AN NSF+USGS CENTER

Southern California Earthquake Center
2017 Science Plan

Proposals Due: November 15, 2016

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1. New This Year

The SCEC Science Plan (aka RFP) reflects research priorities articulated in the SCEC5 proposal. **The SCEC Science Plan as detailed in this document is provisional pending a formal award decision on the SCEC5 proposal by the National Science Foundation and U.S. Geological Survey, and approval of a final budget authorization associated with the first year of SCEC5.** Substantial changes have been made to the RFP, so we strongly encourage researchers to read carefully the RFP in its entirety.

- The Science Planning Committee (PC) is reconfigured for SCEC5. Some working groups remain, some have evolved to reflect a changed emphasis, and others have been discontinued. The four disciplinary committees (Seismology, Geodesy, Geology, and Computational Science), and three of the interdisciplinary focus groups (FARM, SDOT, and EERI) are the same. GMP and SoSAFE have changed slightly to the more general Ground Motions (GM) and San Andreas Fault System (SAFS), respectively. The USR focus group will broaden to include all community models under the new CXM group. Finally, Special Projects will no longer be represented individually on the PC, but rather in aggregate by the Executive Director for Special Projects (Christine Goulet) and the SCEC IT Architect (Phil Maechling).

- All Technical Activity Groups (TAGs) will sunset at the end of SCEC4. Established TAGs, and proposed new TAGs, will have to be re-initiated in SCEC5 through submission of a successful proposal to the Planning Committee.

- A new focus area, called "Earthquake Gates" will be started in the first year of SCEC5. This initiative is designed to foster multidisciplinary studies of the factors that permit earthquakes to start or stop (as at a gate). To organize this initiative within the SCEC community, an incubator workshop will be held in the early spring of Year 1. See the SAFS section for more details.

- The San Gorgonio Pass and Ventura Special Fault Study Areas are wrapping up at the end of SCEC4. This does not mean that we will no longer fund proposals that concern research in these areas.

- Investigators on proposals that anticipate use of SCEC computational resources and/or help from SCEC software developers must consult with SCEC IT leadership for budget time support estimates and coordination planning.

- Investigators interested in undergraduate summer interns should include an "intern project" description in their proposal. The undergraduate intern will be recruited by the SCEC CEO Program staff. Selected intern projects will be awarded as supplemental funds on the proposal award. Funds will be disbursed and managed at USC to use for a summer stipend and travel support to the SCEC annual meeting for the selected undergraduate student. The number of intern projects awarded each year will depend on available funding in the SCEC annual budget and the available applicant interest pool.

- Geochronology infrastructure supports Accelerator Mass Spectrometer analysis of ^{14}C, ^{10}Be, ^{26}Al, and 36Cl, through collaboration with Lawrence Livermore National Laboratory and the University of California, Irvine (^{14}C only). Luminescence dating (OSL, pIR-IRSL) will be supported through regular proposal budgets, through arrangement with a luminescence laboratory (see Earthquake Geology section for suggestions). This change reflects the close collaboration required for luminescence dating.

- The CCSP has an increased emphasis on geological studies that will inform seismic hazard in central California, particularly for those faults west of the San Andreas and within the southern Sierra Nevada.

- SCEC no longer supports proposals solely for annual meeting participation. Funding for travel to participate in the SCEC Annual Meeting will be considered only in the context of a research proposal in response to the current Science Plan. International travel funding for a co-investigator to participate in the SCEC Annual Meeting will be considered, provided the proposal clearly states (a) how the investigators are critical to the project and (b) a plan for how the international participant's institution will cost-share the anticipated travel expenses.

2. 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). The Center has been extended for another 5-year period, effective 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 participate 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.

2.1 The 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 continues 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.

2.2 The SCEC5 Science Plan

The SCEC5 Science Plan was 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 is 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.

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.

2.2.1 Basic Questions of Earthquake Science

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 (CSM) 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 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 and more limited in-situ data, as well as 3D dynamic models of stress; e.g., from finite-element simulations of long-term tectonics, including nonlinear laboratory rheologies. A new approach 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. Though we are encouraged by our recent progress, understanding stress is a long-term proposition.

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. (Geology, Geodesy, SDOT, SAFS)

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. (SDOT, Geodesy, EFP, CXM)

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. (SDOT, CXM, Geology)

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. (Seismology, SDOT, FARM, Geology)

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. (SDOT, Geodesy, Seismology, FARM, CS)

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, together with time-dependent evolution of seismic velocities following stress perturbations 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, 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. 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, affect measurements of coseismic slip at the surface, and inferences of long-term slip rates from the geologic record.

