11009, doi:10.1029/2008GC002231.

Ma, S. (2009), Distinct asymmetry in rupture-induced inelastic strain across dipping faults: *Geophys. Res. Lett.*, **36**, L20317, doi:10.1029/2009GL040666.

Ma, S., and D. J. Andrews (2010). Inelastic off-fault response and three-dimensional dynamics of earthquake rupture on a strike-slip fault, *J. Geophys. Res.*, **115**, B04304, doi:10.1029/2009JB006382.

Main, I. G., L. Li, K. J. Heffer, O. Papasouliotis, and T. Leonard (2006). Long-range, critical-point dynamics in oil field flow rate data, *Geophys. Res. Lett.*, **33**, L18308-5.

Marinkovic, P. and Y. Larsen (2013). Consequences of Long-Term ASAR Local Oscillator Frequency Decay - an Empirical Study of 10 Years of Data, *ESA Living Planet Symposium 2013*, Sep 9-13, Edinburgh, UK.

Marshall, S. T., G. J. Funning, and S. E. Owen (2014). The Distribution of Fault Slip Rates in the Ventura Fault System, CA, *2014 SCEC Annual Meeting*, Palm Springs, CA.

Marzocchi, W., and T. H. Jordan (2014), Testing for ontological errors in probabilistic forecasts of natural systems, *Proc. Nat. Acad. Sci.*, **111**, 11973-11978, doi/10.1073/pnas.1410183111.

Marzocchi, W., A. M. Lombardi and E. Casarotti (2014). The establishment of an operational earthquake forecasting system in Italy, *Seismol. Res. Lett.*, **85**, p. 961-969, doi:10.1785/0220130219.

Mase, C. W., and L. Smith (1987). Effects of frictional heating on the thermal, hydrologic, and mechanical response of a fault, *J. Geophys. Res.*, **92**, 6249-6272.

Mason, H. B., N. W. Trombetta, Z. Chen, J. D. Bray, T. C. Hutchinson, and B. L. Kutter (2013). Seismic soil–foundation–structure interaction observed in geotechnical centrifuge experiments, *Soil Dynamics and Earthquake Engineering*, **48**, 162-174.

Matasovic, N., and Vucetic, M. (1995). Generalized cyclic degradation pore pressure generation model for clays, *J. Geotech. Eng.*, **121**, 33-42.

Mayne, P. W. (2007). *Cone Penetration Testing*, v. 368, Transportation Research Board, National Academy of Sciences, Washington DC.

Mayoral Seismic Safety Task Force (2015). *Resilience by Design*, Office of the Mayor of Los Angeles, December, 2015, 123 pp.

McAuliffe, L. J., J. F. Dolan, E. Kirby, C. Rollins, B. Haravitch, S. Alm, and T. M. Rittenour (2013). Paleoseismology of the Southern Panamint Valley Fault: Implications for Regional Earthquake Occurrence and Seismic Hazard in Southern California, *J. Geophys. Res.*, **118**, 5126–46. doi:10.1002/jgrb.50359.

McAuliffe, L., J. F. Dolan, E. Rhodes, J. Hubbard, J. H. Shaw, and T. Pratt (2015). Characterizing the recent behavior and earthquake potential of the blind Ventura fault system, *Geosphere*, in revision.

McCaffrey, R. (2005). Block kinematics of the Pacific-North America plate boundary in the southwestern United States from inversion of GPS, seismological, and geologic data, *J. Geophys. Res.*, **110**, B07401, doi:10.1029/2004JB003307.

McGarr, A. (2014). Maximum magnitude earthquakes induced by fluid injection. *J. Geophys. Res.*, **119**, 1008-1019.

McGill, S., L. Owen, R. J. Weldon, and K. Kendrick (2013). Latest Pleistocene and Holocene slip rate for the San Bernardino strand of the San Andreas fault, Plunge Creek, Southern California: Implications for strain partitioning within the southern San Andreas fault system for the last ~35 k.y., *Geol. Soc. Am. Bull.*, **125** (1/2), 48-72, doi: 10.1130/B30647.1.

McGill, S. F., J. C. Spinler, J. D. McGill, R. A. Bennett, M. A. Floyd, J. E. Fryxell, and G. Funning (2015). Kinematic modeling of fault slip rates using new geodetic velocities from a transect across the Pacific‐North America plate boundary through the San Bernardino Mountains, California. *J. Geophys. Res.*, **120**, 2772-2793, doi: 10.1002/2014JB011459.

McKenzie, J. F., B. L. Neiger, and R. Thackeray (2013). *Planning, Implementing, and Evaluating Health Promotion Programs*, 6th ed., Pearson Education, Boston.

Meng, L., H. Huang, R. Burgmann, J.-P. Ampuero and A. Strader (2014). Aseismic slow-slip and dynamic ruptures of the 2014 Iquique earthquake sequence, *Proc. of the Southern California Earthquake Center (SCEC) Annual Meeting*, Palm Springs, California.

Meng, X., and Z. Peng (2014). Seismicity rate changes in the Salton Sea Geothermal Field and the San Jacinto Fault Zone after the 2010 *M*w 7.2 El Mayor-Cucapah earthquake, *Geophys. J. Int.*, **197,** 1750-1762, doi: 10.1093/gji/ggu085.

Meng, X., X. Yu, Z. Peng and B. Hong (2012). Detecting earthquakes around Salton Sea following the 2010 Mw7.2 El Mayor-Cucapah earthquake using GPU parallel computing, *Procedia Computer Science*, **9**, 937-946.

Mileti, D. S., and P. W. O'Brien (1991). *Public Response to the Loma Prieta Earthquake Emergency and Aftershock Warnings: Findings and Lessons*, Hazards Assessment Laboratory, Colorado State University, Fort Collins, CO.

Mileti, D. S., R. Bandy, L. B. Bourque, A. Johnson, M. Kano, L. Peek, L., and M. Wood (2006). *Annotated Bibliography for Public Risk Communication on Warnings for Public Protective Actions Response and Public Education (Revision 5)*, National Hazards Institute, University of Colorado, Boulder, CO.

Miller, M. S., P. Zhang, D. Okaya, and J. F. Dolan (2014). Moho structure across the San Jacinto fault zone: insights into strain localization at depth, *Lithosphere*, **6**, 43-47.

Milliner, C., J. Dolan, J. Hollingsworth, S. Leprince, F. Ayoub, and C. Sammis (2015). Quantifying near-field and off-fault deformation patterns of the 1992 Mw 7.3 Landers earthquake, *Geochem. Geophys. Geosyst.*, **16**, 1577-1598, doi:10.1002/2014GC005693.

Milner, K. R., T. H. Jordan, The Working Group on California Earthquake Probabilities, and The CyberShake Collaboration (2015). Operational earthquake forecasting in California: A prototype system combining UCERF3 and CyberShake (abstract), *Seismol. Res. Lett.*, **86**, 591, doi:10.1785/0220150017.

Montési, L. G. J. (2013). Fabric development as the key for forming ductile shear zones and enabling plate tectonics, *J. Struct. Geol.*, **50**, 254-266.

Morelan, A., M. Oskin, J. Chester and D. Elizondo (2014). Active Dextral Slip on the Mill Creek fault through San Gorgonio Pass, *2014 SCEC Annual Meeting*.

Mu, D., P. Chen and L. Wang (2013). Accelerating the discontinuous Galerkin method for seismic wave propagation simulations using the graphic processing unit (GPU): single GPU implementation, *Computers and Geosciences*, **51**, 282-292.

Mu, D., P. Chen and L. Wang (2013). Accelerating the discontinuous Galerkin method for seismic wave propagation simulations using multiple GPUs with CUDA and MPI, *Earthquake Science*, **26**, 6, 377-393.

Murphy, J. M., G. S. Fuis, T. Ryberg, W. J. Lutter, R. D. Catchings, and M. R. Goldman, (2010). Detailed P- and S-Wave Velocity Models along the LARSE II Transect, Southern California, *Bull. Seismol. Soc. Am.*, **100**, p. 3194-3212, doi:10.1785/0120090004.

Muto, M., and S. Krishnan (2011). Hope for the best, prepare for the worst: response of tall steel buildings to the ShakeOut scenario earthquake, *Earthquake Spectra*, **27**, 375, doi:10.1193/1.3563621.

Mylonakis, G., and G. Gazetas (2000). Seismic soil-structure interaction: Beneficial or detrimental, *J. Earthquake Engineering*, **4**, 377-401.

Nakata, N., J. P. Chang, J. F. Lawrence, and P. Boué (2015). Body-wave extraction and tomography at Long Beach, California, with ambient-noise tomography, *J. Geophys. Res.*, **120**, 1159-1173, doi:10.1002/2015JB01870.

National Research Council Committee on National Earthquake Resilience (2011). *National Earthquake Resilience: Research, Implementation, and Outreach*, National Academies Press, Washington, D.C., ISBN:978-0-309-18677-3, 198 pp.

National Research Council Committee on Increasing National Resilience to Hazards and Disasters (2012). *Disaster Resilience: A National Imperative*, National Academies Press, Washington, D.C., ISBN:978-0-309-26150-0. 260 pp.

National Research Council Committee on New Research Opportunities in the Earth Sciences at the National Science Foundation (2012). *New Research Opportunities in the Earth Sciences*, National Academies Press, Washington, D.C., ISBN: 978-0-309-21924-2, 117 pp.

National Science and Technology Council Committee on Environment and Natural Resources (2005). *Grand Challenges for Disaster Reduction*, Report of the Subcommittee on Disaster Reduction, June, 2005, 21 pp.

National Science Foundation (2012). *Diversity and Inclusion Strategic Plan, 2012-2016*, National Science Foundation, Washington DC, 22 pp.

Natural Hazards Engineering Research Infrastructure (NHERI) Program website: *http://www.designsafe-ci.org/.*

NEHRP Consultants Joint Venture (2012). *Soil-Structure Interaction for Building Structures*, NIST GCR 12-917-21, U.S. Department of Commerce, Washington DC, 292 pp.

NetCDF: Network Common Data Form (NetCDF) available at *http://www.unidata.ucar.edu/software/netcdf/.*

Networking and Information Technology Research and Development (2012). *Program 2012 Strategic Plan*, Executive Office of the President National Science and Technology Council, July, 2012.

NHERI: Natural Hazards Engineering Research Infrastructure (NHERI) Network Coordination Office, Computational Modeling and Simulation Center, and Post-Disaster, Rapid Response Research Facility available at *http://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf15598.*

Nicholson, C. (2014). Assessing Fault Geometry from Seismicity, *San Gorgonio Pass Special Fault Study Area Workshop,* available at *http://www.scec.org/workshops/*.

Nicholson, C., A. Plesch, C. C. Sorlien, J. H. Shaw, and E. Hauksson (2014). The SCEC 3D Community Fault Model (CFM Version 5.0): An updated and expanded fault set of oblique crustal deformation and complex fault interaction for southern California (abstract), *Eos*, 95, T31B-4585.

Nissen, E., A. K. Krishnan, J. R. Arrowsmith, and S. Saripalli (2012). Three-dimensional surface displacements and rotations from differencing pre- and post-earthquake Lidar point clouds, *Geophys. Res. Lett.*, **39**, L16301, doi:10.1029/2012GL052460.

Nissen, E., T. Maruyama, J. R. Arrowsmith, J. R. Elliott, A. K. Krishnan, M. E. Oskin, and S. Saripalli (2014). Coseismic fault zone deformation revealed with differential LiDAR: examples from Japanese Mw 7 intraplate earthquakes, *Earth Planet. Sci. Lett.*, **405**, 244-256, doi: 10.1016/j.epsl.2014.08.031.

NIST (2012). *Soil-Structure Interaction for Building Structures*, NIST GCR 12-917-21, National Institute of Standards and Technology, U.S. Department of Commerce, Washington D.C.; available at http:/*/www.nehrp.gov/pdf/nistgcr12-917-21.pdf*.

Noda, H., E. M. Dunham, and J. R. Rice (2009), Earthquake ruptures with thermal weakening and the operation of major faults at low overall stress levels, *J. Geophys. Res.*, **114**, B07302, doi:10.1029/2008JB006143.

Noda, H., and N. Lapusta (2010). Three-dimensional earthquake sequence simulations with evolving temperature and pore pressure due to shear heating: Effect of heterogeneous hydraulic diffusivity, Journal of Geophysical Research, **115**, B12314, doi:10.1029/2010JB007780.

Noda, H., & Lapusta, N. (2013). Stable creeping fault segments can become destructive as a result of dynamic weakening. *Nature*, **493**, 518-21. doi:10.1038/nature11703.

NSF Advisory Committee for Geosciences (2009). *Geovision Report: Unraveling Earth's Complexities through the Geosciences*, National Science Foundation, October, 2009, 39 pp.

NSF Advisory Committee for Geosciences (2014). *Dynamic Earth: GEO Imperatives & Frontiers 2015–2020*, National Science Foundation, Washington, D.C., December, 2014, 36 pp.

Oglesby, D. D. (2005). The dynamics of strike-slip stepovers with linking dip-slip faults, *Bull. Seis-mol. Soc. Am.*, **95**, 1604-1622.

Olsen, K.B. (2000). Site amplification in the Los Angeles Basin from 3D modeling of ground motion, *Bull. Seis. Soc. Am.* **90**, S77-S94.

Olsen, K. B., S. M. Day, J. B. Minster, Y. Cui, A. Chourasia, M. Faerman, R. Moore, P. Maechling, and T. Jordan (2006). Strong shaking in Los Angeles expected from southern San Andreas earthquake, *Geophys. Res. Lett.*, **33**, L07305, doi:10.1029/2005GL025472.

Olsen, K. B., S. M. Day, J. B. Minster, Y. Cui, A. Chourasia, D. Okaya, P. Maechling, and T. H. Jordan (2008). TeraShake2: Spontaneous rupture simulations of Mw 7.7 earthquakes on the southern San Andreas fault, *Bull. Seismol. Soc. Am.*, **98**, 1162-1185, doi:10.1785/0120070148.

Olsen, K. B., S. M. Day, L. A. Dalguer, J. Mayhew, Y. Cui, J. Zhu, V. M. Cruz-Atienza, D. Roten, P. Maechling, T. H. Jordan, D. Okaya, and A. Chourasia (2009), ShakeOut-D: Ground motion estimates using an ensemble of large earthquakes on the southern San Andreas fault with spontaneous rupture propagation, *Geophys. Res. Lett.*, **36**, L04303, doi:10.1029/2008GL036832.

Olsen, K. B. (2014). *Statistical modeling of shallow velocity heterogeneities with validation against strong ground motion*, Final Technical Report for USGS award G12AP20015.

Onderdonk, N., S. F. McGill, and T. K. Rockwell (2015). Short-term variations in slip rate and size of prehistoric earthquakes during the past 2000 years on the northern San Jacinto fault zone, a major plate-boundary structure in southern California, *Lithosphere*, **7**, 211-234.

OpenData: Project Open Data Metadata Schema v1.1 available at *https://project-open-data.cio.gov/v1.1/schema/.*

ORCID: Open Researcher and Contributor ID available at *http://orcid.org.*

O'Reilly, O., J. Nordstrom, J. E. Kozdon, and E. M. Dunham (2015). Simulation of earthquake rupture dynamics in complex geometries using coupled finite difference and finite volume methods, *Communications in Computational Physics*, **17**(2), 337-370, doi:10.4208/cicp.111013.120914a.

O'Rourke T.D. (2007). Critical infrastructure, interdependencies, and resilience, *The Bridge*, **37**, 22-29.

O'Rourke, T. D., S. Toprak, and Y. Sano (1998). Factors affecting water supply damage caused by the Northridge earthquake, in *Proceedings, 6th U.S. National Conference on Earthquake Engineering*, Seattle, WA, 12 pp.

O'Rourke, T. D., S.-S. Jeon, S. Toprak, M. Cubrinovski, M. Hughes, S. van Ballegooy, and D. Bouziou (2014). Earthquake response of underground pipeline networks in Christchurch, NZ, *Earthquake Spectra*, **30**, 183-204.

Oskin, M., J. Arrowsmith, C. Hinojosa, A. Elliot, J. Fletcher, E. Fielding, P. Gold, J. Gonzalez, K. Hudnut, J. Liu-Zeng, O. Teran (2012). Near-field deformation from the El Mayor-Cucapah earthquake revealed by differential LiDAR, *Science*, **335**, 702-705, doi:10.1126/science.

OSTP 2013-2: President's Office of Science and Technology Policy (OSTP) Memorandum, Increasing Access to the Results of Federally Funded Scientific Research, February 23, 2013, available at *https://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf.*

Pacific Earthquake Engineering Research (PEER) Center website: *http://peer.berkeley.edu/.*

Park, D., and Y. M. Hashash (2004). Soil damping formulation in nonlinear time domain site response analysis, *J. Earthquake Eng.,* **8**, 249-274.

Papadimitriou, A. G., G. D. Bouckovalas, and Y. F. Dafalias (2011). Plasticity model for sand under small and large cyclic strains, *J. Geotech. Geoenviron. Eng.*, **127**, 973-83.

Parsons, T. (2006). Tectonic stressing in California modeled from GPS observations, *J. Geophys. Res.*, **111**, doi:10.1029/2005JB003946.

Pelties, C., A. A. Gabriel and J.-P. Ampuero (2014). Verification of an ADER-DG method for complex dynamic rupture problems, *Geosci. Model Dev.*, **7**, 847-866, doi:10.5194/gmd-7-847-2014.

Pitarka, A., H. K. Thio, P.I Somerville, and L. F. Bonilla (2013). Broadband ground‐motion simulation of an intraslab earthquake and nonlinear site response: 2010 Ferndale, California, earthquake case study, *Seismol. Res. Lett.*, **84**, 785-795.

Platt, J. D., N. Brantut, and J. R. Rice (2014). Strain localization driven by thermal decomposition during seismic shear, *J. Geophys. Res.*, submitted.

Platt, J. D., J.W. Rudnicki, and J.R. Rice (2014). Stability and localization of rapid shear in fluid-saturated fault gouge, 2. Localized zone width and strength evolution, *J. Geophys. Res.*, **119**, doi: 10.1002/2013JB010711.

Platt, J. P., and W. M. Behr (2011). Grainsize evolution in ductile shear zones: implications for strain localization and the strength of the lithosphere, *J. Struct. Geol.*, **33**, 537-550.

Plesch, A., J. H. Shaw, C. Benson, W. A. Bryant, S. Carena, M. Cooke, J. Dolan, G. Fuis, E. Gath, L. Grant, E. Hauksson, T. H. Jordan, M. Kamerling, M. Legg, S. Lindvall, H. Magistrale, C. Nicholson, N. Niemi, M. Oskin, S. Perry, G. Planansky, T. Rockwell, P. Shearer, C. Sorlien, M. P. Süss, J. Suppe, J. Treiman, and R. Yeats (2007). Community Fault Model (CFM) for Southern California, *Bull. Seismol. Soc. Am.*, **97**, 1793-1802, doi 10.1785/0120050211.

Pollitz, F. F. (2012). ViscoSim earthquake simulator, *Seismol. Res. Lett.*, 83, 979-982.

Power, M., B. Chiou, N. A. Abrahamson, Y. Bozorgnia, T. Shantz, and C. Roblee (2008). An overview of the NGA project, *Earthquake Spectra*, **24**, 3-21.

Powers, P., and T. H. Jordan (2010). Seismicity distribution across strike-slip faults in California, *J. Geophys. Res.*, **115**, B05305, doi:10.1029/2008JB006234.

Presidential Policy Directive 8 (2011). http://www.dhs.gov/presidential-policy-directive-8-national-preparedness.

Proctor, B. P., T. M. Mitchell, G. Hirth, D. Goldsby, F. Zorzi, J. D. Platt, and G. Di Toro (2014). Dynamic weakening of serpentinite gouges and bare surfaces at seismic slip rates, *J. Geophys. Res.*, **119**, 8107–8131, doi: 10.1002/2014JB011057.

Qiu, H., Y. Ben-Zion, Z. E. Ross, P.-E. Share and F. Vernon (2015). Internal structure of the San Jacinto fault zone at Jackass Flat from data recorded by a dense linear array, *Proc. of the Seismological Society of America Annual Meeting*, Pasadena, California.

Raleigh, C. B., J. H. Healy, and J. D. Bredehoeft (1976). Experiment in earthquake control at Rangely, Colorado, *Science*, **191**, 1230-1237.

Ramirez-Guzman, L., R. W. Graves, K. B. Olsen, O.S. Boyd, C. Cramer, S. Hartzell, S. Ni, P. Somerville, R. A. Williams, and J. Zhong (2015). Ground ‐ motion simulations of 1811–1812 New Madrid earthquakes, central United States, *Bull. Seismol. Soc. Am.*, **105**, 1961-1988, doi:10.1785/0120140330.

Régnier, J., L.F. Bonilla, E. Bertrand, and J.F. Semblat (2014). Influence of the Vs profiles beyond 30 m depth on linear site effects: assessment from the KiK‐net data, *Bull. Seismol. Soc. Am.*, **104**, 2337-2348.

Rhoades, D. A., M. C. Gerstenberger, A. Christophersen and M. Liukis (2013). Utilising short-term and medium-term forecasting models for earthquake hazard estimation in the wake of the Canterbury earthquakes, *GNS Science Consultancy Report* 2013/141, 52 pp.

Rhodes, E. (2015) Optically Stimulated Luminescence Dating of Sediments over the Past 200,000 Years, *Ann. Rev. Earth and Planet. Sci.*, **39**, 461–488, do: 10.1146/annurev-earth-040610-133425.

Rice, J. R. (1999). Flash heating at asperity contacts and rate-dependent friction, *Eos*, **80**, F681l.

Rice, J. R. (2006). Heating and weakening of faults during earthquake slip, *J. Geophys. Res.*, **111**, B05311, doi:10.1029/2005JB004006.

Rice, J. R., C. G. Sammis, and R. Parsons (2005). Off-fault secondary failure induced by a dynamic slip-pulse, *Bull. Seismol. Soc. Am.*, **95**, 109-134, doi 10.1785/0120030166.

Rice, J. R., J. W. Rudnicki, and J. D. Platt (2014). Stability and localization of rapid shear in fluid-saturated fault gouge, 1. Linearized stability analysis, *J. Geophys. Res.*, **119**, 4311-4333, doi: 10.1002/2013JB010711.

Richards-Dinger, K., and J. H. Dieterich (2012). RSQSim earthquake simulator, *Seism. Res. Lett.*, **83**, 983-990.