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. 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.

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. (FARM, Geodesy, CS)

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. (GM, CS, Seismology)

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. (FARM, CS, GM, Seismology)

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

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. (EFP, FARM, CS, Geology, SAFS)

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, Taiwan's Chelungpu Fault, and the Japan Trench megathrust, imply that shear stress acting during sliding is an order of magnitude lower than estimates from Byerlee's law 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, slip-vector rake rotations during faulting, and significant rotations of principal stresses after large earthquakes. 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.

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, thermal pressurization of pore fluids, partial or full melting of the shearing zone, silica-gel formation, and thermal decomposition of sheared materials into friction-reducing byproducts. Coseismic weakening may lead to large unexpected slip in creeping fault regions, including deeper fault extensions below the seismogenic layer, a phenomenon compatible with a range of observations. Fluids play a key role in several of the weakening processes, potentially dominating coseismic resistance to slip. In fact, fluids can lead to extreme localization of the shearing layer, promoting coseismic weakening. 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.

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. (CXM, Seismology, Geodesy, Geology, SAFS)

P3.b. Constrain the active geometry and rheology of the ductile roots of fault zones. (CXM, SDOT, FARM, Geology)

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

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. (FARM, Geology, CS)

P3.e Constrain the extent of permanent, off-fault deformation, and its contribution to geologic and geodetic fault slip-rate estimates. (Geology, SAFS, Geodesy, EFP)

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. (FARM, Geology, EFP)

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. (Seismology, Geodesy, Geology, GM, FARM)

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, operational earthquake forecasting, and earthquake early warning. Validated numerical simulations that yield predictions adapted to local geologic conditions, such as sedimentary basins, structural boundaries, and steep topography, can 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, 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 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, crustal material heterogeneities, intrinsic attenuation, near-surface nonlinearities and ground surface topography in controlling ground motions. (GM, Seismology, EEII)

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. (GM, EEII)

P4.c. Develop ground-motion simulations for anticipated large events that are suitable for probabilistic seismic hazard and risk analysis. (CS, GM, EEII)

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

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. (EFP, CS, FARM)

P5.b. Place useful geologic bounds on the character and frequency of multi-segment and multi-fault ruptures of extreme magnitude. (SAFS, Geology, EFP)

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. (EFP, SAFS, Geology)

P5.d. Test the hypothesis that “seismic supercycles’’ seen in earthquake simulators actually exist in nature and explore the implications for earthquake predictability. (EFP, SAFS, Geology)

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

2.2.2 SCEC5 Thematic Areas and Topical Elements

The basic science questions 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.

1. 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.
- 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.

2. 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 coseismic dynamic rupture models with inter-seismic 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.

3. 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.

4. 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 by incorporating nonlinear rheological models of near-surface rock and soil layers into full-physics earthquake simulations.

2.3 Management of the SCEC Research Program

The SCEC Science Planning Committee (PC) is responsible for developing the SCEC Annual Science Plan, which describes the Center's research interests and priorities, and the SCEC Annual Collaboration Plan, which details how resources will be allocated to projects. The PC is chaired by the SCEC Co-Director (Greg Beroza), who is assisted by a PC Vice-Chair (Judi Chester). The PC comprises the leaders of the SCEC science working groups—disciplinary committees, focus groups, and special project groups—who, together with the working group co-leaders, guide SCEC's research program. The Executive Director for Special Projects (Christine Goulet) manages science activities in the externally funded SCEC Special Projects and coordinates these activities with PC and the SCEC IT Architect (Phil Maechling), who has oversight of SCEC Information Technology, including the software standards for data structures and model interfaces. The Center Director (Tom Jordan) and the Associate Directors for Administration (John McRaney) and CEO (Mark Benthien) serve as *ex officio* members. The PC is responsible for formulating the Center's science plan, conducting proposal reviews, and recommending projects to the Board of Directors for SCEC support. Its members play key roles in implementing the SCEC5 science plans. With the beginning of SCEC5, we have restructured the PC – reducing it slightly in size, evolving some groups, and changing the membership significantly in an effort to both revitalize the PC, and to ensure that it is aligned with the goals of SCEC5.

3. Annual SCEC Science Plan

The SCEC Science Plan solicits proposals from individuals and groups to participate in the SCEC research program on an annual basis. Typical grants awarded under the SCEC Science Plan fall in the range of $10,000 to $35,000. This is not intended to limit SCEC to a fixed award amount, nor to a specified number of awards, but rather to calibrate expectations for proposals submitted to SCEC. Field research investigations outside southern California are generally not supported.

3.1 Investigator Eligibility and Responsibilities

3.1.1 Who May Submit Proposals

Proposals can be submitted by eligible Principal Investigators (PIs) from U.S. academic institutions and U.S. private corporations.

SCEC rarely provides support to foreign institutions. Collaborative projects involving U.S. and foreign organizations will be considered, provided funding is requested only for the U.S. portion of the collaborative effort.

Collaborative proposals with investigators from the U.S. Geological Survey are encouraged. USGS employees should submit requests for support through USGS channels.

Any person with an overdue project report (for prior SCEC-funded awards) at the time of the proposal deadline will not be allowed to submit a new or continuation proposal as a PI or co-PI.

3.1.2 Investigator Responsibilities

By submitting a proposal to SCEC, investigators agree to all three conditions listed below. Investigators who fail to meet these conditions may (a) not receive funding until conditions are satisfied and/or (b) become ineligible to submit a future proposal to SCEC.

1. Community Participation. Principal investigators will interact with other SCEC scientists on a regular basis and contribute data, results, and/or models to the appropriate SCEC resource.

> SCEC Annual Meeting. The PI will attend the annual meeting and present results of SCEC-funded research in the poster sessions, workshops and/or working group meetings.
>
> Data Sharing. Funded investigators are required to contribute data and results to the appropriate SCEC resource (e.g., Southern California Earthquake Data Center, database, community model).

2. Project Reporting. Principal investigators will submit a project report by the due date listed below.

> Workshop Awards. A report on results and recommendations of the workshop funded by SCEC is due no later than 30 days following the completion of the workshop. The report will be posted on the SCEC website as soon as possible after review by SCEC leadership.
>
> All Other Awards. Investigators funded by SCEC must submit a project report no later than March 15 (5:00 pm PST) in the year after the funding was received. Reports should be a maximum of 5 pages (including text and figures). Reports must include references to all SCEC publications during the past year (including papers submitted and in review) with their SCEC contribution number (see 3 below).

3. Registration of Publications. Principal investigators will register publications resulting entirely or partially from SCEC funding in the SCEC Publications System (www.scec.org/publications) to receive a SCEC contribution number. Publications resulting from SCEC funding should acknowledge SCEC and include the SCEC contribution number.

3.2 Proposal Categories

3.2.1 Research Proposals

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

B. ***Integration and Theory.*** SCEC supports and coordinates interpretive and theoretical investigations on earthquake problems related to the Center's mission. Proposals in this category should be for the integration of data or data products from category A, or for general or theoretical studies. Proposals in categories A and B should address one or more of the basic questions of earthquake science (see Questions), and may include a brief description (<200 words) as to how the proposed research and/or its results might be used in a special initiative (see Special Projects) or in education and/or outreach (see CEO).

3.2.2. Collaborative Proposals and Technical Activity Groups

A. ***Collaborative Proposals*** involving multiple investigators and/or institutions are strongly encouraged. The lead investigator should submit only one proposal for the collaborative project. Information on all investigators requesting SCEC funding (including budgets, current and pending support statements) must be included in the proposal submission. Note that funding for Collaborative Proposals may be delayed or denied if any of the investigators listed on the proposal has overdue project report(s) for a prior SCEC award.

B. ***Technical Activity Groups (TAGs)*** self-organize to develop and test critical methodologies for solving specific problems. TAGs have formed to verify the complex computer calculations needed for wave propagation and dynamic rupture problems, to assess the accuracy and resolving power of source inversions, and to develop geodetic transient detectors and earthquake simulators. TAGs share a *modus operandi:* the posing of well-defined "standard problems", solution of these problems by different researchers using alternative algorithms or codes, a common cyberspace for comparing solutions, and meetings to discuss discrepancies and potential improvements. TAG proposals typically involve a workshop and should include a research coordination plan that sets a timetable for successful completion of TAG activities no later than the end of SCEC5.

3.2.3 Participant Support Proposals

A. ***Workshops.*** SCEC participants who wish to convene a workshop between February 1, 2017 and January 31, 2018 should submit a proposal for the workshop in response to this Science Plan. The proposed lead convener of the workshop must contact Tran Huynh (scecmeet@usc.edu) for guidance in planning the scope, budget and scheduling of the proposed workshop before completing the proposal submission. Note that workshops scheduled in conjunction with the SCEC Leadership Retreat (June) or SCEC Annual Meeting (September) are limited in number and may have further constraints due to space and time availability.