Rittase, W. M., E. Kirby, E. McDonald, J. D. Walker, J. Gosse, J. O.G. Spencer, and A. J. Herrs (2014). Temporal variations in Holocene slip rate along the central Garlock fault, Pilot Knob Valley, California**,** *Lithosphere,* **6**, 48-58, doi: 10.1130/L286.1.

Roder, B., M. Lawson, E. Rhodes, J. Dolan, L. McAuliffe, and S. McGill (2011). Assessing the potential of luminescence dating for fault slip rate studies on the Garlock Fault, Mojave Desert, California, USA, *Quaternery Geochronology,* **10**, 285-290.

Rodriguez-Marek, A., G. A. Montalva, F. Cotton, and F. Bonilla (2013). A model for single-station standard deviation using data from various tectonic regions, *Bull. Seismol. Soc. Am.*, **103**, 3149 🎗3163.

Rockwell, T. K. (2011). Large co-seismic uplift of coastal terraces across the Ventura Avenue anticline: Implications for the size of earthquakes and the potential for tsunami generation, plenary talk, *2011 SCEC Annual Meeting*, Palm Springs, CA.

Rockwell, T. K. (2013). Documentation of tsunami deposits in the Carpenteria Estuary: A signal of great earthquakes on the Pitas Point thrust, *2013 SCEC Annual Report*, Award 13008, 6 pp..

Rockwell, T. K., T. E. Dawson, J. Y. BenHorin, and G. Seitz (2015). A 21-Event, 4,000-Year History of Surface Ruptures in the Anza Seismic Gap, San Jacinto Fault, and Implications for Long-term Earthquake Production on a Major Plate Boundary Fault, *PAGEOPH*, **172**, 1143–1165, doi:10.1007/s00024-014-0955-z.

Rockwell, T. K., E. A. Keller, and G. R. Dembroff (1988). Quaternary rate of folding of the Ventura Avenue anticline, western Transverse Ranges, southern California, *GSA Bull.*, **100**, 850–858.

Rockwell, T., K. Scharer, and T. Dawson (2015). Earthquake Geology and Paleoseismology of Major Strands of the San Andreas Fault System, *in* Anderson R.L, and Ferriz, R., *Applied Geology in California*, Association of Environmental and Engineering Geology Special Publication Number 26, Star Publishing Company, Menlo Park California, in press.

Roten, D., K. B. Olsen, S. M. Day, Y. Cui, and D. Fäh (2014). Expected seismic shaking in Los Angeles reduced by San Andreas fault zone plasticity, *Geophys. Res. Lett.*, **41**, 2769-2777, doi:10.1002/2014GL059411.

Rundle, P. B., J. B. Rundle, K. F. Tiampo, A. Donnellan, and D. L. Turcotte (2006). Virtual California: Fault model, frictional parameters, applications, *Pure Appl. Geophys.*, **163**, 1819-1846.

Ryan, K. J., D. D. Oglesby, and E. L. Geist (2014). Modeling earthquake rupture on the Pitas Point fault: Implications for tsunami generation and propagation, *2014 SCEC Annual Meeting*.

Ryberg, T., J. A. Hole, G. S. Fuis, M. J. Rymer, F. Bleibinhaus, D. Stromeyer, and K. Bauer (2012). Tomographic Vp and Vs structure of the California Central Coast Ranges, in the vicinity of SAFOD, from controlled-source seismic data, *Geophys. J. Int.*, **109**, 1341-1360, doi: 10.1111/j1365-246X.2012.05585.x.

Sachs, M. K., E. M. Heien, D. L. Turcotte, M. B. Yikilmaz, J. B. Rundle, and L. H. Kellogg (2012). Virtual California earthquake simulator, *Seism. Res. Lett.*, **83**, 973-978.

Sagy, A., E. E. Brodsky, and G. J. Axen (2007). Evolution of fault-surface roughness with slip, *Geology*, **35**, 283-286, doi:10.1130/G23235A.1.

Sarna-Wojcicki, A. M., and R. F. Yerkes (1982). Comment on article by R. S. Yeats entitled “Low-shake faults of the Ventura Basin, California”. In: Cooper, J. D. (ed.), Neotectonics in Southern California. *Geological Society of America*, 78th Cordilleran Section Annual Meeting, Guidebook, pp. 17–19.

Savage, H. M., P. J. Polissar, R. E. Sheppard, C. D. Rowe, E. E. Brodsky (2014). Biomarkers heat up during earthquakes: New evidence of seismic slip from the rock record, *Geology*, **42**(2), 99-102.

SCEC Community Stress Model (2015). *http://sceczero.usc.edu/projects/CSM*.

Scharer, K. M., K. Blisniuk, W. Sharp, P. Williams and K. Johnson (2014). Vertical deformation along the Indio Hills, San Andreas Fault, California, *SCEC Annual Meeting*.

Scharer, K., R. Weldon II, A. Streig, and T. Fumal (2014). Paleoearthquakes at Frazier Mountain, California delimit extent and frequency of past San Andreas Fault ruptures along 1857 trace, *Geophys. Res. Lett*., **41**, 4527–4534, doi:10.1002/2014GL060318.

Scheitlin, T., P. Domingo, K. Olsen, W. Sarvan, Y. Cui, E. Poyraz, P. Maechling and T. Jordan (2013). Simulated Wave Propagation for the Mw5.4 Chino Hills, CA, Earthquake, Including a Statistical Model of Small-Scale Heterogeneities, *SC2013 Visualization Showcase*, Denver, Nov 17-22, 2013.

Schmedes, J., R. J. Archuleta, and D. Lavallée (2010). Correlation of earthquake source parameters inferred from dynamic rupture simulations, *J. Geophys. Res.*, 115,: B03304.

Schmitt, S. V., P. Segall, and E. M. Dunham (2015). Nucleation and dynamic rupture on weakly stressed faults sustained by thermal pressurization, *J. Geophys Res.,* submitted.

Segall, P. (1989). Earthquakes triggered by fluid extraction, *Geology*, **17**, 942-946.

Segall, P., J. R. Grasso, and A. Mossop (1994). Poroelastic stressing and induced seismicity near the Lacq gas field, southwestern France, *J. Geophys. Res.*, **99**, 15,423-15,438.

Segall, P., A. M. Rubin, A. M. Bradley, and J.R. Rice (2010). Dilatant strengthening as a mechanism for slow slip events, *J. Geophys. Res.*, **115**, B12305.

Segall, P., and S. Lu (2015). Injection induced seismicity: Poroelastic and earthquake nucleation effects, *J. Geophys. Res.*, **120**, doi:10.1002/2015JB012060.

Shaw, B. E. (2015). Developing earthquake simulators for use in seismic hazard estimates, *SCEC Annual Report*, Award 14053, 7 pp.

Shaw, B. E. and S. G. Wesnousky (2008). Slip-Length scaling in large earthquakes: The role of deep penetrating slip below the seismogenic layer, *Bull. Seismol. Soc. Am.*, **98**, 1633-1641, doi:10.1785/0120070191.

Shaw, J. H., A. Plesch, C. Tape, M. P. Suess. T. H. Jordan, G. Ely, E. Hauksson. J. Tromp, T. Tanimoto, R. Graves, K. Olsen, C. Nicholson, P. J. Maechling, C. Rivero, P. Lovely, C. M. Brankman, and J. Munster (2015). Unified Structural Representation of the southern California crust and upper mantle, *Earth Planet. Sci. Lett.*, **415**, 1-15, doi:10.1016/j.epsl.2015.01.016.

Shelly, D. R. (2010). Periodic, chaotic, and doubled earthquake recurrence intervals on the deep San Andreas Fault, *Science* **328**, 1385, doi:10.1126/science.1189741.

Shi, J., and D. Asimaki (2015). From stiffness to strength in site response analyses: Formulation and validation of a hybrid hyperbolic nonlinear soil model, *Bull. Seismol. Soc. Am.*, in review.

Shi, Z., and S. M. Day (2013). Rupture dynamics and ground motion from 3-D rough-fault simulations, *J. Geophys. Res.*, **118**, 1122-1141, doi:10.1002/jgrb.50094.

Shi, Z and S. Day (2014). Dynamic Rupture Models along Irregular Faults, *San Gorgonio Pass Special Fault Study Area Workshop,* available at *http://www.scec.org/workshops/*.

Sibson, R. H. (1973). Interaction between temperature and pore-fluid pressure during earthquake faulting — A mechanism for partial or total stress relief, *Nature*, **243**, 66-68.

Small, P., P. Maechling, T. Jordan, G. Ely, R. Taborda (2011). SCEC UCVM – Unified California Velocity Model, Abstract S21B-2200, 2011 Fall Meeting, American Geophysical Union, San Francisco, California.

Small, P., R. Taborda, J. Bielak and T. Jordan (2014). GPU Accleration of Hercules, *Proc of the Southern California Earthquake Center (SCEC*) *Annual Meeting*, September 6-10, 2014, Palm Springs, California.

Spudich, P.K.P. (1992). On the inference of absolute stress levels from seismic radiation, *Tectonophysics*, **211**, 99–106, doi:10.1016/0040-1951(92)90053-9.

Spudich P., M. Guatteri, K. Otsuki, and J. Minagawa (1998). Use of fault striations and dislocation models to infer tectonic shear stress during the 1995 Hyogo-Ken Nanbu (Kobe) earthquake, *Bull. Seismol. Soc. Am.*, **88**, 413-427.

Spudich, P., and K. Olsen (2001). Fault zone amplified waves as a possible seismic hazard along the Calaveras fault in Central California, *Geophys. Res. Lett.*, **28**, 2533–2536, doi:10.1029/2000GL011902.

Strasser, F. O., N. A. Abrahamson, and J. J. Bommer (2009). Sigma: Issues, insights, and challenges, *Seismol. Res. Lett.*, **80**, 40-56.

Stewart, J. P., R. B. Seed, and G. L. Fenves (1999). Seismic Soil-Structure Interaction in Buildings. II: Empirical Findings, *J. Geotech. Geoenviron. Eng.*, **125** , 38-48.

Stokes, D. E. (1997). *Pasteur's Quadrant—Basic Science and Technological Innovation*, Brookings Institution Press, 180 pp.

Suckale, J. (2009). Induced seismicity in hydrocarbon fields, *Advances in Geophysics*, **51**, 55-106.

Sulem, J., and V. Famin (2009). Thermal decomposition of carbonates in fault zones: Slip-weakening and temperature limiting effects, *J. Geophys. Res.*, **114**, B03309, doi:10.1029/2008JB006004.

Taborda, R. (2010). Three Dimensional Nonlinear Soil and Site-City Effects in Urban Regions, *Ph.D., Thesis,* Civil and Environmental Engineering, Carnegie Institute of Technology, Carnegie Mellon University, Pittsburgh, Pennsylvania.

Taborda, R. and Bielak, J. (2011). Large-scale earthquake simulation — Computational seismology and complex engineering systems, *Comput. Sci. Eng.* **13**. 14-26.

Taborda, R., J. Bielak, and D. Restrepo (2012). Earthquake ground motion simulation including nonlinear soil effects under idealized conditions with application to two case studies, *Seismol. Res. Lett.*, **83**, 1047-1060.

Taborda, R. and J. Bielak (2013). Ground-motion simulation and validation of the 2008 Chino Hills, California, earthquake, *Bull. Seismol. Soc. Am.*, **103**, 131–156, doi: 10.1785/0120110325.

Taborda, R., and J. Bielak (2014). Ground-Motion Simulation and Validation of the 2008 Chino Hills, California, Earthquake Using Different Velocity Models, *Bull. Seismol. Soc. Am.*, **104**, doi:10.1785/0120130266.

Taiebat, M., Jeremic, B., Dafalias, Y. F., Kaynia, A. M., and Cheng, Z. (2010). Propagation of seismic waves through liquefied soils, *Soil Dynamics and Earthquake Engineering*, **30**, 236-257.

Takeuchi, C., and Y. Fialko (2012). Dynamic models of interseismic deformation and stress transfer from plate motion to continental transform faults, *J. Geophys. Res.*, **117**, B05403, doi:10.1029/2011JB009056.

Takeuchi, C., and Y. Fialko (2013). On the effects of thermally weakened ductile shear zones on post-seismic deformation, *J. Geophys. Res.*, **118**, 6295-6310, doi:10.1002/2013JB010215.

Tanaka, H., W. M. Chen, C. Y. Wang, K. F. Ma, N. Urata, J. Mori, and M. Ando (2006). Frictional heat from faulting of the 1999 Chi-Chi, Taiwan earthquake, *Geophys. Res. Lett.*, **33**, L16316, doi:10.1029/2006GL026673.

Tanikawa, W., and T. Shimamoto (2009). Frictional and transport properties of the Chelungpu fault from shallow borehole data and their correlation with seismic behavior during the 1999 Chi-Chi earthquake, *J. Geophys. Res.*, **114**(B1), doi: 10.1029/2008JB005750.

Tape, C., Q. Liu, A. Maggi, and J. Tromp (2010). Seismic tomography of the southern California crust based on spectral-element and adjoint methods, *Geophys. J. Int.*, **180**, 433-462.

Tchalenko, J. S., and M. Berberian (1975). Dasht-e-Bayaz fault, Iran: earthquake and earlier related structures in bedrock. *Bull. Geol. Soc. Am*. **86**, 703- 709.

Templeton, E. L., and J. R. Rice (2008). Off-fault plasticity and earthquake rupture dynamics: 1. Dry materials or neglect of fluid pressure changes, *J. Geophys. Res.*, **113**, B09306, doi10.1029/2007JB005529.

Thatcher, W., E. H. Hearn, and G. Hirth (2013). Ductile rheology of the Southern California Lithosphere: Constraints from deformation modeling, rock mechanics, and field observations, *Eos*, **94**, 32, 280.

Thio, H. K., W. Li, J. Shaw, J. Hubbard, A. Plesch, and R. Wilson (2014). Tsunami hazard from the Ventura-Pitas fault and fold system, *2014 SCEC Annual Meeting*, Palm Springs, CA.

Thomas, M. Y., N. Lapusta, H. Noda, and J.-P. Avouac (2014). Quasi-dynamic versus fully-dynamic simulations of earthquakes and aseismic slip with and without enhanced coseismic weakening, *J. Geophys. Res.*, **119**, 1986-2004.

Townend, J., and M. D. Zoback (2004). Regional tectonic stress near the San Andreas fault in central and southern California, *Geophys. Res. Lett.*, **31**, L15S11, doi:10.1029/203GL018918.

Trifunac, M. D. (2000). Discussion of ‘seismic soil-structure interaction in buildings. I: Analytical methods, and II: Empirical findings.’ by Jonathan P. Stewart, Gregory L. Fenves, and Raymond B. Seed., *J. Geotech. and Geoenvir. Engrg.*, ASCE, 126(7), 668–670.

Trifunac, M. D., M. I. Todorovska, and T.-Y. Hao (2001). Full-Scale Experimental Studies of Soil-Structure Interaction — A Review, *Proc. 2nd UJNR Workshop on Soil-Structure Interaction,* UJNR Workshop on Soil-Structure Interaction March 6 to 8, Tsukuba, Japan.

Trugman, D. T., A. A. Borsa, and D. T. Sandwell (2014). Did stresses from the Cerro Prieto Geothermal Field influence the El Mayor-Cucapah rupture sequence?, *Geophys. Res. Lett.,* **41**, doi:10.1002/2014GL061959.

Trugman, D. T. and E. M. Dunham (2014) A 2D pseudo-dynamic rupture model generator for earthquakes on geometrically complex faults, *Bull. Seismol. Soc. Am.*, **104**(1), 95-112, doi:10.1785/0120130138.

Tullis, T. E (2007). Friction of rock at earthquake slip rates, in *Treatise on Geophysics*, vol. 4, ed. H. Kanamori, 131-152, Elsevier, Amsterdam.

Tullis, T. E. (2012). Preface to the Focus Issue on Earthquake Simulators, *Seism. Res. Lett.*, **83**, 957-958.

Tullis, T., and D. L. Goldsby (2013). *Laboratory Experiments on Rock Friction Focused on Understanding Earthquake Mechanics*, Final Technical Report for USGS Grant Number: G12AP20080.

Tullis, T. E., K. Richards-Dinger, M. Barall, J. H. Dieterich, E. H. Field, E. M. Heien, L. H. Kellogg, F. F. Pollitz, J. B. Rundle, M. K. Sachs, D. L. Turcotte, S. N. Ward, and M. B. Yikilmaz (2012). Comparison among observations and earthquake simulator results for the allcal2 California fault model, *Seism. Res. Lett.* **83**, 994–1006.

Ucarkus, G., N. Driscoll, D. Brothers, G. Kent, and T. Rockwell (2013). Holocene folding deformation associated with large uplift events on the Ventura Avenue Anticline, *2013 SCEC Annual Meeting*, Palm Springs, CA.

USCDR: USC Digital Repository available at *http://repository.usc.edu/storage/.*

U.S. Geological Survey (2007), Facing Tomorrow's Challenges—U.S. Geological Survey Science in the Decade 2007–2017, U.S. Geological Survey Circular 1309, 70 pp.

U.S. Geological Survey (2014). USGS Strategy for Operational Earthquake Forecasting, Reston VA, 13 pp., Oct 2014.

van Dinther, Y. T.V. Gerya, L. A. Dalguer, P. M. Mai, G. Morra, and D. Giardini (2013). The seismic cycle at subduction thrusts: insights from seismo-thermo-mechanical models, *J. Geophys. Res.*, 118, 6183-6202, doi:10.1002/2013JB010380.

Velasco, A. A., and E. Jaurrieta de Velasco (2010). Striving to diversify the geosciences workforce, *Eos*, **91**, 289–290, doi:10.1029/2010EO330001.

Vidale, J. E., and Y.-G. Li (2003). Damage to the shallow Landers fault from the nearby Hector Mine earthquake, *Nature*, **421**, 524–526, doi:10.1038/ nature01354.

Viens, L., A. Laurendeau, L. F. Bonilla, and N. M. Shapiro (2014). Broad-band acceleration time histories synthesis by coupling low-frequency ambient seismic field and high frequency stochastic modeling, *Geophys. J. Int.,* **199**, 1784-1797.

Viens, L., H. Miyake, and K. Koketsu (2015). Long-period ground motion simulation of a subduction earthquake using the offshore–onshore ambient seismic field, *Geophys. Res. Lett.,* **42**, 5282-5287.

Wang, F., and T. H. Jordan (2014). Comparison of probabilistic seismic hazard models using averaging-based factorization, *Bull. Seismol. Soc. Am.*, **104**, 1230-1257, doi: 10.1785/0120130263.

Wang, T.-H., E. S. Cochran, D. Agnew, and D. D. Oglesby (2013). Infrequent triggering of tremor along the San Jacinto Fault near Anza, California, *Bull. Seismol. Soc. Am.,* **103**, 2482-2497, doi: 10.1785/0120120284.

Ward, S. N. (2012). The ALLCAL earthquake simulator, *Seism. Res. Lett.*, **83**, 964-972.

Ward, S. (2013). Earthquake rupture and tsunamic simulations: Ventura-Pitas Point fault system, *SCEC Annual Report*, Award 13014, 6 pp.

Weldon, R.J., T. E. Dawson, G. Biasi, C. Madden, and A. R. Streig (2013). Appendix G: Paleoseismic Sites Recurrence Database, in *http://pubs.usgs.gov/of/2013/1165/pdf/ofr2013-1165_appendixG.pdf.*

Werner, M., W. Marzocchi, M. Taroni, J. Zechar, M. Gerstenberger, M. Liukis, D. Rhoades, C. Cattania, A. Christophersen, S. Hainzl, A. Helmstetter, A. Jimenez, S. Steacy, and T. H. Jordan (2015). Retrospective evaluation of time-dependent earthquake forecasting models during the 2010-12 Canterbury, New Zealand, earthquake sequence, extended abstract submitted to SECED 2015 Conference: *Earthquake Risk and Engineering towards a Resilient World*, 9-10 July 2015, Cambridge UK.

Wesnousky, S. G. (2006). Predicting the endpoints of earthquake ruptures, *Nature* **444**, 358–360, doi: 10.1038/nature05275.

Wesson, R. L., and O. S. Boyd (2007). Stress before and after the 2002 Denali fault earthquake. *Geophys. Res. Lett.*, **34**, 7303, doi:10.1029/2007GL029189.

Williams, Q. L., V. Morris, and T. Furman (2007). A real-world plan to increase diversity in the geosciences, *Phys. Today*, **60**, 54-55.

Withers, K. B., K. B. Olsen, and S. M. Day (2015). Memory-efficient simulation of frequency dependent Q, *Bull. Seismol. Soc. Am.*, in press.

Withers, K.B., K.B. Olsen, Z. Shi, and S.M. Day (2015). Broadband (0-8Hz) ground motion variability from ensemble simulations of the 1994 Mw 6.7 Northridge earthquake including rough fault descriptions and Q(f), *Seism. Res. Lett.* **86**:2B, 653.

Withers, K.B., K.B. Olsen, and S.M. Day (2015). Deterministic high-frequency ground motion using dynamic rupture along rough faults, small-scale media heterogeneities, and frequency-dependent attenuation, *2015 SCEC Annual Meeting*, Palm Springs, CA, September 13-16, 2015.

Wood, M. M. (2015a). *Evaluation of SCEC Communication, Education, and Outreach Program*, September, 43 pp.

Wood, M. M. (2015b). Communicating actionable risk: The challenge of communicating risk to motive preparedness in the absence of calamity, in H. Egner, M. Schorch, and M. Voss, eds., *Learning and Calamities: Practices, Interpretations, Patterns*, pp. 143-158, Routledge, New York.

Wood, M. M., D. S. Mileti, M. Kano, M. M. Kelley, R. Regan, R., and L. B. Bourque (2012). Communicating actionable risk for terrorism and other hazards, Risk Analysis, **32**, 601-615. doi:10.1111/j.1539-6924.2011.01645.x.

Worthen, J., G. Stadler, N. Petra, M. Gurnis, and O. Ghattas (2014). Towards an adjoint-based inversion for rheological parameters in nonlinear viscous mantle flow, *Phys. Earth Planet. Int.*, **234**, 23-34.

Xu, S. and Y. Ben-Zion (2013). Numerical and theoretical analyses of in-plane dynamic rupture on a frictional interface and off-fault yielding patterns at different scales, *Geophys. J. Int.*, **193**, 304-320.

Xue, L., H.-B. Li, E. E. Brodsky Z.-Q. Xu, Y. Kano, H. Wang, J. J. Mori, J.-L. Si, J.-L. Pei, W Zhang, G. Yang, K.-M. Sun, and Y. Huang (2013). Continuous permeability measurements record healing inside the Wenchuan earthquake fault zone, *Science*, **340**, 1555-1559, doi:10.1126/science.1237237.

Yagoda-Biran, G. and J. G. Anderson (2015). Investigation of the ground-motion variability associated with site response for sites with Vs30 over 500 m/s, *Bull. Seismol. Soc. Am.,* **105***,* 1011-1028.

Yang, W., and E. Hauksson (2013). The tectonic crustal stress field and style of faulting along the Pacific-North America plate boundary in southern California, *Geophys. J. Int.,* **194**, 100-117, doi:10.1093/gji/ggt113.

Yang, Z., A. Elgamal, and E. Parra (2003). Computational model for cyclic mobility and associated shear deformation, *J. of Geotechnical and Geoenvironmental Engineering*, **129**, 1119-27.

Yerkes, R. F., A. M. Sarna-Wojcicki, and K. R. Lajoie, 1987, Geology and Quaternary deformation of the Ventura area. In: Recent Reverse Faulting in the Transverse Ranges. *U.S. Geological Survey Professional Paper 1339*, pp. 169–178.

Yikilmaz, M. B., D. L. Turcotte, E. M. Heien, L. H. Kellogg, and J. B. Rundle (2014). Critical jump distance for propagating earthquake ruptures across step-overs, *Pure Appl. Geophys.*, doi:10.1007/s00024-014-0786-y.

Yoon, C. E., O. O'Reilly, K. Bergen, and G. C. Beroza (2015). Earthquake detection through computationally efficient similarity search, *Science Advances*, submitted.

Yule, D. (2009). The enigmatic San Gorgonio Pass, *Geology,* **72**, 2, 191-192, doi:10.1130/focus022009.1.

Yule, D., D. Heermance, I. Desjarlais and K. Sieh (2014). Late Pleistocene and Holocene rates of slip and size of prehistoric earthquakes on the San Andreas Fault System in San Gorgonio Pass, *2014 SCEC Annual Meeting*.

Zechar, J. D., D. Schorlemmer, M. Liukis, J. Yu, F. Euchner, P. J. Maechling & T. H. Jordan (2009). The Collaboratory for the Study of Earthquake Predictability perspectives on computational earthquake science, *Concurrency Computat.: Pract. Exper.*, **22**, 1836-1847, doi:10.1002/cpe.1519.

Zhang, J., H. Zhang, E. Chen, Y. Zheng, W. Kuang, and X. Zhang (2014). Real-time earthquake monitoring using a search engine method, *Nature Comm.*, **5**, 5664, doi:10.1038/ncomms6664.

Zhou, J., Y. Cui, E. Poyraz, D. Choi, and C. Guest (2013). Multi-GPU implementation of a 3D finite difference time domain earthquake code on heterogeneous supercomputers, *Proceedings of International Conference on Computational Science*, **18**, 1255-1264, Elsevier, ICCS 2013, Barcelona, June 5-7.

Zielke, O., Y. Klinger, J. R. Arrowsmith (2015). Fault slip and earthquake recurrence along strike-slip faults–contributions of high-resolution geomorphic data [Invited Review], *Tectonophysics*, **638**, 43–62, doi: 10.1016/j.tecto.2014.11.004.

Zoback, M. D., S. Hickman and W. Ellsworth (2007). The role of fault zone drilling, in *Treatise on Geophysics*, vol. 4, ed. H. Kanamori, Elsevier, Amsterdam.

References (endnotes)

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1 National Research Council Committee on New Research Opportunities in the Earth Sciences at the National Science Foundation (2012). *New Research Opportunities in the Earth Sciences*, National Academies Press, Washington, D.C., ISBN: 978-0-309-21924-2, 117 pp.

2 Field, E. H., R. J. Arrowsmith, G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, T. Parsons, P. M. Powers, B. E. Shaw, W. R. Thatcher, R. J. Weldon, II, and Y. Zeng (2014). Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model, *Bull. Seismol. Soc. Am.*, **104**, 1122-1180, doi:10.1785/0120130164. [Also published in U.S. Geological Survey Open-File Report 2013–1165, 96 p., California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792, *http://pubs.usgs.gov/of/2013/1165/*.]

3 Field, E. H., G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, Y. Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Y. Zeng (2015). Long-term, time-dependent probabilities for UCERF3, *Bull. Seismol. Soc. Am.*, **105**, doi:10.1785/0120140093.

4 Dieterich, J. H., and K. B. Richards-Dinger (2010). Earthquake recurrence in simulated fault systems, *Pure Appl. Geophys.,* **167**, 1087–1104, doi:10.1007/s00024-010-0094-0; Richards-Dinger, K., and J. H. Dieterich (2012). RSQSim earthquake simulator, *Seism. Res. Lett.*, **83**, 983-990.

5 Ward, S. N. (2012). The ALLCAL earthquake simulator, *Seism. Res. Lett.*, **83**, 964-972.

6 Tullis, T. E. (2012). Preface to the Focus Issue on Earthquake Simulators, *Seism. Res. Lett.*, **83**, 957-958; Tullis, T. E., K. Richards-Dinger, M. Barall, J. H. Dieterich, E. H. Field, E. M. Heien, L. H. Kellogg, F. F. Pollitz, J. B. Rundle, M. K. Sachs, D. L. Turcotte, S. N. Ward, and M. B. Yikilmaz (2012). Comparison among observations and earthquake simulator results for the allcal2 California fault model, *Seism. Res. Lett.* **83**, 994–1006.

7 Graves, R., T. H. Jordan, S. Callaghan, E. Deelman, E. Field, G. Juve, C. Kesselman, P. Maechling, G. Mehta, K. Milner, D. Okaya, P. Small, and K. Vahi (2011). CyberShake: A physics-based probabilistic hazard model for Southern California, *Pure Appl. Geophys.*, **167**, 367-381, doi:10.1007/s00024-010-0161-6.

8 Wang, F., and T. H. Jordan (2014). Comparison of probabilistic seismic hazard models using averaging-based factorization, *Bull. Seismol. Soc. Am.*, **104**, 1230-1257, doi: 10.1785/0120130263.

9 U.S. Geological Survey (2007), Facing Tomorrow's Challenges—U.S. Geological Survey Science in the Decade 2007–2017, U.S. Geological Survey Circular 1309, 70 pp.

10 National Science and Technology Council Committee on Environment and Natural Resources (2005). *Grand Challenges for Disaster Reduction*, Report of the Subcommittee on Disaster Reduction, June, 2005, 21 pp.

11 NSF Advisory Committee for Geosciences (2009). *Geovision Report: Unraveling Earth's Complexities through the Geosciences*, National Science Foundation, October, 2009, 39 pp.

12 Weldon, R.J., T. E. Dawson, G. Biasi, C. Madden, and A. R. Streig (2013). Appendix G: Paleoseismic Sites Recurrence Database, in *http://pubs.usgs.gov/of/2013/1165/pdf/ofr2013-1165_appendixG.pdf*

13 Jackson, D. (2014). Did someone forget to pay the earthquake bill? [abstract], *Seismol. Res. Lett.*, **85**, 421.

14 Cummings, J., T. Finholdt, I. Foster, C. Kesselman, and K. A. Lawrence (2008). *Beyond Being There: A Blueprint for Advancing the Design, Development, and Evaluation of Virtual Organizations*, Final Report from Workshops on Building Effective Virtual Organizations, National Science Foundation, May 2008, 58 pp.

15 Plesch, A., J. H. Shaw, C. Benson, W. A. Bryant, S. Carena, M. Cooke, J. Dolan, G. Fuis, E. Gath, L. Grant, E. Hauksson, T. H. Jordan, M. Kamerling, M. Legg, S. Lindvall, H. Magistrale, C. Nicholson, N. Niemi, M. Oskin, S. Perry, G. Planansky, T. Rockwell, P. Shearer, C. Sorlien, M. P. Süss, J. Suppe, J. Treiman, and R. Yeats (2007). Community Fault Model (CFM) for Southern California, *Bull. Seismol. Soc. Am.*, **97**, 1793-1802, doi 10.1785/0120050211.

16 Tape, C., Q. Liu, A. Maggi & J. Tromp (2010). Seismic tomography of the southern California crust based on spectral-element and adjoint methods, *Geophys. J. Int.*, **180**, 433-462; Lee E.-J., P. Chen,

T. H. Jordan, P. B. Maechling, M. A.M. Denolle and G. C. Beroza (2014). Full-3D tomography for crustal structure in Southern California based on the scattering-integral and the adjoint-wavefield methods, *J. Geophys. Res.*, **119**, 6421-6451, doi:10.1002/2014JB011346.

17 Shaw, J. H., A. Plesch, C. Tape, M. P. Suess. T. H. Jordan, G. Ely, E. Hauksson. J. Tromp, T. Tanimoto, R. Graves, K. Olsen, C. Nicholson, P. J. Maechling, C. Rivero, P. Lovely, C. M. Brankman, and J. Munster (2015). Unified Structural Representation of the southern California crust and upper mantle, *Earth Planet. Sci. Lett.*, **415**, 1-15, doi:10.1016/j.epsl.2015.01.016.

18 Global Earthquake Modeling (GEM) Project: *http://www.globalquakemodel.org.*

19 Federal Emergency Management Agency (2008), *HAZUS® MH Estimated Annualized Earthquake Losses for the United States*, FEMA Report 366, Washington, D.C., April, 2008, 53 pp.

20 Mayoral Seismic Safety Task Force (2015). *Resilience by Design*, Office of the Mayor of Los Angeles, December, 2015, 123 pp.

21 Graves, R., B. Aagaard, K. Hudnut, L. Star, J. Stewart and T. H. Jordan (2008). Broadband simulations for Mw 7.8 southern San Andreas earthquakes: Ground motion sensitivity to rupture speed, *Geophys. Res. Lett.*, **35**, L22302, doi:10.1029/2008GL035750.

22 Jones, L. M., R. Bernknopf, D. Cox, J. Goltz, K. Hudnut, D. Mileti, S. Perry, D. Ponti, K. Porter, M. Reichle, H. Seligson, K. Shoaf, J. Treiman, and A. Wein (2008). The ShakeOut Scenario: U.S. Geological Survey Open-File Report 2008-1150 and California Geological Survey Preliminary Report 25; *http://pubs.usgs.gov/of/2008/1150/*.

23 Gerstenberger, M. C., G. H. McVerry, D. A. Rhoades, M.W. Stirling (2014). Seismic hazard modeling for the recovery of Christchurch, New Zealand, *Earthquake Spectra*, **30**, 17-29; Rhoades, D. A., M. C. Gerstenberger, A. Christophersen and M. Liukis (2013). Utilising short-term and medium-term forecasting models for earthquake hazard estimation in the wake of the Canterbury earthquakes, *GNS Science Consultancy Report* 2013/141, 52 pp.

24 Marzocchi, W., A. M. Lombardi and E. Casarotti (2014). The establishment of an operational earthquake forecasting system in Italy, *Seismol. Res. Lett.*, **85**, p. 961-969, doi:10.1785/0220130219.

25 U.S. Geological Survey (2014). USGS Strategy for Operational Earthquake Forecasting, Reston VA, 13 pp., Oct 2014; Holmes, R. R., L. M. Jones, J. C. Eidenshink, J. W.Godt, S. H. Kirby, J. J. Love, C. A. Neal, N. G. Plant, M. L. Plunkett, C. S. Weaver, A. Wein, and S. C. Perry (2012). Natural Hazards Science Strategy—Public Review Release, USGS Open File Report #2012-1088, 75 pp., *http://pubs.usgs.gov/of/2012/1088*; Field, E. H., T. H. Jordan, L. M. Jones, A. J. Michael, and M. L. Blanpied (2015). The potential uses of operational earthquake forecasting (Powell Center workshop report), *Seismol. Res. Lett.*, submitted.

26 Jordan, T. H., Y.-T. Chen, P. Gasparini, R. Madariaga, I. Main, W. Marzocchi, G. Papadopoulos, G. Sobolev, K. Yamaoka, and J. Zschau (2011). *Operational Earthquake Forecasting: State of Knowledge and Guidelines for Implementation*, Final Report of the International Commission on Earthquake Forecasting for Civil Protection, *Annals Geophys.,* **54**(4), 315-391, doi:10.4401/ag-5350.

27 Böse, M., R. Allen, H. Brown, G. Gua, M. Fischer, E. Hauksson, T. Heaten, M. Hellweg, M. Liukis, D. Neuhauser, P. Maechling, K. Solanki, M. Vinci, I. Henson, O. Khainovski, S. Kuyuk, M. Carpio, M.-A. Meier, and T. Jordan (2014). CISN ShakeAlert: An earthquake early warning demonstration system for California, *Early Warning for Geological Disasters*, ed. F. Wenzel and J. Zschau, Springer-Verlag, Berlin, pp. 49-69, doi:10.1007/978-3-642-12233-0_3.

28 Field, E. H., R. J. Arrowsmith, G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, T. Parsons, P. M. Powers, B. E. Shaw, W. R. Thatcher, R. J. Weldon, II, and Y. Zeng (2014). Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model, *Bull. Seismol. Soc. Am.*, **104**, 1122-1180, doi:10.1785/0120130164. [Also published in U.S. Geological Survey Open-File Report 2013–1165, 96 p., California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792, *http://pubs.usgs.gov/of/2013/1165/.*]

29 Field, E. H., G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, Y. Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Y. Zeng (2015). Long-term, time-dependent probabilities for UCERF3, *Bull. Seismol. Soc. Am.*, **105**, 511–543, doi:10.1785/0120140093.

30 Bird, P. (2014). Stress field models from Maxwell stress functions, *SCEC Annual Report*, Award

12053, March 2014, 12 pp.; submitted to *Geophys. J. Int.*

31 Hearn, E. H. (2015). Contributions to the SCEC CSM: A finite-element model of the southern California lithosphere, SCEC Annual Report, Award 14023, 8 pp.

32 Takeuchi, C., and Y. Fialko (2012). Dynamic models of interseismic deformation and stress transfer from plate motion to continental transform faults, *J. Geophys. Res.*, **117**, B05403, doi:10.1029/2011JB009056.

33 Amos, C. B., P. Audet, W. C. Hammond, R. Burgmann, I. A. Johanson, and G. Blewitt (2014). Uplift and seismicity driven groundwater depletion in central California, *Nature*, **509**, 483-486, doi:10.1038/nature13275.

34 Borsa, A. A., D. C. Agnew, and D. R. Cayan (2014). Ongoing drought-induced uplift in the western United States, *Science*, **345**, 1587-1590, doi:10.1126/ science.1260279.

35 Liu, Z., and Z.-K. Shen (2015) Improve and integrate InSAR deformation map with GPS towards improved Community Geodetic Model, *SCEC Annual Report*, Award 14102, 5 pp.

36 Marinkovic, P. and Y. Larsen (2013). Consequences of Long-Term ASAR Local Oscillator Frequency Decay - an Empirical Study of 10 Years of Data, *ESA Living Planet Symposium 2013*, Sep 9-13, Edinburgh, UK.

37 Nissen, E., A. K. Krishnan, J. R. Arrowsmith, and S. Saripalli (2012). Three-dimensional surface displacements and rotations from differencing pre- and post-earthquake Lidar point clouds, *Geophys. Res. Lett.*, **39**, L16301, doi:10.1029/2012GL052460.

38 Glennie, C., A. Hinojosa, E. Nissen, A. Kusari, M. Oskin, J. R. Arrowsmith, A. Borsa (2014). Optimization of Legacy LiDAR Datasets for Measuring Near-Field Earthquake Displacements, *Geophys. Res. Lett.*, **41**, 3494-3501, doi: 10.1002/2014GL059919.

39 Donnellan, A., J. R. Arrowsmith, and V. Langenheim (2015). Select Airborne Techniques for Mapping and Problem Solving, Applied Geology in California, eds. R. Anderson and H. Ferriz, Association of Engineering Geology, in press.

40 Zielke, O., Y. Klinger, J. R. Arrowsmith (2015). Fault slip and earthquake recurrence along strike-slip faults–contributions of high-resolution geomorphic data [Invited Review], *Tectonophysics*, **638**, 43–62, doi: 10.1016/j.tecto.2014.11.004.

41 Oskin, M., J. Arrowsmith, C. Hinojosa, A. Elliot, J. Fletcher, E. Fielding, P. Gold, J. Gonzalez, K. Hudnut, J. Liu-Zeng, O. Teran (2012). Near-field deformation from the El Mayor-Cucapah earthquake revealed by differential LiDAR, *Science*, **335**, 702-705, doi:10.1126/science.

42 Nissen, E., T. Maruyama, J. R. Arrowsmith, J. R. Elliott, A. K. Krishnan, M. E. Oskin, and S. Saripalli (2014). Coseismic fault zone deformation revealed with differential LiDAR: examples from Japanese Mw 7 intraplate earthquakes, *Earth Planet. Sci. Lett.*, **405**, 244-256, doi: 10.1016/j.epsl.2014.08.031.

43 Onderdonk, N. W., T. K. Rockwell, S. F. McGill, and G. Marliyani (2013). Evidence for Seven Surface Ruptures in the Past 1600 Years on the Claremont Fault at Mystic Lake, Northern San Jacinto Fault Zone, California, *Bull. Seismol. Soc. Am.,* **103**, 519-541, doi: 10.1785/0120120060.

44 Onderdonk, N., S. F. McGill, and T. K. Rockwell (2015). Short-term variations in slip rate and size of prehistoric earthquakes during the past 2000 years on the northern San Jacinto fault zone, a major plate-boundary structure in southern California, *Lithosphere*, **7**, 211-234.

45 Scharer, K., R. Weldon II, A. Streig, and T. Fumal (2014). Paleoearthquakes at Frazier Mountain, California delimit extent and frequency of past San Andreas Fault ruptures along 1857 trace, *Geophys. Res. Lett.*, **41**, 4527–4534, doi:10.1002/2014GL060318.

46 Roder, B., M. Lawson, E. Rhodes, J. Dolan, L. McAuliffe, and S. McGill (2011). Assessing the potential of luminescence dating for fault slip rate studies on the Garlock Fault, Mojave Desert, California, USA, *Quaternery Geochronology,* **10**, 285-290.

47 Rhodes, E. (2015) Optically Stimulated Luminescence Dating of Sediments over the Past 200,000 Years, *Ann. Rev. Earth and Planet. Sci.*, **39**, 461–488, do: 10.1146/annurev-earth-040610-133425.

48 Blisniuk, K., M. Oskin, K. Fletcher, T. Rockwell, and W. Sharp (2012). Assessing the reliability of U-series and 10Be dating techniques on alluvial fans in the Anza Borrego Desert, California, *Quaternary Geochronology*, **13**, 26-41.

49 Blisniuk, K., M. Oskin, A. Mériaux, T. Rockwell, R. Finkel, and F. Ryerson (2013). Stable, rapid rate of slip since inception of the San Jacinto Fault, California, *Geophys. Res. Lett.,* **40**, 1-5, doi: 10.1002/grl.50819.

50 Balco, G. (2014). Quaternary fault slip behavior of the Mission Creek fault of the southern San Andreas fault zone in the San Gorgonio Pass, CA, *SCEC Annual Report*, Award 14103, 3 pp.

51 DeVechio, D. (2013). Precise Fault Slip Rates on the Oak Ridge fault: New age constraints on the Saugus Formation using 36C/10Be isochron burial dating, *SCEC Annual Report*, Award 13105, 10 pp.

52 SCEC Community Stress Model (2015). *http://sceczero.usc.edu/projects/CSM*.

53 Meng, X., X. Yu, Z. Peng and B. Hong (2012). Detecting earthquakes around Salton Sea following the 2010 Mw7.2 El Mayor-Cucapah earthquake using GPU parallel computing, *Procedia Computer Science*, **9**, 937-946.

54 Hauksson, E. and W. Yang, and P. M. Shearer (2012). Waveform Relocated Earthquake Catalog for Southern California (1981 to June 2011), *Bull. Seismol. Soc. Am.,* **102**, 5, 2239-2244, doi:10.1785/0120120010.

55 Chen, X. and P. M. Shearer (2011). Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, **116**, doi: 10.1029/2011JB008263.

56 Meng, X., and Z. Peng (2014). Seismicity rate changes in the Salton Sea Geothermal Field and the San Jacinto Fault Zone after the 2010 *M*w 7.2 El Mayor-Cucapah earthquake, *Geophys. J. Int.*, **197,** 1750-1762, doi: 10.1093/gji/ggu085.

57 Werner, M., W. Marzocchi, M. Taroni, J. Zechar, M. Gerstenberger, M. Liukis, D. Rhoades, C. Cattania, A. Christophersen, S. Hainzl, A. Helmstetter, A. Jimenez, S. Steacy, and T. H. Jordan (2015). Retrospective evaluation of time-dependent earthquake forecasting models during the 2010-12 Canterbury, New Zealand, earthquake sequence, extended abstract submitted to SECED 2015 Conference: *Earthquake Risk and Engineering towards a Resilient World*, 9-10 July 2015, Cambridge UK.

58 Trugman, D. T., A. A. Borsa, and D. T. Sandwell (2014). Did stresses from the Cerro Prieto Geothermal Field influence the El Mayor-Cucapah rupture sequence?, *Geophys. Res. Lett.,* **41**, doi:10.1002/ 2014GL061959.

59 Brodsky, E. E., and L. J. Lajoie (2013). Anthropogenic seismicity rates and operational parameters at the Salton Sea Geothermal Field, *Science*, **341**(6), 543–546, doi:10.1126/science.1239213.

60 Rockwell, T. K., T. E. Dawson, J. Y. BenHorin, and G. Seitz (2015). A 21-Event, 4,000-Year History of Surface Ruptures in the Anza Seismic Gap, San Jacinto Fault, and Implications for Long-term Earthquake Production on a Major Plate Boundary Fault, *PAGEOPH*, **172**, 1143–1165, doi:10.1007/s00024-014-0955-z.

61 Rockwell, T., K. Scharer, and T. Dawson (2015). Earthquake Geology and Paleoseismology of Major Strands of the San Andreas Fault System, *in* Anderson R.L, and Ferriz, R., *Applied Geology in California*, Association of Environmental and Engineering Geology Special Publication Number 26, Star Publishing Company, Menlo Park California, in press.

62 Grant-Ludwig, L., J. N. Brune, A. Anooshehpoor, M. D. Purvance, R. J. Brune, and J. N. Brune (2015). Reconciling precariously balanced rocks (PBRs) with large earthquakes on the San Andreas Fault system, *Seismol. Res. Lett.,* **86**, 1-9, doi: 10.1785/0220140239.