B. ***SCEC/SURE Intern Project Supplement.*** SCEC coordinates a Summer Undergraduate Research Experience (SURE) Program that enables undergraduate students to work alongside SCEC scientists on a variety of research projects during the summer. Investigators interested in mentoring an undergraduate student over the summer should include an "intern project" description in their proposal that aligns with the overall proposed project plan. The undergraduate intern will be recruited by the SCEC Communication, Education, and Outreach (CEO) Program staff. Selected intern projects will be awarded as supplemental funds to the proposal award. The supplemental funds will provide (1) a summer stipend up to $5,000 for the selected undergraduate student and (2) travel support for the student to participate in the all intern field trip and to present his/her summer research at the SCEC annual meeting. The number of intern projects awarded each year will depend on available funding in the SCEC annual budget and the available student applicant (interest) pool. The funds will be disbursed and managed at USC. Questions about the SCEC/SURE Program should be directed to Mark Benthien (213-740-0323; benthien@usc.edu).

3.3 Guidelines for Proposal Submission

3.3.1 Proposal Due Date

The deadline date is Tuesday, November 15, 2016 (5:00pm Pacific Time). Late proposals will not be accepted.

3.3.2 How to Submit Proposals

Every investigator listed on the proposal must have a registered account on www.SCEC.org, with current contact information and profile information updated. Proposals must be submitted through the SCEC Proposal System, accessible via www.scec.org/scienceplan.

Proposals do not need to be formally signed by institutional representatives.

3.3.3 Project Duration

The proposed project period should be 1-year duration (starting Feb 1, 2017 and ending Jan 31, 2018).

3.3.4 Proposal Contents

Every proposal submitted must include all of the contents listed below. Proposals must be received through the online system by the due date, with all all required information, to be considered complete. Incomplete proposals may be rejected and returned without comment.

1. Cover Page. The proposal cover page should include all the following information, which will be required when submitting the proposal online:

- Project Title, Principal Investigator(s), and Institutional Affiliation(s)
- Total Amount of Request on Proposal, Amount of Request per Investigator
- Proposal Category (see Section 3)
- Three SCEC science priorities, listed in ranked order, that the proposal addresses (e.g. P4.c, P3.d and P2.a; see Section 2).
- Include the words "SCEC/SURE Intern Project" if requesting supplemental funding through the SCEC/SURE Program

2. Project Plan. In 5 pages maximum (including figures), describe the proposed project and how it relates to SCEC5 objectives and priorities (see Section 2). References are excluded from the 5-page limit.

- Continuation Projects. If the proposed project is a continuation of a prior SCEC award, the project plan must include a 1-page summary of the research results obtained from that SCEC funding. The research summary is counted towards the 5-page limit. Continuation proposals must have a section outlining how the proposed research relates to the SCEC5 science objectives.
- Collaborative Proposals. The project plan may include one extra page per investigator to report recent results from previously-funded, related research.
- Technical Activity Proposals. TAG proposals should include a research coordination plan that sets a timetable for successful completion of TAG activities no later than the end of SCEC5. The research coordination plan is counted towards the 5-page limit.
- Workshop Proposals. Workshop proposals that include travel support for international participants must clearly state how such participants are critical to the workshop.
- SURE Intern Project Supplement. The project must include an "intern project" description (1 page maximum) if requesting support for a summer undergraduate intern. In the description briefly describe the project, location(s) where research will take place, the role of the intern in the project, and any specific skills or educational background required. The project description submitted will be used to recruit students and posted on the SCEC Internship website. This description is not included in the 5-page limit.

3. Budget and Budget Justification. Every proposal must include a budget table and budget justification for each institution requesting funding. The budgets should be constructed using NSF categories.

- Budget Guidance. Typical SCEC awards range from $10,000 to $35,000. This is not intended to limit SCEC to a fixed award amount, nor to a specified number of awards, but rather to calibrate expectations for proposals written by SCEC investigators.
- Central California Seismic Project (CCSP) Budgets. The master agreement funding CCSP limits indirect costs to 15%. Use only this rate on budgets for proposals responding to CCSP.
- Field Research. Field research investigations outside southern California are not supported by the SCEC core program. Proposals submitted under the Central California Seismic Project are not subject to this restriction.
- Salary Support. An investigator can receive no more than 1 month of summer salary support in any given year from all combined SCEC funded awards in that year.
- SCEC IT Support. Investigators on proposals that anticipate use of SCEC computational resources and/or help from SCEC software developers should consult with SCEC IT leadership for budget time support estimates and coordination planning.
- International Travel Funding Support. Funding for international travel to participate in the SCEC Annual Meeting will be considered, provided the proposal clearly states (a) how the investigators are critical to the project and (b) a plan for how the international participant's institution will cost-share the anticipated travel expenses.
- Unallowable Direct Expenses. Under guidelines of the SCEC Cooperative Agreements and A-81 regulations, secretarial support and office supplies are not allowable as direct expenses.
- For each organization requesting funding, the budget information must be entered through the online submission system. This information should also be included in the PDF uploaded at the time of proposal submission.