63 Dolan, J. F., L. J. McAuliffe, E. J. Rhodes, S. F. and McGill (2015). Extreme multi-millennial slip rate variations on the Garlock fault, California: Strain super-cycles, time-variable fault strength, and implications for system-level earthquake occurrence, *Earth Planet Sci Lett.,* submitted.

64 McAuliffe, L. J., J. F. Dolan, E. Kirby, C. Rollins, B. Haravitch, S. Alm, and T. M. Rittenour (2013). Paleoseismology of the Southern Panamint Valley Fault: Implications for Regional Earthquake Occurrence and Seismic Hazard in Southern California, *J. Geophys. Res.*, **118**, 5126–46. doi:10.1002/jgrb.50359.

65 Dolan, J. F., and B. D. Haravitch (2014). How well do surface slip measurements track slip at depth in large strike-slip earthquakes? The importance of fault structural maturity in controlling on-fault slip versus off-fault surface deformation, *Earth Planet. Sci. Lett.*, **388**, 38-47, doi:10.1016/j.epsl.2013.11.043.

66 Herbert, J. W., M. L. Cooke, M. Oskin, and O. Difo (2014). How much can off-fault deformation contribute to the slip rate discrepancy within the Eastern California Shear Zone?, *Geology*, **42**, 71-75, doi:10.1130/G34738.1.

67 Tullis, T. E., K. Richards-Dinger, M. Barall, J. H. Dieterich, E. H. Field, E. M. Heien, L. H. Kellogg, F. F. Pollitz, J. B. Rundle, M. K. Sachs, D. L. Turcotte, S. N. Ward, and M. B. Yikilmaz (2012). Compar-

ison among observations and earthquake simulator results for the allcal2 California fault model, *Seism. Res. Lett.* **83**, 994–1006.

68 Fulton, P. M., E. E. Brodsky, Y. Kano, J. Mori, F. Chester, T. Ishikawa, R. N. Harris, W. Lin, N. Eguchi, S. Toczko, Expedition 343, 343T, and KR13-08 Scientists (2013). Low coseismic friction on the Tohoku-Oki fault determined from temperature measurements, *Science*, **342**, 1214–1217, doi:10.1126/science.1243641.

69 Platt, J. D., N. Brantut, and J. R. Rice (2014). Strain localization driven by thermal decomposition during seismic shear, *J. Geophys. Res.*, submitted.

70 Platt, J. D., J.W. Rudnicki, and J.R. Rice (2014). Stability and localization of rapid shear in fluid-saturated fault gouge, 2. Localized zone width and strength evolution, *J. Geophys. Res.*, **119**, doi: 10.1002/2013JB010711.

71 Schmitt, S. V., P. Segall, and E. M. Dunham (2015). Nucleation and dynamic rupture on weakly stressed faults sustained by thermal pressurization, *J. Geophys Res.,* submitted.

72 Proctor, B. P., T. M. Mitchell, G. Hirth, D. Goldsby, F. Zorzi, J. D. Platt, and G. Di Toro (2014). Dynamic weakening of serpentinite gouges and bare surfaces at seismic slip rates, *J. Geophys. Res.*, **119**, 8107–8131, doi: 10.1002/2014JB011057.

73 Tullis, T., and D. L. Goldsby (2013). *Laboratory Experiments on Rock Friction Focused on Understanding Earthquake Mechanics*, Final Technical Report for USGS Grant Number: G12AP20080.

74 Savage, H. M., P. J. Polissar, R. E. Sheppard, C. D. Rowe, E. E. Brodsky (2014). Biomarkers heat up during earthquakes: New evidence of seismic slip from the rock record, *Geology*, **42**(2), 99-102.

75 Evans, J. P., M. R. Prante, S. U. Janecke, A. K. Ault, and D. L. Newell (2014). Hot faults: Iridescent slip surfaces with metallic luster document high- temperature ancient seismicity in the Wasatch fault zone, Utah, USA, *Geology*, **42**, 623-626, doi:10.1130/G35617.1.

76 Sagy, A., E. E. Brodsky, and G. J. Axen (2007). Evolution of fault-surface roughness with slip, *Geology*, **35**, 283-286, doi:10.1130/G23235A.1; Candela, T., F. Renard, Y. Klinger, K. Mair, J. Schmittbuhl, and E. E. Brodsky (2012). Roughness of fault surfaces over nine decades of length scales, *J. Geophys. Res.*, **117**, B08409, doi:10.1029/2011JB009041.

77 Fang, Z., and E. M. Dunham (2013). Additional shear resistance from fault roughness and stress levels on geometrically complex faults, *J. Geophys. Res.*, **118**(7), 3642-3654, doi:10.1002/jgrb.50262.

78 Bruhat, L., Z. Fang, and E. M. Dunham (2015). Rupture complexity and the supershear transition on rough faults, *J. Geophys. Res.*, submitted.

79 Goebel, T. H. W., Candela, T., Sammis, C. G., Becker, T. W., Dresen, G., and Schorlemmer, D. (2014). Seismic event distributions and off-fault damage during frictional sliding of saw-cut surfaces with predefined roughness, *Geophys. J. Int.,* **196**, 612-625.

80 Shaw, B. E. (2015). Developing earthquake simulators for use in seismic hazard estimates, *SCEC Annual Report*, Award 14053, 7 pp.

81 Kang, J., and B. Duan (2014). Inelastic response of compliant fault zones to nearby earthquaks in three dimensions, *Tectonophysics* , **612-613**, 56-62, doi:10.1016/j.tecton.2013.11.033.

82 Qiu, H., Y. Ben-Zion, Z. E. Ross, P.-E. Share and F. Vernon (2015). Internal structure of the San Jacinto fault zone at Jackass Flat from data recorded by a dense linear array, *Proc. of the Seismological Society of America Annual Meeting*, Pasadena, California.

83 Roten, D., K. B. Olsen, S. M. Day, Y. Cui, and D. Fäh (2014). Expected seismic shaking in Los Angeles reduced by San Andreas fault zone plasticity, *Geophys. Res. Lett.*, **41**, 2769-2777, doi:10.1002/2014GL059411.

84 Takeuchi, C., and Y. Fialko (2013). On the effects of thermally weakened ductile shear zones on postseismic deformation, *J. Geophys. Res.*, **118**, 6295-6310, doi:10.1002/2013JB010215.

85 Lapusta, N., and J. Jiang (2014). Long-Term Fault Slip in Models With Coseismic Weakening: Depth Extent and Spatio-Temporal Complexity of Earthquake Ruptures, *Proc. of the American Geophysical Union Fall Meeting*, San Francisco, California.

86 Jiang, J., and N. Lapusta (2014). Long-term fault behavior at the seismic-aseismic transition: space-time evolution of microseismicity and depth extent of earthquake rupture, *Proc. of the Southern California Earthquake Center (SCEC) Annual Meeting*, Palm Springs, California.

87 Meng, L., H. Huang, R. Burgmann, J.-P. Ampuero and A. Strader (2014). Aseismic slow-slip and

dynamic ruptures of the 2014 Iquique earthquake sequence, *Proc. of the Southern California Earthquake Center (SCEC) Annual Meeting*, Palm Springs, California.

88 Dunham, E. M., D. Belanger, L. Cong, and J. E. Kozdon (2011). Earthquake ruptures with strongly rate-weakening friction and off-fault plasticity, Part 2: Nonplanar faults, *Bull. Seismol. Soc. Am.*, **101**, 2308-2322, doi:10.1785/0120100076.

89 Shi, Z., and S.M. Day (2013). Rupture dynamics and ground motion from 3-D rough-fault simulations, *J. Geophy. Res.*, **118**, 1-20, doi:10.1002/jgrb.50094.

90 Trugman, D. T. and E. M. Dunham (2014) A 2D pseudo-dynamic rupture model generator for earthquakes on geometrically complex faults, *Bull. Seismol. Soc. Am.*, **104**(1), 95-112, doi:10.1785/0120130138.

91 Kozdon, J. E., and L. C. Wilcox (2015). Provably stable, general purpose projection operators for high-order finite difference methods, submitted.

92 Pelties, C., A. A. Gabriel and J.-P. Ampuero (2014). Verification of an ADER-DG method for complex dynamic rupture problems, *Geosci. Model Dev.*, **7**, 847-866, doi:10.5194/gmd-7-847-2014.

93 Kozdon, J. E., and E. M. Dunham (2015). Adaptive mesh refinement for earthquake rupture simulation, *Geophys. Res. Lett.*, in preparation.

94 Withers, K.B., K.B. Olsen, Z. Shi, and S.M. Day (2015). Broadband (0-8Hz) ground motion variability from ensemble simulations of the 1994 Mw 6.7 Northridge earthquake including rough fault descriptions and Q(f), *Seism. Res. Lett.* **86**:2B, 653.

95 Wang, F., and T. H. Jordan (2014). Comparison of probabilistic seismic hazard models using averaging-based factorization, *Bull. Seismol. Soc. Am.*, **104**, 1230-1257, doi: 10.1785/0120130263.

96 Withers, K. B., K. B. Olsen, and S. M. Day (2015). Memory-efficient simulation of frequency dependent Q, *Bull. Seismol. Soc. Am.*, in press.

97 Taborda, R., and J. Bielak (2014). Ground-Motion Simulation and Validation of the 2008 Chino Hills, California, Earthquake Using Different Velocity Models, *Bull. Seismol. Soc. Am.*, **104**, doi:10.1785/0120130266.

98 Scheitlin, T., P. Domingo, K. Olsen, W. Sarvan, Y. Cui, E. Poyraz, P. Maechling and T. Jordan (2013). Simulated Wave Propagation for the Mw5.4 Chino Hills, CA, Earthquake, Including a Statistical Model of Small-Scale Heterogeneities, *SC2013 Visualization Showcase*, Denver, Nov 17-22, 2013.

99 Lee, E., H. Huang, J. M. Dennis, P. Chen and L. Wang (2013). An optimized parallel LSQR algorithm for seismic tomography, *Computers & Geosciences*, **61**, 184-197.

100 Isbiliroglu, Y., R. Taborda, and J. Bielak (2015). Coupled soil-structure interaction effects of building clusters during earthquakes, *Earthquake Spectra*, **31**, No. 1, 463-500.

101 Taborda, R. and J. Bielak (2013). Ground-motion simulation and validation of the 2008 Chino Hills, California, earthquake, *Bull. Seismol. Soc. Am.*, **103**, 131–156, doi: 10.1785/0120110325.

102 Callaghan, S., P. Maechling, K. Vahi, G., Juve, E. Deelman, Y. Cui, E. Poyraz, T. H. Jordan (2013). Running A Seismic Workflow Application on Distributed Resources*, SC13*, poster, Denver, Nov 17-22.

103 Cui, Y., E. Poyraz, K. B. Olsen, J. Zhou, K. Withers, S. Callaghan, J. Larkin, C. Guest, D. Choi, A. Chourasia, Z. Shi, S. M. Day, P. J. Maechling, T. H. Jordan (2013). Physics-based seismic hazard analysis on petascale heterogeneous supercomputers, *SC13*, Denver, CO, November 18-21, 2013.

104 Zhou, J., Y. Cui, E. Poyraz, D. Choi, and C. Guest (2013). Multi-GPU implementation of a 3D finite difference time domain earthquake code on heterogeneous supercomputers, *Proceedings of International Conference on Computational Science*, **18**, 1255-1264, Elsevier, ICCS 2013, Barcelona, June 5-7.

105 Mu, D., P. Chen and L. Wang (2013). Accelerating the discontinuous Galerkin method for seismic wave propagation simulations using the graphic processing unit (GPU): single GPU implementation, *Computers and Geosciences*, **51**, 282-292.

106 Mu, D., P. Chen and L. Wang (2013). Accelerating the discontinuous Galerkin method for seismic wave propagation simulations using multiple GPUs with CUDA and MPI, *Earthquake Science*, **26**, 6, 377-393.

107 Small, P., R. Taborda, J. Bielak and T. Jordan (2014). GPU Accleration of Hercules, *Proc of the Southern California Earthquake Center (SCEC) Annual Meeting*, September 6-10, 2014, Palm

Springs, California.

108 Cui, Y., E. Poyraz, S. Callaghan, P. Maechling, P. Chen and T. Jordan (2013). Accelerating CyberShake Calculations on XE6/XK7 Platforms of Blue Waters, *Extreme Scaling Workshop 2013*, August 15-16, Boulder, Colorado.

109 Power, M., B. Chiou, N. A. Abrahamson, Y. Bozorgnia, T. Shantz, and C. Roblee (2008). An overview of the NGA project, *Earthquake Spectra*, **24**, 3-21.

110 Tchalenko, J. S., and M. Berberian (1975). Dasht-e-Bayaz fault, Iran: earthquake and earlier related structures in bedrock. *Bull. Geol. Soc. Am*. **86**, 703- 709.

111 Wesnousky, S. G. (2006). Predicting the endpoints of earthquake ruptures, *Nature* **444**, 358–360, doi: 10.1038/nature05275.

112 Biasi, G. P., T. Parsons, R. J. Weldon II, and T. E. Dawson (2013). Appendix J: Fault-to-fault rupture probabilities, *U.S. Geol. Surv. Open-File Rept. 2013-1165-J*, and *California Geol. Surv. Special Rept. 228-J*.

113 Lozos, J. C., D. D. Oglesby, B. Duan, and S. G. Wesnousky (2011). The effects of fault bends on rupture propagation: a geometrical parameter study, *Bull. Seismol. Soc. Am.*, **101**(1), 385-398.

114 Lozos, J. C., D. D. Oglesby, J. N. Brune, and K. B. Olsen (2012). Small intermediate fault segments can either aid or hinder rupture propagation at stepovers, *Geophys. Res. Lett.,* **39**, 10.1029/2012GL053005.

115 Lozos, J. C., J. H. Dieterich, and D. D. Oglesby (2014). The effects of d_o on rupture propagation on fault stepovers, *Bull. Seismol. Soc. Am.,* 10.1785/0120130305.

116 O'Reilly, O., J. Nordstrom, J. E. Kozdon, and E. M. Dunham (2015). Simulation of earthquake rupture dynamics in complex geometries using coupled finite difference and finite volume methods, *Communications in Computational Physics*, **17**(2), 337-370, doi:10.4208/cicp.111013.120914a.

117 Duru, K., and E. M. Dunham (2015). Dynamic earthquake rupture simulations on nonplanar faults embedded in 3D geometrically complex, heterogeneous elastic solids, *J. Comput. Phys.*, in revision.

118 Yule, D. (2009). The enigmatic San Gorgonio Pass, *Geology,* **72**, 2, 191-192, doi:10.1130/focus022009.1.

119 Gold, P. O., W. M. Behr, D. Rood, W. D. Sharp, T. K. Rockwell, K. Kendrick, and A. Salin (2015). Holocene geologic slip rate for the Banning strand of the southern San Andreas Fault, southern California. *J. Geophys. Res.*, **120**, doi:10.1002/2015JB012004.

120 Blisniuk, K., K. Scharer, W. Sharp, R. Burgmann, M. Rymer, and P. Williams (2013). New geological slip rate estimates for the Mission Creek strand of the San Andreas Fault Zone, *2013 SCEC Annual Meeting*.

121 Morelan, A., M. Oskin, J. Chester and D. Elizondo (2014). Active Dextral Slip on the Mill Creek fault through San Gorgonio Pass, *2014 SCEC Annual Meeting*.

122 Kendrick, K. J., J. C. Matti, and S. A. Mahan (2015). Late Quaternary slip history of the Mill Creek strand of the San Andreas fault in San Gorgonio Pass, Southern California: The role of a subsidiary left-lateral fault in strand switching, *Geol. Soc. Am. Bull.*, **127**, 825-849.

123 Scharer, K. M., K. Blisniuk, W. Sharp, P. Williams and K. Johnson (2014). Vertical deformation along the Indio Hills, San Andreas Fault, California, *SCEC Annual Meeting*.

124 Nicholson, C. (2014). Assessing Fault Geometry from Seismicity, *San Gorgonio Pass Special Fault Study Area Workshop,* available at *http://www.scec.org/workshops/*.

125 McGill, S. F., J. C. Spinler, J. D. McGill, R. A. Bennett, M. A. Floyd, J. E. Fryxell, and G. Funning (2015). Kinematic modeling of fault slip rates using new geodetic velocities from a transect across the Pacific-North America plate boundary through the San Bernardino Mountains, California. *J. Geophys. Res.*, **120**, 2772-2793, doi: 10.1002/2014JB011459.

126 Cooke, M. (2014). Impact of Fault Geometry within the San Gorgonio Pass on Deformation, *San Gorgonio Pass Special Fault Study Area Workshop,* available at *http://www.scec.org/workshops/*.

127 Shi, Z and S. Day (2014). Dynamic Rupture Models along Irregular Faults, *San Gorgonio Pass Special Fault Study Area Workshop,* available at *http://www.scec.org/workshops/*.

128 Goebel, T., E. Hauksson, A. Plesch and J. H. Shaw (2014). A comparative study of the seismotectonics in the San Gorgonio and Ventura Special Fault Study Areas, *SCEC Annual Meeting*.

129 Yule, D., D. Heermance, I. Desjarlais and K. Sieh (2014). Late Pleistocene and Holocene rates of slip and size of prehistoric earthquakes on the San Andreas Fault System in San Gorgonio Pass, *2014 SCEC Annual Meeting*.

130 McGill, S., L. Owen, R. J. Weldon, and K. Kendrick (2013). Latest Pleistocene and Holocene slip rate for the San Bernardino strand of the San Andreas fault, Plunge Creek, Southern California: Implications for strain partitioning within the southern San Andreas fault system for the last ~35 k.y., *Geol. Soc. Am. Bull*., **125** (1/2), 48-72, doi: 10.1130/B30647.1.

131 Herbert, J. W., and M. L. Cooke (2012). Sensitivity of the southern San Andreas fault system to tectonic boundary conditions, *Bull. Seismol. Soc. Am.*, **105**, 2046-2062, doi: 10.1785/0120110316.

132 Rockwell, T. K., E. A. Keller, and G. R. Dembroff (1988). Quaternary rate of folding of the Ventura Avenue anticline, western Transverse Ranges, southern California, *GSA Bull*., **100**, 850–858.

133 Rockwell, T. K. (2011). Large co-seismic uplift of coastal terraces across the Ventura Avenue anticline: Implications for the size of earthquakes and the potential for tsunami generation, plenary talk, *2011 SCEC Annual Meeting*, Palm Springs, CA.

134 McAuliffe, L., J. F. Dolan, E. Rhodes, J. Hubbard, J. H. Shaw, and T. Pratt (2015). Characterizing the recent behavior and earthquake potential of the blind Ventura fault system, *Geosphere*, in revision.

135 Thio, H. K., W. Li, J. Shaw, J. Hubbard, A. Plesch, and R. Wilson (2014). Tsunami hazard from the Ventura-Pitas fault and fold system, *2014 SCEC Annual Meeting*, Palm Springs, CA.

136 Ryan, K. J., D. D. Oglesby, and E. L. Geist (2014). Modeling earthquake rupture on the Pitas Point fault: Implications for tsunami generation and propagation, *2014 SCEC Annual Meeting*.

137 Hubbard, J., J. H. Shaw, J. Dolan, T. L. Pratt, L. McAuliffe, and T. K. Rockwell (2014). Structure and seismic hazard of the Ventura Avenue anticline and Ventura fault, California: Prospect for large, multisegment ruptures in the Western Transverse Ranges. *Bull. Seismol. Soc. Am.,* **104**, 1070-1087, doi:10.1785/0120130125.

138 Sarna-Wojcicki, A. M., K. M. Williams, and R. F. Yerkes, 1976, Geology of the Ventura Fault, Ventura County, California. *U.S. Geological Survey Miscellaneous Field Studies*, map MF-781, 3 sheets, scale 1:6,000.

139 Sarna-Wojcicki, A. M., and R. F. Yerkes (1982). Comment on article by R. S. Yeats entitled "Low-shake faults of the Ventura Basin, California". In: Cooper, J. D. (ed.), Neotectonics in Southern California. *Geological Society of America*, 78th Cordilleran Section Annual Meeting, Guidebook, pp. 17–19.

140 Yerkes, R. F., and W. H. K. Lee (1987). Late Quaternary deformation in the western Transverse Ranges. In: Recent Reverse Faulting in the Transverse Ranges. *U.S. Geological Survey Professional Paper 1339*, pp. 71–82.

141 Yerkes, R. F., A. M. Sarna-Wojcicki, and K. R. Lajoie, 1987, Geology and Quaternary deformation of the Ventura area. In: Recent Reverse Faulting in the Transverse Ranges. *U.S. Geological Survey Professional Paper 1339*, pp. 169–178.

142 Huftile, G. J., and R. S. Yeats (1995). Convergence rates across a displacement transfer zone in the western Transverse Ranges, Ventura Basin, California, J*. Geophys. Res*. **100** (B2), 2043–2067.

143 Kamerling, M. J. and C. C. Sorlien (1999). Quaternary slip and geometry of the Red Mountain and Pitas Point-North Channel faults, California (abstract), *Eos. Trans. AGU*, **80** 46 (1003).

144 Kamerling, M. J., C. C. Sorlien, and C. Nicholson (2003). 3D development of an active, oblique fault system: Northern Santa Barbara Channel, CA (poster), *SSA Annual Meeting*.

145 McAuliffe, L., J. F. Dolan, E. Rhodes, J. Hubbard, J. H. Shaw, and T. Pratt (2015). Characterizing the recent behavior and earthquake potential of the blind Ventura fault system, *Geosphere*, in revision.

146 Ucarkus, G., N. Driscoll, D. Brothers, G. Kent, and T. Rockwell (2013). Holocene folding deformation associated with large uplift events on the Ventura Avenue Anticline, *2013 SCEC Annual Meeting*, Palm Springs, CA.

147 Marshall, S. T., G. J. Funning, and S. E. Owen (2014). The Distribution of Fault Slip Rates in the Ventura Fault System, CA, *2014 SCEC Annual Meeting*, Palm Springs, CA.

148 Johnson, K. J., W. C. Hammond, and R. Burgette (2014). Geodetic constraints on shortening, uplift, and fault slip across the Ventura Basin, *SCEC Annual Meeting*, Palm Springs, CA.

149 Hammond, W. C., R. Burgette, and K. Johnson (2014). Measuring Ventura Area Uplift: A Four-Technique Geodetic Study of Vertical Tectonics Combining GPS, InSAR, Leveling and Tide Gauges, *SCEC Annual Meeting*, Palm Springs, CA.

150 Gomberg, J., J. L. Rubinstein, Z. Peng, K. C. Creager, J. E. Vidale, and P. Bodin (2008). Widespread Triggering of Nonvolcanic Tremor in California, *Science,* **319***,* 5860, 10.1126/science.1149164.

151 Wang, T.-H., E. S. Cochran, D. Agnew, and D. D. Oglesby (2013). Infrequent triggering of tremor along the San Jacinto Fault near Anza, California, *Bull. Seismol. Soc. Am.,* **103**, 2482-2497, doi: 10.1785/0120120284.

152 Yoon, C. E., O. O'Reilly, K. Bergen, and G. C. Beroza (2015). Earthquake detection through computationally efficient similarity search, *Science Advances*, submitted.

153 Hawthorne, J. C. and J.-P. Ampuero (2014). A search for seismic precursors to earthquakes in southern California, *2014 SCEC Annual Meeting*, September, Palm Springs, CA.

154 Llenos, A. L. and J. J. McGuire (2011). Detecting aseismic strain transients from seismicity data, *J. Geophys. Res.,* **116**, B06305, doi:10.1029/2010JB007537.

155 Chen, X., and P. M. Shearer (2013). California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett.*, **40**, doi:10.1002/grl.50444.

156 Chen, X., P. M. Shearer, and R. E. Abercrombie (2102). Spatial migration of earthquakes within seismic clusters in Southern California: Evidence for fluid diffusion, *J. Geophys. Res.*, **117**, B04301, doi: 10.1029/2011JB008973.

157 Lohman, R. B., and J. R. Murray (2013). The SCEC geodetic transient-detection validation exercise, *Seismol. Res. Lett.*, **84**, 419-425.

158 Crouse, C. B. (2012). The Role SCEC can play in improving seismic provisions in US codes through ground-motion simulations, *2012 SCEC Annual Meeting.*

159 Shaw, J. H., A. Plesch, C. Tape, M. P. Suess. T. H. Jordan, G. Ely, E. Hauksson. J. Tromp, T. Tanimoto, R. Graves, K. Olsen, C. Nicholson, P. J. Maechling, C. Rivero, P. Lovely, C. M. Brankman, and J. Munster (2015). Unified Structural Representation of the southern California crust and upper mantle, *Earth Planet. Sci. Lett.*, **415**, 1-15, doi:10.1016/j.epsl.2015.01.016.

160 Tape, C., Q. Liu, A. Maggi & J. Tromp (2010). Seismic tomography of the southern California crust based on spectral-element and adjoint methods, *Geophys. J. Int.*, **180**, 433-462; Lee, E., H. Huang, J. M. Dennis, P. Chen and L. Wang (2013). An optimized parallel LSQR algorithm for seismic tomography, *Computers & Geosciences*, **61**, 184-197.; Shaw, J. H., A. Plesch, C. Tape, M. P. Suess. T. H. Jordan, G. Ely, E. Hauksson. J. Tromp, T. Tanimoto, R. Graves, K. Olsen, C. Nicholson, P. J. Maechling, C. Rivero, P. Lovely, C. M. Brankman, and J. Munster (2015). Unified Structural Representation of the southern California crust and upper mantle, *Earth Planet. Sci. Lett.*, **415**, 1-15, doi:10.1016/j.epsl.2015.01.016.

161 Lee, E., H. Huang, J. M. Dennis, P. Chen and L. Wang (2013). An optimized parallel LSQR algorithm for seismic tomography, *Computers & Geosciences*, **61**, 184-197.

162 Lee, E.-J. and P. Chen (2013). Automating seismic waveform analysis for full 3-D waveform inversions, *Geophysical Journal International*, **194**, 572-589, doi: 10.1093/gji/ggt124.

163 Olsen, K. B. (2014). *Statistical modeling of shallow velocity heterogeneities with validation against strong ground motion*, Final Technical Report for USGS award G12AP20015; Jordan, T. H. (2015). An effective medium theory for three-dimensional elastic heterogeneities, *Geophys. J. Int.*, doi:10.1093/gji/ggv355.

164 Dreger, D. S., and T. H. Jordan (2015), Introduction to the focus section on validation of the SCEC Broadband Platform V14.3 simulation methods, *Seismol. Res. Lett.,* **86**, 15-16, doi:10.1785/0220140233.

165 Abrahamson, N., Atkinson, G., Boore, D., Bozorgnia, Y., Campbell, K., Chiou, B., Idriss, I. M., Silva, W., and Youngs, R. (2008). Comparisons of the NGA Ground-Motion Relations, *Earthquake Spectra*, **24**(1), 45–66.

166 Gregor, N., N. A. Abrahamson, G. M. Atkinson, D. M. Boore, Y. Bozorgnia, K. W. Campbell, B. S.-J. Chiou, I. M. Idriss, R. Kamai, E. Seyhan, W. Silva, J. P. Stewart, and R. Youngs (2014). Comparison of NGA-West2 GMPEs, *Earthquake Spectra*, **30**(3), 1179–1197.

167 Goulet, C. A., N. A. Abrahamson, P. G. Somerville, and K. E. Wooddell (2015). The SCEC Broadband Platform validation exercise: Methodology for code validation in the context of seismic-hazard analyses, *Seismol. Res. Lett.*, **86**, 17-26.

---

168 Denolle, M**.**, E. M. Dunham, G. A. Prieto, and G. C. Beroza (2013). Ground motion prediction of realistic earthquake sources using the ambient seismic field, *J. Geophys. Res.*, **118**, 2102-2118, doi:10.1029/2012JB009603; Denolle, M., E. M. Dunham, G. A. Prieto, and G. C. Beroza (2014). Strong ground motion prediction using virtual earthquakes, *Science*, **343**, 399-403, doi:10.1126/science.1245678.

169 Viens, L., A. Laurendeau, L. F. Bonilla, and N. M. Shapiro (2014). Broad-band acceleration time histories synthesis by coupling low-frequency ambient seismic field and high frequency stochastic modeling, Geophys. J. Int., 199, 1784-1797.

170 Viens, L., H. Miyake, and K. Koketsu (2015). Long‐period ground motion simulation of a subduction earthquake using the offshore–onshore ambient seismic field, *Geophys. Res. Lett.,* **42**, 5282-5287.

171 Building Seismic Safety Council, Project 17, *http://www.nibs.org/?page=bssc.*

172 Wood, M. M. (2015a). *Evaluation of SCEC Communication, Education, and Outreach Program*, September, 43 pp.

173 Wood, M. M. (2015a). *Evaluation of SCEC Communication, Education, and Outreach Program*, September, 43 pp.

174 Jordan, T. H. (2014). The prediction problems of earthquake system science, *Seismol. Res. Lett.*, **85**, 767-769, doi:10.1785/0220140088.

175 Marzocchi, W., and T. H. Jordan (2014), Testing for ontological errors in probabilistic forecasts of natural systems, *Proc. Nat. Acad. Sci.*, **111**, 11973-11978, doi/10.1073/pnas.1410183111.

176 National Research Council Committee on National Earthquake Resilience (2011). *National Earthquake Resilience: Research, Implementation, and Outreach*, National Academies Press, Washington, D.C., ISBN:978-0-309-18677-3, 198 pp.

177 Pacific Earthquake Engineering Research (PEER) Center website: http://peer.berkeley.edu/.

178 Natural Hazards Engineering Research Infrastructure (NHERI) Program website: http://www.designsafe-ci.org/.

179 Building Seismic Safety Council, *Project 17*, http://www.nibs.org/?page=bssc.

180 Mileti, D. S., and P. W. O'Brien (1991). *Public Response to the Loma Prieta Earthquake Emergency and Aftershock Warnings: Findings and Lessons*, Hazards Assessment Laboratory, Colorado State University, Fort Collins, CO; Mileti, D. S., R. Bandy, L. B. Bourque, A. Johnson, M. Kano, L. Peek, L., and M. Wood (2006). *Annotated Bibliography for Public Risk Communication on Warnings for Public Protective Actions Response and Public Education (Revision 5)*, National Hazards Institute, University of Colorado, Boulder, CO.

181 National Research Council Committee on Increasing National Resilience to Hazards and Disasters (2012). *Disaster Resilience: A National Imperative*, National Academies Press, Washington, D.C., ISBN:978-0-309-26150-0. 260 pp.

182 NSF Advisory Committee for Geosciences (2014). *Dynamic Earth: GEO Imperatives & Frontiers 2015–2020*, National Science Foundation, Washington, D.C., December, 2014, 36 pp.

183 Lay, T., ed. (2009). *Seismological Grand Challenges in Understanding Earth's Dynamic Systems*, Report to the National Science Foundation, IRIS Consortium, 76 pp.

184 Davis, J. L., Y. Fialko, W. E. Holt, M. M. Miller, S. E. Owen, and M. E. Pritchard (Eds.) (2012), *A Foundation for Innovation: Grand Challenges in Geodesy*, Report from the Long-Range Science Goals for Geodesy Community Workshop, UNAVCO, Boulder, Colorado, 79 pp.

185 Stokes, D. E. (1997). *Pasteur's Quadrant—Basic Science and Technological Innovation*, Brookings Institution Press, 180 pp.

186 SCEC Community Stress Model, http://sceczero.usc.edu/projects/CSM.

187 Yang, W., and E. Hauksson (2013). The tectonic crustal stress field and style of faulting along the Pacific-North America plate boundary in southern California, *Geophys. J. Int.,* **194**, 100-117, doi:10.1093/gji/ggt113.

188 Luttrell K., B. Smith-Konter, and D. Sandwell (2012). Investigating absolute stress in southern California: How well do stress models of compensated topography and fault loading match earthquake focal mechanisms?, *2012 SCEC Annual Meeting*, Poster 039.

189 Yang, W., and E. Hauksson (2013). The tectonic crustal stress field and style of faulting along the Pacific-North America plate boundary in southern California, *Geophys. J. Int.,* **194**: 100-117, doi:10.1093/gji/ggt113.

190 Humphreys, E. D., and D. Coblentz, D. (2007). North American dynamics and western U.S. Tectonics, *Rev. Geophys.*, **45**, doi:10.1029/2005RG000181; Flesch, L. M., W. E. Holt, A. J. Haines, L. Wen, and B. Shen-Tu (2007). The dynamics of western North America: Stress magnitudes and the relative role of gravitational potential energy, plate interaction at the boundary and basal tractions, *Geophys. J. Int.*, **169**, 866-896; Bird, P. (1999). Thin-plate and thin-shell finite element programsfor forward dynamic modeling of plate deformation and faulting, *Computers & Geosc.*, 25, 383-394; Parsons, T. (2006). Tectonic stressing in California modeled from GPS observations, *J. Geophys. Res.*, **111**, doi:10.1029/2005JB003946.

191 Bird, P. (2014). Stress field models from Maxwell stress functions, *SCEC Annual Report*, Award 12053, March 2014, 12 pp.; submitted to *Geophys. J. Int.*

192 Baumann, T., B. J. Kaus, and A. Popov (2014). Constraining effective rheology through parallel joint geodynamic inversion, *Tectonophysics*, **631**, 197-211; Worthen, J., G. Stadler, N. Petra, M. Gurnis, O. Ghattas (2014). Towards an adjoint-based inversion for rheological parameters in nonlinear viscous mantle flow, *Phys. Earth Planet. Int.*, **234**, 23-34.

193 Spudich, P., and K. Olsen (2001). Fault zone amplified waves as a possible seismic hazard along the Calaveras fault in Central California, *Geophys. Res. Lett.*, **28**, 2533–2536, doi:10.1029/2000GL011902; Cochran, E., Y.-G. Li, P. Shearer, S. Barbot, Y. Fialko, and J. Vidale (2009). Seismic and geodetic evidence for extensive, long-lived fault damage zones, *Geology*, 37, 315-318, doi:10.1130/G25306A; Allam, A.A., Y. Ben-Zion, I. Kurzon, and F. Vernon (2014). Seismic velocity structure in the Hot Springs and trifurcation seismicity cluster areas of the San Jacinto Fault Zone from double-difference tomography, *Geophys. J. Int.*, **198**, 978–999; Lindsey, E., V. Sahakian, Y. Fialko, Y. Bock, S. Barbot, and T. Rockwell (2014). Interseismic strain localization in the San Jacinto fault zone, *Pure Appl. Geophys.*, **171**, 2937-2954; Li, Y.-G., G. P. De Pascale, M. C. Quigley, and D. M. Gravley (2014). Fault damage zones of the M7.1 Darfield and M6.3 Christchurch earthquakes characterized by fault-zone trapped waves, *Tectonophysics*, **618**, 79-101.

194 Vidale, J. E., and Y.-G. Li (2003). Damage to the shallow Landers fault from the nearby Hector Mine earthquake, *Nature*, **421**, 524–526, doi:10.1038/ nature01354; Rubinstein, J. L. and G. C. Beroza (2004) Evidence for widespread nonlinear strong ground motion in the Mw 6.9 Loma Prieta earthquake, *Bull. Seismol. Soc. Am.,* **94**, 1595-1608.; Brenguier, F., M. Campillo, C. Hadziioannou, N.M. Shapiro, R.M. Nadeau, and E. Larose (2008). Postseismic relaxation along the San Andreas Fault at Parkfield from continuous seismological observations, *Science*, **321**, 1478-1481, doi:10.1126/science.1160943.

195 Le Pourhiet, L., B. Huet, and N. Traoré (2014). Links between long-term and short-term rheology ofthe lithosphere: Insights from strike-slip fault modelling, *Tectonophysics*, **631**, 146-159; van Dinther, Y. T.V. Gerya, L. A. Dalguer, P. M. Mai, G. Morra, and D. Giardini (2013). The seismic cycle at subduction thrusts: insights from seismo-thermo-mechanical models, *J. Geophys. Res.*, 118, 6183-6202, doi:10.1002/2013JB010380.

196 Andrews, D. J. (2005). Rupture dynamics with energy loss outside the slip zone, *J. Geophys. Res.*, **110**, B01307, doi 10.1029/2004JB003191; Rice, J. R., C. G. Sammis, and R. Parsons (2005). Off-fault secondary failure induced by a dynamic slip-pulse, *Bull. Seismol. Soc. Am.*, **95**, 109-134, doi 10.1785/0120030166; Duan, B., and S. M. Day (2008). Inelastic strain distribution and seismic radiation from rupture of a fault kink, *J. Geophys. Res.*, **113**, B12311, doi:10.1029/2008JB005847; Templeton, E. L., and J. R. Rice (2008). Off-fault plasticity and earthquake rupture dynamics: 1. Dry materials or neglect of fluid pressure changes, *J. Geophys. Res.*, **113**, B09306, doi10.1029/2007JB005529; Ma, S. (2008), A physical model for widespread near-surface and fault zone damage induced by earthquakes: *Geochem. Geophys. Geosyst.*, **9**, Q11009, doi:10.1029/2008GC002231; Ma, S. (2009), Distinct asymmetry in rupture-induced inelastic strain across dipping faults: *Geophys. Res. Lett.*, **36**, L20317, doi:10.1029/2009GL040666; Ma, S., and D. J. Andrews (2010). Inelastic off-fault response and three-dimensional dynamics of earthquake rupture on a strike-slip fault, *J. Geophys. Res.*, **115**, B04304, doi:10.1029/2009JB006382; Dunham, E. M., D. Belanger, L. Cong, and J. E. Kozdon (2011). Earthquake ruptures with strongly rate-weakening friction and off-fault plasticity, Part 2: Nonplanar faults, *Bull. Seismol. Soc. Am.*, **101**, 2308-2322, doi:10.1785/0120100076; DeDontney, N., J. R. Rice, and R. Dmowska (2012). Finite element model of branched ruptures including off-fault plasticity, *Bull. Seismol. Soc. Am.*, **102**, 541-562; Gabriel, A. A., J.-P. Ampuero, L. A. Dalguer, and P. M. Mai (2013). Source properties of dynamic rupture pulses with off-fault plasticity, *J. Geophys. Res.*, **118**, 4117-4126; Xu, S. and Y. Ben-Zion (2013). Numerical and theoretical analyses of in-plane dynamic rupture on a frictional interface and off-fault yielding patterns at different scales, *Geophys. J. Int.*, **193**, 304-320; Shi, Z., and S. M. Day (2013). Rupture dynamics and ground motion from 3-D rough-fault simulations, *J. Geophys. Res.*, **118**, 1122-1141, doi:10.1002/jgrb.50094.

197 Kaneko, Y. and Y. Fialko (2011). Shallow slip deficit due to large strike-slip earthquakes in dynamic rupture simulations with elasto-plastic off-fault response, *Geophys. J. Int.*, **186**, 1389-1403, 2011.

198 Oskin, M., J. Arrowsmith, C. Hinojosa, A. Elliot, J. Fletcher, E. Fielding, P. Gold, J. Gonzalez, K. Hudnut, J. Liu-Zeng, O. Teran (2012). Near-field deformation from the El Mayor-Cucapah earthquake revealed by differential LIDAR, *Science*, **335**, 702-705, doi:10.1126/science.

199 Herbert, J. W., M. L. Cooke, M. Oskin, and O. Difo (2014). How much can off-fault deformation contribute to the slip rate discrepancy within the Eastern California Shear Zone?, *Geology*, **42**, 71-75.

200 Andrews, D. J., T. C. Hanks, and J. W. Whitney (2007). Physical limits on ground motion at Yucca Mountain, *Bull. Seismol. Soc. Am.*, **97**, 1,771-1,792; doi:10.1785/0120070014; Harris, R. A., M. Barall, D. J. Andrews, B. Duan, S. Ma, E. M. Dunham, A.-A. Gabriel, Y. Kaneko, Y. Kase, B. Aagaard, D. D. Oglesby, J.-P. Ampuero, T. C. Hanks, and N. Abrahamson (2011). Verifying a computational method for predicting extreme ground motion, *Seismol. Res. Lett.*, **82**, 638-644, doi:10.1785/gssrl.82.5.638.

201 Roten, D., K. B. Olsen, S. M. Day, Y. Cui, and D. Fäh (2014). Expected seismic shaking in Los Angeles reduced by San Andreas fault zone plasticity, *Geophys. Res. Lett.*, **41**, 2769-2777.

202 Brune, J. N., T. L. Henyey, and R. F. Roy (1969). Heat flow, stress, and rate of slip along the San Andreas fault, California, *J. Geophys. Res.*, **74**, 3821–3827; Lachenbruch, A.H., and Sass, J.H. (1980). Heat flow and energetics of the San Andreas fault zone, *J. Geophys. Res.*, **85**, 6185–6223; Lachenbruch, A. H. (1980). Frictional heating, fluid pressure, and the resistance to fault motion, *J. Geophys. Res.*, 85, 6097-6122.

203 Kano, Y., J. Mori, R. Fujio, H. Ito, T. Yanagidani, S. Nakao, and K. F. Ma (2006). Heat signature on the Chelungpu fault associated with the 1999 Chi-Chi, Taiwan earthquake, *Geophys. Res. Lett.*, **33**, L14306, doi:10.1029/2006GL026733; Tanaka, H., W. M. Chen, C. Y. Wang, K. F. Ma, N. Urata, J. Mori, and M. Ando (2006). Frictional heat from faulting of the 1999 Chi-Chi, Taiwan earthquake, *Geophys. Res. Lett.*, **33**, L16316, doi:10.1029/2006GL026673.

204 Tanikawa, W., and T. Shimamoto (2009). Frictional and transport properties of the Chelungpu fault from shallow borehole data and their correlation with seismic behavior during the 1999 Chi-Chi earth-quake, *J. Geophys. Res.,* **114**(B1), doi: 10.1029/2008JB005750; Fulton, P. M., E. E. Brodsky, Y. Kano, J. Mori, F. Chester, T. Ishikawa, R. N. Harris, W. Lin, N. Eguchi, S. Toczko, Expedition 343, 343T, and KR13-08 Scientists (2013). Low coseismic friction on the Tohoku-Oki fault determined from temperature measurements, *Science*, **342**, 1214–1217, doi:10.1126/science.1243641.

205 Byerlee, J. (1978). Friction of rocks. *Pure Appl. Geophys.*, **116**, 615–626.

206 Townend, J., and M. D. Zoback (2004). Regional tectonic stress near the San Andreas fault in central and southern California, *Geophys. Res. Lett.*, **31**, L15S11, doi:10.1029/203GL018918; Zoback, M. D., S. Hickman and W. Ellsworth (2007). The role of fault zone drilling, in *Treatise on Geophysics*, vol. 4, ed. H. Kanamori, Elsevier, Amsterdam.

207 Spudich, P.K.P. (1992). On the inference of absolute stress levels from seismic radiation, *Tectonophysics*, **211**, 99–106, doi:10.1016/0040-1951(92)90053-9; Spudich P., M. Guatteri, K. Otsuki, and J. Minagawa (1998). Use of fault striations and dislocation models to infer tectonic shear stress during the 1995 Hyogo-Ken Nanbu (Kobe) earthquake, *Bull. Seismol. Soc. Am.*, **88**, 413-427.

208 Beroza, G. C., and M. D. Zoback (1993). Mechanism diversity of the Loma Prieta aftershocks and the mechanics of mainshock-aftershock interaction, *Science*, **259**, 210-213; Wesson, R. L., and O. S. Boyd (2007). Stress before and after the 2002 Denali fault earthquake. *Geophys. Res. Lett.*, **34**, 7303, doi:10.1029/2007GL029189.

209 Harris, R. A., J. F. Dolan, R. Hartleb, and S.M. Day (2002). The 1999 Izmit, Turkey earthquake - a 3D dynamic stress transfer model of intraearthquake triggering, *Bull. Seismol. Soc. Am.*, **92**, 245-255.

---

210 Rice, J. R. (1999). Flash heating at asperity contacts and rate-dependent friction, *Eos*, **80**, F681l; Rice, J. R. (2006). Heating and weakening of faults during earthquake slip, *J. Geophys. Res.*, **111**, B05311, doi:10.1029/2005JB004006; Beeler, N. M., T. E. Tullis, and D. L. Goldsby (2008). Constitutive relationships and physical basis of fault strength due to flash heating, *J. Geophys. Res*. **113**, B01401, doi 10.1029/2007JB004988; Tullis, T. E (2007). Friction of rock at earthquake slip rates, in *Treatise on Geophysics*, vol. 4, ed. H. Kanamori, 131-152, Elsevier, Amsterdam; Goldsby, D. L., and T. E. Tullis (2011). Flash heating leads to low frictional strength of crustal rocks at earthquake slip rates. *Science*, **334**, 216–218. doi:10.1126/science.1207902.