4. Current and Pending Support. Statements of current and pending support must be included for each Principal Investigator requesting funding on the proposal, following NSF guidelines. Proposals without a current and pending support statement may be rejected and returned without review.

- Each investigator requesting funding must enter his/her current and pending support information through the online submission system. This information should also be included in the PDF uploaded at the time of proposal submission.
- Workshop Proposals. Current and pending support information is not required from investigators submitting workshop proposals.

3.4 Proposal Review Process

Structuring of the SCEC science plan begins with discussions at the SCEC Leadership Retreat in June every year, and continues at the Annual Meeting in September. A Science Plan document is issued in October and proposals are submitted to SCEC in November of each year.

In December, proposals are sent out for review. Every proposal is independently reviewed by the Center Director (Tom Jordan), Center Co-Director/Science Planning Committee Chair (Greg Beroza), and Science Planning Committee Vice-Chair (Judi Chester). Each proposal is also reviewed by the leaders of three relevant SCEC science working groups (primary, secondary, and tertiary) – totaling five or more independent reviews for each proposal submitted. Reviewers recuse themselves when conflicts of interest arise. Proposals are also reviewed by USGS members of the SCEC/USGS Joint Planning Committee (JPC).

The SCEC Planning Committee (PC), chaired by the Center Co-Director, meets the following January to review and discuss all submitted proposals. USGS members of the JPC also participate in the proposal review meeting. Based on a combination of reviews and full panel discussion, the PC assigns a rating and recommended funding level for each proposal.

The Planning Committee's objective each year is to formulate a coherent science/infrastructure program consistent with SCEC's basic mission given the Center's short-term objectives, long-term goals, and institutional composition, and recommend a budget given the available funding.

Proposals are evaluated on the criteria below (not necessarily in order of priority):

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

It is important to note that proposals receiving a low rating or no funding does not necessarily imply a scientifically inferior proposal. Rather, proposals may be downgraded based on other criteria noted above.

After the PC finalizes the proposed Collaboration Plan, it is sent for review and approval by the SCEC Board of Directors in February. The proposed plan is then sent to the funding agencies for final review. Upon approval by the agencies, notifications are sent out to the investigators beginning in March. Notifications may be delayed if investigators have overdue reports on prior SCEC awards.

3.5 Award Procedure

The Southern California Earthquake Center is funded by the National Science Foundation (NSF) and the U.S. Geological Survey (USGS) through cooperative agreements with the University of Southern California (USC). Additional funding for the SCEC research program is provided by the Pacific Gas & Electric Company, the Keck Foundation, geodesy royalty funds, and potentially other sources.

All research awards will be funded as subawards or fixed-priced contracts from the University of Southern California. Because SCEC5 operates under new cooperative agreements with the NSF and USGS, all 2017 research awards will be established as new subcontracts between USC and the institution to receive funding. When SCEC award funding becomes available to investigators will depend on (1) how soon SCEC/USC receives SCEC5 funds from the NSF and USGS, and (2) how quickly contracts are negotiated between USC and institution to receive funding.

Participant support (workshops, intern project supplement, and travel) award expenditures will be managed through the master SCEC account at USC.

Funding for Collaborative Proposals may also be delayed or denied if any of the investigators has overdue project report(s) for prior SCEC award.

3.6 SCEC / USGS-EHP Research Coordination

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

SCEC and EHP coordinate research activities through formal means, including USGS membership on the SCEC Board of Directors, a SCEC/USGS Joint Planning Committee, appointment of a SCEC representative (usually the PC Chair) to the USGS external research proposal review panel for Southern California, and through a variety of less formal means. Interested researchers are invited to contact Dr. Rob Graves, EHP coordinator for Southern California, or other SCEC and EHP staff to discuss opportunities for coordinated research.