211 Sibson, R. H. (1973). Interaction between temperature and pore-fluid pressure during earthquake faulting — A mechanism for partial or total stress relief, *Nature*, **243**, 66-68; Lachenbruch, A. H. (1980). Frictional heating, fluid pressure, and the resistance to fault motion, *J. Geophys. Res.*, 85, 6097-6122; Mase, C. W., and L. Smith (1987). Effects of frictional heating on the thermal, hydrologic, and mechanical response of a fault, *J. Geophys. Res.*, **92**, 6249-6272; Andrews, D. J. (2002). A fault constitutive relation accounting for thermal pressurization of pore fluid, *J. Geophys. Res.*, **107**, B2363; Rice, J. R. (2006). Heating and weakening of faults during earthquake slip, *J. Geophys. Res.*, **111**, B05311, doi:10.1029/2005JB004006; Noda, H., E. M. Dunham, and J. R. Rice (2009), Earthquake ruptures with thermal weakening and the operation of major faults at low overall stress levels, *J. Geophys. Res.*, **114**, B07302, doi:10.1029/2008JB006143.

212 Di Toro, G., D. L. Golbsby, and T. E. Tullis (2004). Friction falls toward zero in quartz rock as slip velocity approaches seismic rates, *Nature*, **427**, 436–439; Tullis, T. E (2007). Friction of rock at earthquake slip rates, in *Treatise on Geophysics*, vol. 4, ed. H. Kanamori, 131-152, Elsevier, Amsterdam.

213 Han, R., T. Shimamoto, T. Hirose, J.-H. Ree, and J.-I. Ando (2007). Ultralow friction of carbonate faults caused by thermal decomposition, *Science*, **316**, 878-881, doi:10.1126/science.1139763; Hirose, T., and M. Bystricky (2007). Extreme dynamic weakening of faults [containing serpentine] during dehydration by coseismic shear heating, *Geophys. Res. Lett.*, **34**, L14311, doi:10.1029/2007GL030049; Brantut, N., A. Schubnel, J.-N. Rouzaud, F. Brunet, and T. Shimamoto (2008). High-velocity frictional properties of a clay-bearing fault gouge and implications for earthquake mechanics, *J. Geophys. Res.*, **113**, B10401, doi:10.1029/2007JB005551; Sulem, J., and V. Famin (2009). Thermal decomposition of carbonates in fault zones: Slip-weakening and temperature limiting effects, *J. Geophys. Res.*, **114**, B03309, doi:10.1029/2008JB006004; Brantut, N., A. Schubnel, J. Corvisier, and J. Sarout (2010). Thermo-chemical pressurization of faults during coseismic slip, *J. Geophys. Res.*, **115**, B05314, doi:10.1029/2009JB006533.

214 Noda, H., & Lapusta, N. (2013). Stable creeping fault segments can become destructive as a result of dynamic weakening. *Nature*, **493**, 518-21. doi:10.1038/nature11703.

215 Jiang, J., and N. Lapusta (2015). Variability in earthquake slip and arresting depths in rate-and-state fault models with coseismic weakening, *J. Geophys. Res.*, in preparation.

216 Shaw, B. E. and S. G. Wesnousky (2008). Slip-Length scaling in large earthquakes: The role of deep penetrating slip below the seismogenic layer, *Bull. Seismol. Soc. Am.*, **98**, 1633-1641, doi:10.1785/0120070191; Noda, H., & Lapusta, N. (2013). Stable creeping fault segments can become destructive as a result of dynamic weakening. *Nature*, **493**, 518-21. doi:10.1038/nature11703.

217 Platt, J.D., J.W. Rudnicki, and J.R. Rice (2014). Stability and Localization of Rapid Shear in Fluid-Saturated Fault Gouge, 2. Localized zone width and strength evolution, *J. Geophys. Res.*, **119**, doi: 10.1002/2013JB010711.

218 Segall, P., A. M. Rubin, A. M. Bradley, and J.R. Rice (2010). Dilatant strengthening as a mechanism for slow slip events, *J. Geophys. Res.*, **115**, B12305.

219 Hall, J. F., T. H. Heaton, M. W. Halling, and D. J. Wald (1995). Near-source ground motion and its effects on flexible buildings, *Earthquake Spectra*, **11**, 569-605; Krishnan, S., C. Ji, D. Komatitsch, and J. Tromp (2006a). Performance of two 18-story steel moment-frame buildings in Southern California during two large simulated San Andreas earthquakes, *Earthquake Spectra*, **22**, 1035-1061; Krishnan, S., C. Ji, D. Komatitsch, and J. Tromp (2006b). Case studies of damage to tall steel moment-frame buildings in Southern California during large San Andreas earthquakes, *Bull. Seismol. Soc. Am.*, **96**, 1523-1537; Muto, M., and S. Krishnan (2011). Hope for the best, prepare for the worst: response of tall steel buildings to the ShakeOut scenario earthquake, *Earthquake Spectra*, **27**,

375, doi:10.1193/1.3563621.

220 Jordan, T. H., W. Marzocchi, A. J. Michael, and M. C. Gerstenberger (2014). Operational earthquake forecasting can enhance earthquake preparedness. *Seismol. Res. Lett.*, **85**, 955-959, doi:10.1785/0220140143; Milner, K. R., T. H. Jordan, The Working Group on California Earthquake Probabilities, and The CyberShake Collaboration (2015). Operational earthquake forecasting in California: A prototype system combining UCERF3 and CyberShake (abstract), *Seismol. Res. Lett.*, **86**, 591, doi:10.1785/0220150017.

221 Kuyuk, H. S., R. M. Allen, H. Brown, M. Hellweg, I. Henson, and D. Neuhauser (2014). Designing a network-based earthquake early warning algorithm for California: ElarmS-2., *Bull. Seismol. Soc. Am.*,, **104**, 162-173, doi:10.1785/0120130146.; Böse, M., R. Allen, H. Brown, G. Gua, M. Fischer, E. Hauksson, T. Heaten, M. Hellweg, M. Liukis, D. Neuhauser, P. Maechling, K. Solanki, M. Vinci, I. Henson, O. Khainovski, S. Kuyuk, M. Carpio, M.-A. Meier, and T. Jordan (2014). CISN ShakeAlert: An earthquake early warning demonstration system for California, *Early Warning for Geological Disasters*, ed. F. Wenzel and J. Zschau, Springer-Verlag, Berlin, pp. 49-69, doi:10.1007/978-3-642-12233-0_3.

222 Olsen, K.B. (2000). Site amplification in the Los Angeles Basin from 3D modeling of ground motion, *Bull. Seis. Soc. Am.* **90**, S77-S94; Day, S. M., R. W. Graves, J. Bielak, D. Dreger, S. Larsen, K. B. Olsen, A. Pitarka, and L. Ramirez-Guzman (2008). Model for basin effects on long-period response spectra in southern California, *Earthquake Spectra* **24**, 257-277; Day, S.M., D. Roten, and K.B. Olsen (2012). Adjoint analysis of the source and path sensitivities of basin-guided waves, *Geophys. J. Int.* , **189**, 1103-1124, doi: 10.1111/j.1365-246X.2012.05416.x; Delorey, A. A., A. D. Frankel, P. Liu, and W. J. Stephenson (2014). Modeling the effects of source and path heterogeneity on ground motions of great earthquakes on the Cascadia Subduction Zone using 3D simulations, *Bull. Seismol. Soc. Am.*, **104**, 1430-1446, doi:10.1785/0120130181.

223 Ma, S., R. J. Archuleta, and M. T. Page (2007), Effects of large-scale surface topography on ground motions, as demonstrated by a study of the San Gabriel Mountains, Los Angeles, California, *Bull. Seismol. Soc. Am.*, **97**, 2066-2079, doi:10.1785/0120070040; Ely, G., S.M. Day, and J-B. Minster (2010). Dynamic rupture models for the southern San Andreas fault, *Bull. Seismol. Soc. Am.*, **100**, 131-150, doi:10.1785/0120090187.

224 Callaghan, S., P. Maechling, G. Juve, K. Vahi, R. W. Graves, K. B. Olsen, K. Milner, D. Gill, Y. Cui, and T. H. Jordan (2015). Using CyberShake workflows to calculate a 1 Hz urban seismic hazard map on large-scale open-science HPC resources (abstract), *2015 SCEC Annual Meeting*, Palm Springs, California.

225 Graves, R., T. H. Jordan, S. Callaghan, E. Deelman, E. Field, G. Juve, C. Kesselman, P. Maechling, G. Mehta, K. Milner, D. Okaya, P. Small, and K. Vahi (2011). CyberShake: A physics-based probabilistic hazard model for Southern California, *Pure Appl. Geophys.*, **167**, 367-381, doi:10.1007/s00024-010-0161-6.

226 King, G. C. P., R. S. Stein, and J. Lin (1994). Static stress changes and the triggering of earthquakes, *Bull. Seismol. Soc. Am.*, **84**, 935-953.

227 McCaffrey, R. (2005). Block kinematics of the Pacific-North America plate boundary in the southwestern United States from inversion of GPS, seismological, and geologic data, *J. Geophys. Res.*, **110**, B07401, doi:10.1029/2004JB003307; Bird, P. (2009). Long-term fault slip rates, distributed deformation rates, and forecast of seismicity in the western United States from joint fitting of community geologic, geodetic, and stress direction data sets, *J. Geophys. Res.*, **114**, B11403, doi:10.1029/2009JB006317; Johnson, K.M. and J. Fukuda (2010). New methods for estimating the spatial distribution of locked asperities and stress-driven interseismic creep on faults with application to the San Francisco Bay Area, California, *J. Geophys. Res.*, **115**, B12408, doi:10.1029/2010JB007703; Loveless, J. P., and B. J. Meade (2011). Stress modulation on the San Andreas fault due to interseismic fault system interactions, *Geology,* **39**, 1035-1038, doi:10.1130/G32215.1; Hammond, W. C., G. Blewitt, and C. Kreemer (2011). Block modeling of crustal deformation of the northern Walker Lane and Basin and Range from GPS velocities, *J. Geophys. Res.,* **166**, B04402.

228 Blisniuk, K., K. Scharer, W. Sharp, R. Burgmann, M. Rymer, and P. Williams (2013). New geological slip rate estimates for the Mission Creek strand of the San Andreas Fault Zone, *2013 SCEC Annual*

Meeting.

229 Dawson, T. E., S.F. McGill, and T. K. Rockwell (2003). Irregular recurrence of paleoearthquakes along the central Garlock fault near El Paso Peaks, California, *J. Geophys. Res.*, **108**, doi: 10.1029/2001JB001744.

230 Dolan, J.F., Bowman, D.D., and Sammis, C.G. (2007). Long-range and long- term fault interactions in southern California, *Geology*, **35**, 855–858, doi: 10.1130/G23789A.1.

231 McAuliffe, L. J., J. F. Dolan, E. Kirby, C. Rollins, B. Haravitch, S. Alm, and T. M. Rittenour (2013). Paleoseismology of the Southern Panamint Valley Fault: Implications for Regional Earthquake Occurrence and Seismic Hazard in Southern California, *J. Geophys. Res.*, **118**, 5126–46. doi:10.1002/jgrb.50359.

232 Rittase, W. M., E. Kirby, E. McDonald, J. D. Walker, J. Gosse, J. O.G. Spencer, and A. J. Herrs (2014). Temporal variations in Holocene slip rate along the central Garlock fault, Pilot Knob Valley, California**,** *Lithosphere,* **6**, 48-58, doi: 10.1130/L286.1.

233 Blisniuk, K., M. Oskin, A. Mériaux, T. Rockwell, R. Finkel, and F. Ryerson (2013). Stable, rapid rate of slip since inception of the San Jacinto Fault, California, *Geophys. Res. Lett.,* **40**, 1-5, doi: 10.1002/grl.50819.

234 Roder, B., M. Lawson, E. Rhodes, J. Dolan, L. McAuliffe, and S. McGill (2011). Assessing the potential of luminescence dating for fault slip rate studies on the Garlock Fault, Mojave Desert, California, USA, *Quaternery Geochronology,* **10**, 285-290.

235 Kame, N., J. R. Rice, and R. Dmowska (2003). Effects of prestress state and rupture velocity on dynamic fault branching, *J. Geophys. Res.*, **108**, doi:10.1029/2002JB002189.

236 Duan, B. C., and D. D. Oglesby (2005). Multicycle dynamics of nonplanar strike-slip faults, *J. Geophys. Res.*, **110**, doi:10.1029/2004JB003298.

237 Lozos, J. C., D. D. Oglesby, B. Duan, and S. G. Wesnousky (2011). The effects of double fault bends on rupture propagation: a geometrical parameter study, *Bull. Seismol. Soc. Am.*, **101**, doi:10.1785/0120100029.

238 Liu, Z. (2014). *Rupture Dynamics of Strike-Slip Faults with Stepovers: From Conceptually Simplified to Realistically Complex Fault Systems* (Ph.D thesis), Texas A&M University, 107 pp.

239 Yikilmaz, M. B., D. L. Turcotte, E. M. Heien, L. H. Kellogg, and J. B. Rundle (2014). Critical jump distance for propagating earthquake ruptures across step-overs, *Pure Appl. Geophys.*, doi:10.1007/s00024-014-0786-y.

240 Field, E. H., G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, Y. Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Y. Zeng (2015). Long-term, time-dependent probabilities for UCERF3, *Bull. Seismol. Soc. Am.*, **105**, doi:10.1785/0120140093.

241 Olsen, K. B., S. M. Day, J. B. Minster, Y. Cui, A. Chourasia, D. Okaya, P. Maechling, and T. H. Jordan (2008). TeraShake2: Spontaneous rupture simulations of Mw 7.7 earthquakes on the southern San Andreas fault, *Bull. Seismol. Soc. Am.*, **98**, 1162-1185; Olsen, K. B., S. M. Day, L. A. Dalguer, J. Mayhew, Y. Cui, J. Zhu, V. M. Cruz-Atienza, D. Roten, P. Maechling, T. H. Jordan, D. Okaya, and A. Chourasia (2009), ShakeOut-D: Ground motion estimates using an ensemble of large earthquakes on the southern San Andreas fault with spontaneous rupture propagation, *Geophys. Res. Lett.*, **36**, L04303, doi:10.1029/2008GL036832.

242 Blisniuk, K. D., K. Scharer, W. D. Sharp, R. Bürgmann, M. J. Rymer, and P. Williams (2013). New geological slip rate estimates for the Mission Creek strand of the San Andreas fault zone, *2013 SCEC Annual Meeting*.

243 McGill, S. F., J. C. Spinler, J. D. McGill, R. A. Bennett, M. A. Floyd, J. E. Fryxell, and G. Funning (2015). Kinematic modeling of fault slip rates using new geodetic velocities from a transect across the Pacific-North America plate boundary through the San Bernardino Mountains, California. *J. Geophys. Res.*, **120**, 2772-2793.

244 Yule, D., D. Heermance, I. Desjarlais and K. Sieh (2014). Late Pleistocene and Holocene rates of slip and size of prehistoric earthquakes on the San Andreas Fault System in San Gorgonio Pass, *2014 SCEC Annual Meeting*.

245 Shi, Z., and S. M. Day (2013). Rupture dynamics and ground motion from 3-D rough-fault simulations, *J. Geophys. Res.*, **118**, 1122-1141, doi:10.1002/jgrb.50094.

246 Gold, P. O., W. M. Behr, D. Rood, W. D. Sharp, T. K. Rockwell, K. Kendrick, and A. Salin (2015). Holocene geologic slip rate for the Banning strand of the southern San Andreas Fault, southern California. *J. Geophys. Res.*, **120**, doi:10.1002/2015JB012004.

247 Kendrick, K. J., J. C. Matti, and S. A. Mahan (2015). Late Quaternary slip history of the Mill Creek strand of the San Andreas fault in San Gorgonio Pass, Southern California: The role of a subsidiary left-lateral fault in strand switching, *Geol. Soc. Am. Bull.*, **127**, 825-849.

248 Hubbard, J., J. H. Shaw, J. Dolan, T. L. Pratt, L. McAuliffe, and T. K. Rockwell (2014). Structure and seismic hazard of the Ventura Avenue anticline and Ventura fault, California: Prospect for large, multisegment ruptures in the Western Transverse Ranges, *Bull. Seismol. Soc. Am.,* **104**, 1070-1087, doi:10.1785/0120130125.

249 Rockwell, T. K. (2013). Documentation of tsunami deposits in the Carpenteria Estuary: A signal of great earthquakes on the Pitas Point thrust, *2013 SCEC Annual Report*, Award 13008, 6 pp.

250 Ward, S. (2013). Earthquake rupture and tsunamic simulations: Ventura-Pitas Point fault system, *SCEC Annual Report*, Award 13014, 6 pp.

251 Lozos, J., D.D. Oglesby, J. Brune, and K.B. Olsen (2015). Rupture and ground-motion models on the northern San Jacinto Fault, incorporating realistic complexity, *Bull. Seismol. Soc. Am.*, **105**, 1931-1946, doi:10.1785/0120140327.

252 Ben-Zion,Y., F. L. Vernon, Y. Ozakin, D. Zigone, Z. E. Ross, H. Meng, M. White, J. Reyes, D. Hollis, and M. Barklage (2015). Basic data features and results from a spatially dense seismic array on the San Jacinto fault zone, *Geophys. J. Int.*, **202,** 370-380 doi:10.1093/gji/ggv142.

253 Small, P., P. Maechling, T. Jordan, G. Ely, R. Taborda (2011). SCEC UCVM – Unified California Velocity Model, Abstract S21B-2200, 2011 Fall Meeting, American Geophysical Union, San Francisco, California.

254 Lindsey, E. O., Y. Fialko, Y. Bock, D. T. Sandwell, and R. Bilham (2014). Localized and distributed creep along the southern San Andreas Fault, *J. Geophys. Res.*, **119**, 7909-7922, doi:10.1002/2014JB011275.

255 Brocher, T. (2005). Empirical relations between elastic wavespeeds and density in the Earth's crust, *Bull. Seismol. Soc. Am*., **95**, 2081-2092; Murphy, J. M., G. S. Fuis, T. Ryberg, W. J. Lutter, R. D. Catchings, and M. R. Goldman, (2010). Detailed P- and S-Wave Velocity Models along the LARSE II Transect, Southern California, *Bull. Seismol. Soc. Am.*, **100**, p. 3194-3212, doi:10.1785/0120090004; Ryberg, T., J. A. Hole, G. S. Fuis, M. J. Rymer, F. Bleibinhaus, D. Stromeyer, and K. Bauer (2012). Tomographic Vp and Vs structure of the California Central Coast Ranges, in the vicinity of SAFOD, from controlled-source seismic data, *Geophys. J. Int.*, **109**, 1341-1360, doi: 10.1111/j1365-246X.2012.05585.x.

256 Getsinger, A. J., G. Hirth, H. Stunitz, and E. T. Goergen (2013). Influence of water on rheology and strain localization in the lower continental crust, *Geophysics, Geochemistry, Geosystems,* **14**, 2247-2264; Auzende, A.-L., J. Escartin. N. P. Walte, S. Guillot, G. Hirth, and D. J. Frost (2015). Deformation mechanisms of antigorite serpentinite at subduction zone conditions determined from experimentally and naturally deformed ro*cks,* **Earth Planet Sci. Lett., 411**, 229-240.

257 Hardebeck, J. L. (2015). Stress orientation in subduction zones and the strength of subduction megathrust faults, *Science*, **349**, 1213-1216; Bettinelli, P., J.-P. Avouac' , M. Flouzat, L. Bollinger, G. Ramillien, S. Rajaure, NS S. Sapkota (2008). Seasonal variations of seismicity and geodetic strain in the Hamalya induced by surface hydrology, *Earth Planet. Sci. Lett.,* **266**, 332-344, doi:10.1016/j.epsl.2007.11.021.

258 Nakata, N., J. P. Chang, J. F. Lawrence, and P. Boué (2015). Body-wave extraction and tomography at Long Beach, California, with ambient-noise tomography, *J. Geophys. Res.*, **120**, 1159-1173, doi:10.1002/2015JB01870.

259 Brenguier, F., M. Campillo, C. Hadziioannou, N.M. Shapiro, R.M. Nadeau, and E. Larose (2008). Postseismic relaxation along the San Andreas Fault at Parkfield from continuous seismological observations, *Science*, **321**, 1478-1481, doi:10.1126/science.1160943.

260 Shelly, D. R. (2010). Periodic, chaotic, and doubled earthquake recurrence intervals on the deep San Andreas Fault, *Science* **328**, 1385, doi:10.1126/science.1189741; Frank, W. B., N. M. Shapiro, A. L. Husker, V. Kostoglodov, A. Romanenko, and M. Campillo (2014). Using systematically characterized low-frequency earthquakes as a fault probe in Guerrero, Mexico, *J. Geophys. Res.*, **119**, 7686–7700, doi:10.1002/2014JB011457; Ben-Zion,Y., F. L. Vernon, Y. Ozakin, D. Zigone, Z. E. Ross, H. Meng, M. White, J. Reyes, D. Hollis, and M. Barklage (2015). Basic data features and results from a spatially dense seismic array on the San Jacinto fault zone, *Geophys. J. Int.*, **202,** 370-380 doi:10.1093/gji/ggv142; Huang, Y. and G. C. Beroza (2015). Temporal variation in the magnitude-frequency distribution during the Guy-Greenbrier earthquake sequence, *Geophys. Res. Lett.*, in press.

261 Addair, T. G., D. A. Dodge, W. R. Walter, and S. D. Ruppert (2014). Large-scale seismic signal analysis with Hadoop, *Comput. Geosci.*, **66**, 145-154; Zhang, J., H. Zhang, E. Chen, Y. Zheng, W. Kuang, and X. Zhang (2014). Real-time earthquake monitoring using a search engine method, *Nature Comm.*, **5**, 5664, doi:10.1038/ncomms6664; Yoon, C. E., O. O'Reilly, K. Bergen, and G. C. Beroza (2015). Earthquake detection through computationally efficient similarity search, *Science Advances*, submitted.

262 Ma, S., and D. J. Andrews (2010). Inelastic off-fault response and three-dimensional dynamics of earthquake rupture on a strike-slip fault, *J. Geophys. Res.*, **115**, B04304, doi:10.1029/2009JB006382.

263 Johri, M., E. M. Dunham, M. D. Zoback, and Z. Fang (2014). Predicting fault damage zones by modeling dynamic rupture propagation and comparison with field observations, *J. Geophys. Res.*, **119** 1251-1272, doi:10.1002/2013JB010335; Huang, Y., J.-P. Ampuero and D. V. Helmberger (2014). Earthquake ruptures modulated by waves in damaged fault zones, *J. Geophys. Res.*, **119**, 3133–3154, doi:10.1002/2013JB010724.

264 Oglesby, D. D. (2005). The dynamics of strike-slip stepovers with linking dip-slip faults, *Bull. Seismol. Soc. Am.*, **95**, 1604-1622; Yikilmaz, M. B., D. L. Turcotte, E. M. Heien, L. H. Kellogg,and J.B. Rundle (2014). Critical jump distance for propagating earthquake ruptures across stepovers, *Pure Appl Geophys.*, **172**, 2195-2201.

265 DeDontney, N., J. R. Rice, and R. Dmowska (2012). Finite element model of branched ruptures including off-fault plasticity, *Bull. Seismol. Soc. Am.*, **102**, 541-562.

266 Lapusta, N, and Y. Liu (2009). Three-dimensional boundary integral modeling of spontaneous earthquake sequences and aseismic slip, *J. Geophys. Res.*, **114**, doi:10.1029/2008JB005934.

267 Powers, P., and T. H. Jordan (2010). Seismicity distribution across strike-slip faults in California, *J. Geophys. Res.*, **115**, B05305, doi:10.1029/2008JB006234.

268 Oskin, M., J. Arrowsmith, C. Hinojosa, A. Elliot, J. Fletcher, E. Fielding, P. Gold, J. Gonzalez, K. Hudnut, J. Liu-Zeng, O. Teran (2012). Near-field deformation from the El Mayor-Cucapah earthquake revealed by differential LiDAR, *Science*, **335**, 702-705, doi:10.1126/science.

269 Nissen, E., T. Maruyama, J. R. Arrowsmith, J. R. Elliott, A. K. Krishnan, M. E. Oskin, and S. Saripalli (2014). Coseismic fault zone deformation revealed with differential LiDAR: examples from Japanese Mw 7 intraplate earthquakes, *Earth Planet. Sci. Lett.*, **405**, 244-256, doi: 10.1016/j.epsl.2014.08.031; Milliner, C., J. Dolan, J. Hollingsworth, S. Leprince, F. Ayoub, and C. Sammis (2015). Quantifying near-field and off-fault deformation patterns of the 1992 Mw 7.3 Landers earthquake, *Geochem. Geophys. Geosyst.*, **16**, 1577-1598, doi:10.1002/2014GC005693.

270 Takeuchi, C., and Y. Fialko (2012). Dynamic models of interseismic deformation and stress transfer from plate motion to continental transform faults, *J. Geophys. Res.*, **117**, B05403, doi:10.1029/2011JB009056; Takeuchi, C., and Y. Fialko (2013). On the effects of thermally weakened ductile shear zones on postseismic deformation, *J. Geophys. Res.*, **118**, 6295-6310, doi:10.1002/2013JB010215; Thatcher, W., E. H. Hearn, and G. Hirth (2013). Ductile rheology of the Southern California Lithosphere: Constraints from deformation modeling, rock mechanics, and field observations, *Eos*, AGU, **94**, 32, 280; Lyakhovsky, V. and Y. Ben-Zion (2014). Damage-breakage rheology model and solid-granular transition near brittle instability, *J. Mech. Phys. Solids*, **64**, 184-197.

271 Platt, J. P., and W. M. Behr (2011). Grainsize evolution in ductile shear zones: implications for strain localization and the strength of the lithosphere, *J. Struct. Geol.*, **33**, 537-550.

272 Montési, L. G. J. (2013). Fabric development as the key for forming ductile shear zones and enabling plate tectonics, *J. Struct. Geol.*, **50**, 254-266.

273 Takeuchi and Fialko, 2012

274 Gueydan, F., Y. M. Leroy, L. Jolivet, and P. Agard (2003). Analysis of continental midcrustal strain localization induced by reaction-softening and microfracturing, *J. Geophys. Res.*, 108, 2064-2081, doi:10.1029/2001JB000611.

275 Baker, J. W., N. Luco, N. A. Abrahamson, R. W. Graves, P. J. Maechling, and K. B. Olsen (2014). Engineering uses of physics-based ground motion simulations, *Proc. Tenth U.S. National Conference on Earthquake Engineering*.; Böse, M., R. Allen, H. Brown, G. Gua, M. Fischer, E. Hauksson, T. Heaten, M. Hellweg, M. Liukis, D. Neuhauser, P. Maechling, K. Solanki, M. Vinci, I. Henson, O. Khainovski, S. Kuyuk, M. Carpio, M.-A. Meier, and T. Jordan (2014). CISN ShakeAlert: An earthquake early warning demonstration system for California, *Early Warning for Geological Disasters*, ed. F. Wenzel and J. Zschau, Springer-Verlag, Berlin, pp. 49-69, doi:10.1007/978-3-642-12233-0_3; Wang, F., and T. H. Jordan (2014). Comparison of probabilistic seismic hazard models using averaging-based factorization, *Bull. Seismol. Soc. Am.*, **104**, 1230-1257, doi: 10.1785/0120130263.

276 Richards-Dinger, K., and J. H. Dieterich (2012). RSQSim earthquake simulator, *Seism. Res. Lett.*, **83**, 983-990.

277 Thomas, M. Y., N. Lapusta, H. Noda, and J.-P. Avouac (2014). Quasi-dynamic versus fully-dynamic simulations of earthquakes and aseismic slip with and without enhanced coseismic weakening, *J. Geophys. Res.*, **119**, 1986-2004.

278 Lapusta, N., J. R. Rice, Y. Ben-Zion, and G. Zheng (2000). Elastodynamic analysis for slow tectonic loading with spontaneous rupture episodes on faults with rate- and state-dependent friction, *J. Geophys. Res.*, **105**, 23765-23789; Lapusta, N, and Y. Liu (2009). Three-dimensional boundary integral modeling of spontaneous earthquake sequences and aseismic slip, *J. Geophys. Res.*, **114**, doi:10.1029/2008JB005934.

279 Noda, H., & Lapusta, N. (2013). Stable creeping fault segments can become destructive as a result of dynamic weakening. *Nature*, **493**, 518-21. doi:10.1038/nature11703; Ader, T. J., N. Lapusta, J.-P. Avouac, and J.-P. Ampuero (2014). Response of rate-and-state seismogenic faults to harmonic shear-stress perturbations, *Geophys. J. Int.*, **198**, 385-413 doi:10.1093/gji/ggu144.

280 Takeuchi, C., and Y. Fialko (2012). Dynamic models of interseismic deformation and stress transfer from plate motion to continental transform faults, *J. Geophys. Res.*, **117**, B05403, doi:10.1029/2011JB009056; Takeuchi, C., and Y. Fialko (2013). On the effects of thermally weakened ductile shear zones on postseismic deformation, *J. Geophys. Res.*, **118**, 6295-6310, doi:10.1002/2013JB010215; Thatcher, W., E. H. Hearn, and G. Hirth (2013). Ductile rheology of the Southern California Lithosphere: Constraints from deformation modeling, rock mechanics, and field observations, *Eos*, **94**, 32, 280.

281 Kaneko, Y., J.-P. Ampuero, and N. Lapusta (2011). Spectral-element simulations of long-term fault slip: Effect of low-rigidity layers on earthquake-cycle dynamics, *J. Geophys. Res.*, **116**, B10313; Erickson, B. A., and E. M. Dunham (2014). An efficient numerical method for earthquake cycles in heterogeneous media: alternating subbasin and surface-rupturing events on faults crossing a sedimentary basin, *J. Geophys. Res.*, **119**, 3290-3316, doi: 10.1002/2013JB010614.

282 Harris, R. A., M. Barall, D. J. Andrews, B. Duan, S. Ma, E. M. Dunham, A.-A. Gabriel, Y. Kaneko, Y. Kase, B. Aagaard, D. D. Oglesby, J.-P. Ampuero, T. C. Hanks, and N. Abrahamson (2011). Verifying a computational method for predicting extreme ground motion, *Seismol. Res. Lett.*, **82**, 638-644, doi:10.1785/gssrl.82.5.638; Barall, M., and R. A. Harris (2014). Metrics for comparing dynamic earthquake rupture simulations, *Seismol. Res. Lett.*, **86**, 1-13, doi: 10.1785/0220140122.

283 Shi, Z., and S. M. Day (2013). Rupture dynamics and ground motion from 3-D rough-fault simulations, *J. Geophys. Res.*, **118**, 1122-1141, doi:10.1002/jgrb.50094; Taborda, R., and J. Bielak (2014). Ground-Motion Simulation and Validation of the 2008 Chino Hills, California, Earthquake Using Different Velocity Models, *Bull. Seismol. Soc. Am.*, **104**, doi:10.1785/0120130266.

284 Dunham, E. M., D. Belanger, L. Cong, and J. E. Kozdon (2011). Earthquake ruptures with strongly rate-weakening friction and off-fault plasticity, Part 2: Nonplanar faults, *Bull. Seismol. Soc. Am.*, **101**, 2308-2322, doi:10.1785/0120100076; Shi, Z., and S. M. Day (2013). Rupture dynamics and ground motion from 3-D rough-fault simulations, *J. Geophys. Res.*, **118**, 1122-1141, doi:10.1002/jgrb.50094.

285 Trugman, D. T., A. A. Borsa, and D. T. Sandwell (2014). Did stresses from the Cerro Prieto Geothermal Field influence the El Mayor-Cucapah rupture sequence?, *Geophys. Res. Lett.,* **41**, doi:10.1002/ 2014GL061959.

286 Day, S. (1998). Effective Simulation of Constant Q Using Coarse-Grained Memory Variables, *Bull.*

Seismol. Soc. Am., 88(4), 1051-1062.

287 Withers, K.B., K.B. Olsen, Z. Shi, and S.M. Day (2015). Broadband (0-8Hz) ground motion variability from ensemble simulations of the 1994 Mw 6.7 Northridge earthquake including rough fault descriptions and Q(f), *Seism. Res. Lett.* **86**:2B, 653.

288 Hauksson, E., and P. M. Shearer (2006). Attenuation models (Q_P and Q_S) in three dimensions of the Southern California crust: Inferred fluid saturation at seismogenic depths, *J. Geophys. Res.*, **111**, B05302, doi:10.1029/2005JB003947.

289 Withers, K.B., K.B. Olsen, and S.M. Day (2015). Deterministic high-frequency ground motion using dynamic rupture along rough faults, small-scale media heterogeneities, and frequency-dependent attenuation, *2015 SCEC Annual Meeting*, Palm Springs, CA, September 13-16, 2015.

290 Roten, D., K. B. Olsen, S. M. Day, Y. Cui, and D. Fäh (2014). Expected seismic shaking in Los Angeles reduced by San Andreas fault zone plasticity, *Geophys. Res. Lett.*, **41**, 2769-2777, doi:10.1002/2014GL059411.

291 Wang, F., and T. H. Jordan (2014). Comparison of probabilistic seismic hazard models using averaging-based factorization, *Bull. Seismol. Soc. Am.*, **104**, 1230-1257, doi: 10.1785/0120130263

292 Dreger, D. S., G. C. Beroza, S. M. Day, C. A. Goulet, T. H. Jordan, P. A. Spudich, and J. P. Stewart (2015). Validation of the SCEC broadband platform v14.3 simulation methods using pseudospectral acceleration data. *Seismol. Res. Lett.*, **86**, 39-47, doi:10.1785/0220140118.

293 Luco, N., T.H. Jordan, and S. Rezaeian (2013). Progress of the Southern California Earthquake Center Technical Activity Group on Ground Motion Simulation Validation (abstract), *Seismol. Res. Lett.*, **84**, 336; Bijelic, N., T. Lin, and G. Deierlein (2014). Seismic response of a tall building to recorded and simulated ground motions, *Proceedings of the Tenth National Conference on Earthquake Engineering*, in press; Burks, L. S., and J. W. Baker (2014). Validation of ground motion simulations through simple proxies for the response of engineered systems, *Bull. Seismol. Soc. Am.*, **105**, doi:10.1785/0120130276.

294 Building Seismic Safety Council (2015). *Project 17*, *http://www.nibs.org/events/event_details.asp?id=645728*.

295 Olsen, K. B., S. M. Day, J. B. Minster, Y. Cui, A. Chourasia, M. Faerman, R. Moore, P. Maechling, and T. Jordan (2006). Strong shaking in Los Angeles expected from southern San Andreas earthquake, *Geophys. Res. Lett.*, **33**, L07305, doi:10.1029/2005GL025472; Olsen, K. B., S. M. Day, J. B. Minster, Y. Cui, A. Chourasia, D. Okaya, P. Maechling, and T. H. Jordan (2008). TeraShake2: Spontaneous rupture simulations of Mw 7.7 earthquakes on the southern San Andreas fault, *Bull. Seismol. Soc. Am.*, **98**, 1162-1185, doi:10.1785/0120070148; Olsen, K. B., S. M. Day, L. A. Dalguer, J. Mayhew, Y. Cui, J. Zhu, V. M. Cruz-Atienza, D. Roten, P. Maechling, T. H. Jordan, D. Okaya, and A. Chourasia (2009), ShakeOut-D: Ground motion estimates using an ensemble of large earthquakes on the southern San Andreas fault with spontaneous rupture propagation, *Geophys. Res. Lett.*, **36**, L04303, doi:10.1029/2008GL036832; Graves, R., B. Aagaard, K. Hudnut, L. Star, J. Stewart and T. H. Jordan (2008). Broadband simulations for Mw 7.8 southern San Andreas earthquakes: Ground motion sensitivity to rupture speed, *Geophys. Res. Lett.*, **35**, L22302, doi: 10.1029/2008GL035750; Day, S.M., D. Roten, and K.B. Olsen (2012). Adjoint analysis of the source and path sensitivities of basin-guided waves, *Geophys. J. Int.* , **189**, 1103-1124, doi: 10.1111/j.1365-246X.2012.05416.x.

296 Denolle, M., E. M. Dunham, G. A. Prieto, and G. C. Beroza (2014). Strong ground motion prediction using virtual earthquakes, *Science*, **343**, 399-403, doi:10.1126/science.1245678; Denolle, M**.**, E. M. Dunham, G. A. Prieto, and G. C. Beroza (2013). Ground motion prediction of realistic earthquake sources using the ambient seismic field, *J. Geophys. Res.*, **118**, 2102-2118, doi:10.1029/2012JB009603.

297 Dreger, D. S., G. C. Beroza, S. M. Day, C. A. Goulet, T. H. Jordan, P. A. Spudich, and J. P. Stewart (2015). Validation of the SCEC broadband platform v14.3 simulation methods using pseudospectral acceleration data. *Seismol. Res. Lett.*, **86**, 39-47, doi:10.1785/0220140118.

298 Loth, C., and J. W. Baker (2013). A spatial cross-correlation model of ground motion spectral accelerations at multiple periods, *Earthquake Engineering & Structural Dynamics*, **42**, 397-417.

299 Baker, J.W., and N. Jayaram (2008)*. Effects of spatial correlation of ground motion parameters for multi-site seismic risk assessment: Collaborative research with Stanford University and AIR*, Final Technical Report for U.S. Geological Survey National Earthquake Hazards Reduction Program

(NEHRP) External Research Program Award 07HQGR0031, 69 pp.

300 al Atik, L., N. Abrahamson, J.J. Bommer, F. Scherbaum, F. Cotton, and N. Kuehn (2010). The variability of ground-motion prediction models and its components, *Seismol. Res. Lett.*, **81**, 794-801.

301 Ellsworth, W. L. (2013), injection-induced earthquakes, *Science*, **341**, 581-584, doi:10.1126/science.1225942.

302 Raleigh, C. B., J. H. Healy, and J. D. Bredehoeft (1976). Experiment in earthquake control at Rangely, Colorado, *Science*, **191**, 1230-1237.

303 Raleigh, C. B., J. H. Healy, and J. D. Bredehoeft (1976). Experiment in earthquake control at Rangely, Colorado, *Science*, **191**, 1230-1237; Segall, P. (1989). Earthquakes triggered by fluid extraction, *Geology*, **17**, 942-946; Segall, P., J. R. Grasso, and A. Mossop (1994). Poroelastic stressing and induced seismicity near the Lacq gas field, southwestern France, *J. Geophys. Res.*, **99**, 15,423-15,438.

304 Frohlich, C., and M. Brunt (2013). Earth Planet. Sci. Lett., **379**, 56-63, doi:10.1016/j.epsl.2013.07.025.

305 Suckale, J. (2009). Induced seismicity in hydrocarbon fields, *Advances in Geophysics*, **51**, 55-106.; McGarr, A. (2014). Maximum magnitude earthquakes induced by fluid injection. *J. Geophys. Res.*, **119**, 1008-1019.

306 Segall, P., and S. Lu (2015). Injection induced seismicity: Poroelastic and earthquake nucleation effects, *J. Geophys. Res.*, **120**, doi:10.1002/2015JB012060.

307 Kanamori, H., and E. Hauksson (1992). A slow earthquake in the Santa Maria Basin, California, *Bull. Seismol. Soc. Am.*, **82**, 2087-2096; Brodsky, E. E., and L. J. Lajoie (2013). Anthropogenic seismicity rates and operational parameters at the Salton Sea Geothermal Field, *Science*, **341**(6), 543–546, doi:10.1126/science.1239213.

308 Zechar, J. D., D. Schorlemmer, M. Liukis, J. Yu, F. Euchner, P. J. Maechling & T. H. Jordan (2009). The Collaboratory for the Study of Earthquake Predictability perspectives on computational earthquake science, *Concurrency Computat.: Pract. Exper.*, **22**, 1836-1847, doi:10.1002/cpe.1519.

309 Glowacka, E., O. Sarychikhina, F. Suarez, F. Alejandro Nava, and R. Mellors (2010). Anthropogenic subsidence in the Mexicali Valley, Baja California, Mexico, and slip on the Saltillo fault, *Environ. Earth Sci.*, **59**, 1515-1524; Trugman, D. T., A. A. Borsa, and D. T. Sandwell (2014). Did stresses from the Cerro Prieto Geothermal Field influence the El Mayor-Cucapah rupture sequence?, *Geophys. Res. Lett.,* **41**, doi:10.1002/ 2014GL061959.

310 Kanamori, H., and E. Hauksson (1992). A slow earthquake in the Santa Maria Basin, California, *Bull. Seismol. Soc. Am.*, **82**, 2087-2096; Goebel, T. H. W. (2015). Comparing seismicity rates and fluid injection operations in Oklahoma and California: Implications for upper crustal stresses, *The Leading Edge*, Spec. Vol.: *Injection-induced seismicity*, eds. R. Habiger and G. Beroza.

311 Amos, C. B., P. Audet, W. C. Hammond, R. Burgmann, I. A. Johanson, and G. Blewitt (2014). Uplift and seismicity driven groundwater depletion in central California, *Nature*, **509**, 483-486, doi:10.1038/nature13275, Borsa, A. A., D. C. Agnew, and D. R. Cayan (2014). Ongoing drought-induced uplift in the western United States, *Science*, **345**, 1587-1590, doi:10.1126/ science.1260279.

312 Luttrell, K., D. Sandwell, B. Smith-Konter, B. Bills, and Y. Bock (2007). Modulation of the earthquake cycle at the southern San Andreas fault by lake loading, *J. Geophys. Res.*, **112**, B08411, doi:10.1029/2006JB004752.; Brothers, D. S., N. W. Driscoll, G. M. Kent, A. J. Harding, J. M. Babcock, R. L. Baskin (2009). Tectonic evolution of the Salton Sea inferred from seismic reflection data, *Nature Geoscience*, **2**, 581-584.

313 Main, I. G., L. Li, K. J. Heffer, O. Papasouliotis, and T. Leonard (2006). Long-range, critical-point dynamics in oil field flow rate data, *Geophys. Res. Lett.*, **33**, L18308-5.

314 Hickman, S. H., and B. Evans (1987). Influence of geometry upon crack healing rate in calcite, *Phys. Chem. Minerals*, **15**, 91-102, doi:10.1007/BF00307614; Xue, L., H.-B. Li, E. E. Brodsky Z.-Q. Xu, Y. Kano, H. Wang, J. J. Mori, J.-L. Si, J.-L. Pei, W Zhang, G. Yang, K.-M. Sun, and Y. Huang (2013). Continuous permeability measurements record healing inside the Wenchuan earthquake fault zone, *Science*, **340**, 1555-1559, doi:10.1126/science.1237237.

315 Powers, P., and T. H. Jordan (2010). Seismicity distribution across strike-slip faults in California, *J. Geophys. Res.*, **115**, B05305, doi:10.1029/2008JB006234; Bozorgnia, Y., N. A. Abrahamson, L. Al Atik, T. D. Ancheta, G. M. Atkinson, J. W. Baker, A. Baltay, D. M. Boore, K. W. Campbell, B. S.-J.

Chiou, R. Darragh, S. Day, J. Donahue, R. W. Graves, N. Gregor, T. Hanks, I. M. Idriss, R. Kamai, T. Kishida, A. Kottke, S. A. Mahin, S. Rezaeian, B. Rowshandel, E. Seyhan, S. Shahi, T. Shantz, W. Silva, P. Spudich, J. P. Stewart, J. Watson-Lamprey, K. Wooddell, and R Youngs (2014). NGA-West2 research project, *Earthquake Spectra*, **30**, 973-987, doi: 10.1193/072113EQS209M.

316 Strasser, F. O., N. A. Abrahamson, and J. J. Bommer (2009). Sigma: Issues, insights, and challenges, *Seismol. Res. Lett.*, **80**, 40-56.

317 Anderson, J. G., and J. N. Brune (1999). Probabilistic seismic hazard analysis without the ergodic assumption, *Seismol. Res. Lett.*, **70**, 19-28; Chen Y-H., and C.-C. P.Tsai (2002). A new method for estimation of the attenuation relationship with variance components, *Bull. Seismol. Soc. Am.*, **92**, 1984−1991; Atkinson, G.M., and D. M. Boore (2006). Earthquake ground-motion prediction equations for Eastern North America, *Bull. Seismol. Soc. Am.*, **96**, 2181-2205; al Atik, L., N. Abrahamson, J.J. Bommer, F. Scherbaum, F. Cotton, and N. Kuehn (2010). The variability of ground-motion prediction models and its components, *Seismol. Res. Lett.*, **81**, 794-801; Lin, P.-S., Chiou B., Abrahamson N.A., Walling M., Lee C.-T., Cheng, C.-T. (2011). Repeatable source, site, and path effects on the standard deviation for empirical ground-motion prediction models, *Bull. Seismol. Soc. Am.*, **101**, 2281-2295; Rodriguez-Marek, A., G. A. Montalva, F. Cotton, and F. Bonilla (2013). A model for single-station standard deviation using data from various tectonic regions, *Bull. Seismol. Soc. Am.*, **103**, 3149–3163.

318 Power, M., B. Chiou, N. A. Abrahamson, Y. Bozorgnia, T. Shantz, and C. Roblee (2008). An overview of the NGA project, *Earthquake Spectra*, **24**, 3-21.

319 Wang, F., and T. H. Jordan (2014). Comparison of probabilistic seismic hazard models using averaging-based factorization, *Bull. Seismol. Soc. Am.*, **104**, 1230-1257, doi: 10.1785/0120130263.

320 Jordan, T. H., F. Wang, R. Graves, S. Callaghan, K. B. Olsen, Y. Cui, K. Milner, G. Juve, K. Vahi, J. Yu, E. Deelman, D. Gill, and P. J. Maechling (2015). How much can the total aleatory variability of empirical ground motion prediction equations be reduced using physics-based earthquake simulations? (abstract), *2015 Annual AGU Meeting*.

321 Jordan, T. H., and L. M. Jones (2010). Operational earthquake forecasting: some thoughts on why and how, *Seismol. Res. Lett.*, **81**, 571-574, doi:10.1785/gssrl.81.4.571; Jordan, T. H., Y.-T. Chen, P. Gasparini, R. Madariaga, I. Main, W. Marzocchi, G. Papadopoulos, G. Sobolev, K. Yamaoka, and J. Zschau (2011). *Operational Earthquake Forecasting: State of Knowledge and Guidelines for Implementation*, Final Report of the International Commission on Earthquake Forecasting for Civil Protection, *Annals Geophys.,* **54**(4), 315-391, doi:10.4401/ag-5350; Jordan, T. H., W. Marzocchi, A. J. Michael, and M. C. Gerstenberger (2014). Operational earthquake forecasting can enhance earthquake preparedness. *Seismol. Res. Lett.*, **85**, 955-959, doi:10.1785/0220140143.

322 U.S. Geological Survey (2014). USGS Strategy for Operational Earthquake Forecasting, Reston VA, 13 pp., Oct 2014; Field, E. H., T. H. Jordan, L. M. Jones, A. J. Michael, and M. L. Blanpied (2015). The potential uses of operational earthquake forecasting (Powell Center workshop report), *Seismol. Res. Lett.*, submitted.

323 Werner, M., W. Marzocchi, M. Taroni, J. Zechar, M. Gerstenberger, M. Liukis, D. Rhoades, C. Cattania, A. Christophersen, S. Hainzl, A. Helmstetter, A. Jimenez, S. Steacy, and T. H. Jordan (2015). Retrospective evaluation of time-dependent earthquake forecasting models during the 2010-12 Canterbury, New Zealand, earthquake sequence, extended abstract submitted to SECED 2015 Conference: *Earthquake Risk and Engineering towards a Resilient World*, 9-10 July 2015, Cambridge UK.

324 Given, D. D., E. S. Cochran, T. Heaton, E. Hauksson, R. Allen, P. Hellweg, J. Vidale, and P.Bodin (2014). *Technical implementation plan for the ShakeAlert production system: an Earthquake Early Warning system for the West Coast of the United States*. U.S. Geological Survey Open File Report 2014-1097; Kuyuk, H. S., R. M. Allen, H. Brown, M. Hellweg, I. Henson, and D. Neuhauser (2014). Designing a network-based earthquake early warning algorithm for California: ElarmS-2., *Bull. Seismol. Soc. Am.*,, **104**, 162-173, doi:10.1785/0120130146.

325 Allen, R. M., and H. Kanamori (2003). The potential for earthquake early warning in Southern California, *Science*, **300**, 786-789.

326 Allen, R. M., and A. Ziv (2011). Application of real-time GPS to earthquake early warning, *Geophys. Res. Lett.*, **38**, L16310, doi:10.1029/ 2011GL047947.

327 Böse, M., R. Allen, H. Brown, G. Gua, M. Fischer, E. Hauksson, T. Heaten, M. Hellweg, M. Liukis, D.

Neuhauser, P. Maechling, K. Solanki, M. Vinci, I. Henson, O. Khainovski, S. Kuyuk, M. Carpio, M.-A. Meier, and T. Jordan (2014). CISN ShakeAlert: An earthquake early warning demonstration system for California, *Early Warning for Geological Disasters*, ed. F. Wenzel and J. Zschau, Springer-Verlag, Berlin, pp. 49-69, doi:10.1007/978-3-642-12233-0_3.

328 Cua, G. B., M. Fischer, T. H. Heaton, and S. Wiemer (2009). Real-time performance of the Virtual Seismologist earthquake early warning algorithm in Southern California, *Seismol. Res. Lett.*, **80**, 740-747, doi:10.1785/gssrl.80.5.740.

329 Behr, Y., J. Clinton, P. Kästli, C. Cauzzi, R. Racine, and M.-A. Meier (2015). Anatomy of an earthquake early warning (EEW) alert: Predicting Time Delays for an End-to-End EEW system, *Seismol. Res. Lett.*, **86**, doi:10.1785/0220140179.

330 California Earthquake Clearinghouse (2015). Website: *http://californiaeqclearinghouse.org*.

331 Mayoral Seismic Safety Task Force (2015). *Resilience by Design*, Office of the Mayor of Los Angeles, December, 2015, 123 pp.

332 O'Rourke, T. D., S. Toprak, and Y. Sano (1998). Factors affecting water supply damage caused by the Northridge earthquake, in *Proceedings, 6th U.S. National Conference on Earthquake Engineering*, Seattle, WA, 12 pp.; O'Rourke, T. D., S.-S. Jeon, S. Toprak, M. Cubrinovski, M. Hughes, S. van Ballegooy, and D. Bouziou (2014). Earthquake response of underground pipeline networks in Christchurch, NZ, *Earthquake Spectra*, **30**, 183-204.

333 Baker, J.W., and N. Jayaram (2008). *Effects of spatial correlation of ground motion parameters for multi-site seismic risk assessment: Collaborative research with Stanford University and AIR*, Final Technical Report for U.S. Geological Survey National Earthquake Hazards Reduction Program (NEHRP) External Research Program Award 07HQGR0031, 69 pp.

334 Asimaki, D., R. Taborda, J. Anderson, and J. Stewart (2015). SCEC Site Effects Workshop (workshop report), Southern California Earthquake Center, May 5, 2015, 14 pp., available at *http://www.scec.org/workshops/.*

335 Bielak, J., C.B. Crouse, and T. H. Jordan (2015). *SCEC Workshop on Soil-Structure Interaction of Complex Systems* (workshop report), Southern California Earthquake Center, January 29, 2015, 7 pp., available at *http://www.scec.org/workshops/*.

336 Dafalias, Y. F., M. T. Manzari, and A. G. Papadimitriou (2006). SANICLAY: simple anisotropic clay plasticity model, *Int. J. Numerical & Analytical Methods in Geomechanics*, **30**, 1231-1257; Taiebat, M., Jeremic, B., Dafalias, Y. F., Kaynia, A. M., and Cheng, Z. (2010). Propagation of seismic waves through liquefied soils, *Soil Dynamics and Earthquake Engineering*, **30**, 236-257.

337 Yang, Z., A. Elgamal, and E. Parra (2003). Computational model for cyclic mobility and associated shear deformation, *J. of Geotechnical and Geoenvironmental Engineering*, **129**, 1119-27; Byrne, P. M., S. S. Park, M. Beaty, M. Sharp, L. Gonzalez, and T. Abdoun (2004). Numerical modeling of liquefaction and comparison with centrifuge tests, *Canadian Geotechnical Journal*, **41**, 193-211; Byrne, P. M., S. S. Park, M. Beaty, M. Sharp, L. Gonzalez, and T. Abdoun (2004). Numerical modeling of liquefaction and comparison with centrifuge tests, *Canadian Geotechnical Journal*, **41**, 193-211; Boulanger, R. W. (2010). A sand plasticity model for earthquake engineering applications, *Report UCD/CGM-10-01*, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA, 77 pp.; Papadimitriou, A. G., G. D. Bouckovalas, and Y. F. Dafalias (2011). Plasticity model for sand under small and large cyclic strains, *J. Geotech. Geoenviron. Eng.*, **127**, 973-83.

338 Matasovic, N., and Vucetic, M. (1995). Generalized cyclic degradation pore pressure generation model for clays, *J. Geotech. Eng.*, **121**, 33-42; Park, D., and Y. M. Hashash (2004). Soil damping formulation in nonlinear time domain site response analysis, *J. Earthquake Eng.,* **8**, 249-274; Bonilla, L. F., R. J. Archuleta, and D. Lavallée (2005). Hysteretic and dilatant behavior of cohesionless soils and their effects on nonlinear site response: Field data observations and modeling, *Bull. Seismol. Soc. Am.*, **95**, 2373-2395; Delépine, N., L. Lenti, G. Bonnet, and J. F. Semblat (2009). Nonlinear viscoelastic wave propagation: an extension of Nearly Constant Attenuation models, *J. Eng. Mech.*, **135**, 1305-1314; Kramer, S. L., A. J. Hartvigsen, S. S. Sideras, and P. T. Ozener (2011). Site response modeling in liquefiable soil deposits, *Proceedings 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion*, University of California, Santa Barbara, 23-26

August 2011; d’Avila, M. P. S., J. F. Semblat, and L. Lenti (2013). Strong ground motion in the 2011 Tohoku Earthquake: A one-directional three-component modeling, *Bull. Seismol. Soc. Am.*, **103**, 1394-1410; Shi, J., and D. Asimaki (2015). From stiffness to strength in site response analyses: Formulation and validation of a hybrid hyperbolic nonlinear soil model, *Bull. Seismol. Soc. Am.*, in review.

339 Hartzell, S., A. Leeds, A. Frankel, R. A. Williams, J. Odum, W. Stephenson, and W. Silva(2002). "Simulation of broadband ground motion including nonlinear soil effects for a magnitude 6.5 earthquake on the Seattle fault, Seattle, Washington." *Bull. Seismol. Soc. Am.*, **92**, 831-853; Pitarka, A., H. K. Thio, P.I Somerville, and L. F. Bonilla (2013). Broadband ground‐motion simulation of an intraslab earthquake and nonlinear site response: 2010 Ferndale, California, earthquake case study, *Seismol. Res. Lett.*, **84**, 785-795.

340 Iwan W. D. (1967). On a class of models for the yielding behaviour of continuous and composite systems, *J. Appl. Mech.*, **34**, 612-617, doi:10.1115/1.3607751.

341 d’Avila, M. P. S., J. F. Semblat, and L. Lenti (2013). Strong ground motion in the 2011 Tohoku Earthquake: A one-directional three-component modeling, *Bull. Seismol. Soc. Am.*, **103**, 1394-1410.

342 Idriss, E. (2011). Use of Vs30 to represent local site conditions, in *Proc. 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion*, August 23-26, 2011, University of Santa Barbara; Asimaki, D., and J. Shi (2014). Site response validation studies using KIK-net strong motion recordings, *Proc. Southern California Earthquake Center* (SCEC) Annual Meeting 2014, Palm Springs, CA, September 2014.

343 Stewart, J. P., R. B. Seed, and G. L. Fenves (1999). Seismic Soil-Structure Interaction in Buildings. II: Empirical Findings, *J. Geotech. Geoenviron. Eng.*, **125** , 38-48; Mylonakis, G., and G. Gazetas (2000). Seismic soil-structure interaction: Beneficial or detrimental, *J. Earthquake Engineering*, **4**, 377-401; Trifunac, M. D. (2000). Discussion of ‘seismic soil-structure interaction in buildings. I: Analytical methods, and II: Empirical findings.’ by Jonathan P. Stewart, Gregory L. Fenves, and Raymond B. Seed., *J. Geotech. and Geoenvir. Engrg.*, ASCE, 126(7), 668–670.

344 Trifunac, M. D., M. I. Todorovska, and T.-Y. Hao (2001). Full-Scale Experimental Studies of Soil-Structure Interaction — A Review, *Proc. 2nd UJNR Workshop on Soil-Structure Interaction,* UJNR Workshop on Soil-Structure Interaction March 6 to 8, Tsukuba, Japan; Jeremić, B., G. Jie, M. Preisig, and N. Tafazzoli (2009). Time domain simulation of soil-foundation-structure interaction in non-uniform soils., *Earthquake Eng. Struct. Dyn.* **38**, 699-718.

345 Guéguen, P., P.-Y. Bard, and J.-F. Semblat (2000). From soil-structure interaction to site-city interaction, *Proc. 12th World Conf. on Earthquake Eng.*, Paper 0555, Auckland, New Zealand.

346 Mason, H. B., N. W. Trombetta, Z. Chen, J. D. Bray, T. C. Hutchinson, and B. L. Kutter (2013). Seismic soil–foundation–structure interaction observed in geotechnical centrifuge experiments, *Soil Dynamics and Earthquake Engineering*, **48**, 162-174; Guéguen, P., P.-Y. Bard, and F. J. Chávez-García (2002). Site-city seismic interaction in Mexico City-like environments: An analytical study." *Bull. Seismol. Soc. Am.*, **92**, 794-811; Kham, M., J.-F. Semblat, Pierre-Yves Bard, and P. Dangla (2006). Seismic site–city interaction: main governing phenomena through simplified numerical models, *Bull. Seismol. Soc. Am.*, **96**, 1934-1951.

347 Taborda, R. (2010). Three Dimensional Nonlinear Soil and Site-City Effects in Urban Regions, *Ph.D., Thesis,* Civil and Environmental Engineering, Carnegie Institute of Technology, Carnegie Mellon University, Pittsburgh, Pennsylvania; Taborda, R. and Bielak, J. (2011). Large-scale earthquake simulation — Computational seismology and complex engineering systems, *Comput. Sci. Eng.* **13**. 14-26; Isbiliroglu, Y., R. Taborda, and J. Bielak (2015). Coupled soil-structure interaction effects of building clusters during earthquakes, *Earthquake Spectra*, **31**, No. 1, 463-500.

348 O’Rourke T.D. (2007). Critical infrastructure, interdependencies, and resilience, *The Bridge*, **37**, 22-29.

349 Chen, P., L. Zhao, and T. H. Jordan (2007). Full 3D tomography for crustal structure of the Los Angeles region, *Bull. Seismol. Soc. Am.*, **97**, 1094-1120, doi: 10.1785/0120060222; Lee E.-J., P. Chen, T. H. Jordan, P. B. Maechling, M. A.M. Denolle and G. C. Beroza (2014). Full-3D tomography for crustal structure in Southern California based on the scattering-integral and the adjoint-wavefield methods, *J. Geophys. Res.*, **119**, 6421-6451, doi:10.1002/2014JB011346.

350 Small, P., P. Maechling, T. Jordan, G. Ely, R. Taborda (2011). SCEC UCVM – Unified California Velocity Model, Abstract S21B-2200, 2011 Fall Meeting, American Geophysical Union, San Francisco, California; Gill, D., P. Small, P. Maechling, T. Jordan, J. Shaw, A. Plesch, P. Chen, E. Lee, R. Taborda, K. Olsen, and S. Callaghan (2014). UCVM: open source framework for 3D seismic velocity models (abstract), *Seismol. Res. Lett.,* **85**, 457.

351 Field, E. H., G. P. Biasi, P. Bird, T. E. Dawson, K. R. Felzer, D. D. Jackson, K. M. Johnson, T. H. Jordan, C. Madden, A. J. Michael, K. R. Milner, M. T. Page, Y. Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Y. Zeng (2015). Long-term, time-dependent probabilities for UCERF3, *Bull. Seismol. Soc. Am.*, **105**, 511–543, doi:10.1785/0120140093.

352 Dieterich, J. H., and K. B. Richards-Dinger (2010). Earthquake recurrence in simulated fault systems, *Pure Appl. Geophys.,* **167**, 1087–1104, doi:10.1007/s00024-010-0094-0; Richards-Dinger, K., and J. H. Dieterich (2012). RSQSim earthquake simulator, *Seism. Res. Lett.*, **83**, 983-990; Sachs, M. K., E. M. Heien, D. L. Turcotte, M. B. Yikilmaz, J. B. Rundle, and L. H. Kellogg (2012). Virtual California earthquake simulator, *Seism. Res. Lett.*, **83**, 973-978; Ward, S. N. (2012). The ALLCAL earthquake simulator, *Seism. Res. Lett.*, **83**, 964-972.; Pollitz, F. F. (2012). ViscoSim earthquake simulator, *Seismol. Res. Lett.*, 83, 979-982.; Tullis, T. E. (2012). Preface to the Focus Issue on Earthquake Simulators, *Seism. Res. Lett.*, **83**, 957-958.

353 Tullis, T. E., K. Richards-Dinger, M. Barall, J. H. Dieterich, E. H. Field, E. M. Heien, L. H. Kellogg, F. F. Pollitz, J. B. Rundle, M. K. Sachs, D. L. Turcotte, S. N. Ward, and M. B. Yikilmaz (2012). Comparison among observations and earthquake simulator results for the allcal2 California fault model, *Seism. Res. Lett.* **83**, 994–1006.

354 Lohman, R. B., and J. R. Murray (2013). The SCEC geodetic transient-detection validation exercise, *Seismol. Res. Lett.*, **84**, 419-425.

355 Werner, M., W. Marzocchi, M. Taroni, J. Zechar, M. Gerstenberger, M. Liukis, D. Rhoades, C. Cattania, A. Christophersen, S. Hainzl, A. Helmstetter, A. Jimenez, S. Steacy, and T. H. Jordan (2015). Retrospective evaluation of time-dependent earthquake forecasting models during the 2010-12 Canterbury, New Zealand, earthquake sequence, extended abstract submitted to SECED 2015 Conference: *Earthquake Risk and Engineering towards a Resilient World*, 9-10 July 2015, Cambridge UK.

356 Wood, M. M. (2015a). *Evaluation of SCEC Communication, Education, and Outreach Program*, September, 43 pp.

357 Wood, M. M. (2015a). *Evaluation of SCEC Communication, Education, and Outreach Program*, September, 43 pp.

358 Ajzen, I. (1991). The theory of planned behavior, *Organizational Behavior and Human Decision Processes*, **50**, 179-211; Bandura, A. (2004). Health promotion by social cognitive means, *Health Education and Behavior*, **31**, 143-164.; Glanz, K., and D. B. Bishop (2010). The role of behavioral science theory in development and implementation of public health interventions. *Annu. Rev. Pub. Health*, **31**, 399-418, doi:10.1146/annurev.publhealth.012809.103604.; McKenzie, J. F., B. L. Neiger, and R. Thackeray (2013). *Planning, Implementing, and Evaluating Health Promotion Programs*, 6th ed., Pearson Education, Boston.

359 Mileti, D. S., R. Bandy, L. B. Bourque, A. Johnson, M. Kano, L. Peek, L., and M. Wood (2006). *Annotated Bibliography for Public Risk Communication on Warnings for Public Protective Actions Response and Public Education (Revision 5)*, National Hazards Institute, University of Colorado, Boulder, CO; Wood, M. M., D. S. Mileti, M. Kano, M. M. Kelley, R. Regan, R., and L. B. Bourque (2012). Communicating actionable risk for terrorism and other hazards, Risk Analysis, **32**, 601-615. doi:10.1111/j.1539-6924.2011.01645.x; Wood, M. M. (2015b). Communicating actionable risk: The challenge of communicating risk to motive preparedness in the absence of calamity, in H. Egner, M. Schorch, and M. Voss, eds., *Learning and Calamities: Practices, Interpretations, Patterns*, pp. 143-158, Routledge, New York.

360 McKenzie, J. F., B. L. Neiger, and R. Thackeray (2013). *Planning, Implementing, and Evaluating Health Promotion Programs*, 6th ed., Pearson Education, Boston.

361 Issel, M. L. (2014). *Health Program Planning and Evaluation*, 3rd ed., Jones and Bartlette Publishing, Burlington, MA.

362 Bronfenbrenner, U. (1989). Ecological systems theory, in R. Vasta (Ed.), *Annals of Child Development*, **6**, 187-249, JAI Press, Greenwich, CT.

363 Wood, M. M., D. S. Mileti, M. Kano, M. M. Kelley, R. Regan, R., and L. B. Bourque (2012). Communicating actionable risk for terrorism and other hazards, Risk Analysis, **32**, 601-615. doi:10.1111/j.1539-6924.2011.01645.x.

364 Wood, M. M. (2015a). *Evaluation of SCEC Communication, Education, and Outreach Program*, September, 43 pp.

365 Wood, M. M. (2015a). *Evaluation of SCEC Communication, Education, and Outreach Program*, September, 43 pp.

366 Presidential Policy Directive 8 (2011). http://www.dhs.gov/presidential-policy-directive-8-national-preparedness.

367 National Science Foundation (2012). *Diversity and Inclusion Strategic Plan, 2012-2016*, National Science Foundation, Washington DC, 22 pp.

368 Huntoon, J. E., and M. J. Lane (2007). Diversity in the geosciences and successful strategies for increasing diversity, *J. Geosci. Educ.*, **55**, 447-457; Velasco, A. A., and E. Jaurrieta de Velasco (2010). Striving to diversify the geosciences workforce, *Eos*, **91**, 289–290, doi:10.1029/2010EO330001.

369 Jolly, E. J, P. B. Campbell, and L. Perlman (2004). *Engagement, Capacity and Continuity: A Trilogy for Student Success*, Science Museum of Minnesota, St Paul, MN, downloaded from *http://www.smm.org/static/about/ecc_paper.pdf*, 4/24/2015.; Williams, Q. L., V. Morris, and T. Furman (2007). A real-world plan to increase diversity in the geosciences, *Phys. Today*, **60**, 54-55; Charlevoix, D. J, and A. R. Morris (2014). Increasing diversity in geoscience through research internships, *Eos*, **95**, 69-70; Doser, D., C. Manduca, D. Rhodes, S. Sempkin, J. Tyburczy, and J. Villalobos (2014). *Broadening Access to the Earth and Environmental Sciences* (workshop report), accessed at *http://serc.carleton.edu/integrate/workshops/broaden_access/report.html*,4/27/2015.

370 Gover, M., R. Trettevik, G. Hoffman, T. Bachman, S. Dingwall, K. Raines, E. Mattingly, J. Kavetsky, and P. Zheng (2014). GradSuccess 2013-2014 Annual Report, UC Riverside internal report.

371 Williams, Q. L., V. Morris, and T. Furman (2007). A real-world plan to increase diversity in the geosciences, *Phys. Today*, **60**, 54-55.

372 Colella, H. V., D. L. Schutt, D. F. Sumy, and A. M. Frassetto (2015). Helping early-career researchers succeed, *Eos*, **96**, doi:10.1029/2015EO034965. Published on 8 September 2015.

373 Networking and Information Technology Research and Development (2012). *Program 2012 Strategic Plan*, Executive Office of the President National Science and Technology Council, July, 2012.