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

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

4. Research by Disciplinary Committees

The Center supports disciplinary science through standing committees in Seismology, Tectonic Geodesy, Earthquake Geology, and Computational Science. They are responsible for disciplinary activities relevant to the SCEC Science Plan, and they make recommendations to the Science Planning Committee regarding the support of disciplinary research and infrastructure.

4.1 Seismology

4.1.1 Research Objectives

The Seismology working group gathers data on the range of seismic phenomena observed in southern California, develops improved techniques for extracting detailed robust information from the data, and integrates the results into models of velocity structures, source properties and seismic hazard. We solicit proposals that foster innovations in network deployments and data collection, especially those that fill important observational gaps, real-time research tools, and data processing. Proposals to develop community products that support one or more SCEC5 goals or include collaboration with network operators in Southern California are especially encouraged. Proposers should consider the SCEC resources available including (a) the Southern California Earthquake Data Center (SCEDC) that provides extensive data on Southern California earthquakes, as well as crustal and fault structure, (b) the network of SCEC funded borehole instruments that record high quality reference ground motions, and (c) the pool of portable instruments operated in support of targeted deployments or aftershock response.

4.1.2. Research Strategies

- Enhance and continue operation of the SCEDC and other existing SCEC facilities, particularly the near-real-time availability of earthquake data and automated access.
- Process network data in real-time to improve estimation of source parameters in relation to faults, short-term evolution of earthquake sequences, and real-time stress perturbations on major fault segments.
- Enhance and continue to develop earthquake catalogs that include smaller events. Develop improved catalogs of focal mechanisms and other source properties. Improve locations of important historical earthquakes.
- Advance innovative, practical strategies for densification of seismic instrumentation in Southern California, including borehole instrumentation; and develop innovative algorithms to utilize data from these networks. Develop metadata, archival and distribution models for these semi-mobile networks.
- Develop innovative methods to search for unusual signals using combined seismic, GPS, and borehole strainmeter data; Encourage collaborations with EarthScope or other network operators.
- Investigate near-fault crustal properties, evaluate fault structural complexity, and develop constraints on crustal structure and state of stress.
- Enhance collaborations, for instance with ANSS, that would augment existing and planned network stations with downhole and surface instrumentation to assess site response, nonlinear effects, and the ground coupling of built structures.
- By preliminary design and data collection, seed future passive and active experiments such as dense array measurements of basin structure, fault zones and large earthquake properties, OBS deployments, and deep basement borehole studies.

- Investigate whether earthquake properties in southern California have systematic dependencies on properties of faults, the crust, and anthropogenic activities, which may be used to extract more detailed information from the available seismic data.

4.1.3 Research Priorities

- ***Low-cost seismic network data utilization and archiving.*** Several groups are developing seismic networks that use low-cost MEMS accelerometers. We seek proposals on innovative algorithms to utilize data from these networks, develop metadata and archiving models, and make the data and products available to the user community.
- ***The shallow crust*.** Seismic properties in top few kilometers of the crust have strong effects on ground motion, but are generally not well known. We seek proposals on deriving detailed regional images of seismic velocities and attenuation coefficients in the shallow crust.
- ***Tremor and related signals.*** Tremor has been observed on several faults in California, although we will continue to consider proposals that explore the distribution and source characteristics of tremor in southern California, and on distinguishing tremor from other sources that may produce similar signals, such proposals should be mindful of the limited success of such endeavors to date.
- ***Earthquake directivity***. Rupture directivity can have strong influence on ground motion, but it is not clear if earthquake directivity on given fault sections is systematic or random. We seek proposals on robust estimations of rupture directivities of a large population of earthquakes in relation to the major faults in southern California.
- ***Seismic coupling.*** The partitioning between seismic and aseismic deformations strongly affects the seismic potential of faults, but is generally not well known. We seek proposals that develop and implement improved techniques for estimating the seismic coupling of different fault sections, and for constraining the depth-extent of seismic faulting in large earthquakes.
- ***Short-term earthquake predictability.*** We seek proposals that develop new methods in earthquake statistics or analyze seismicity catalogs to develop methods for determining short-term (hours to days) earthquake probability gain.
- ***Processes and properties* in special areas.** We seek proposals that use seismic data to improve the knowledge on structural properties and seismotectonics Southern California, especially those identified as “Earthquake Gates” (see SAFS for definition).

4.2 Tectonic Geodesy

4.2.1 Research Objectives

The Tectonic Geodesy working group uses geodetic measurements of crustal deformation to understand the interseismic, coseismic, postseismic, and hydrologic processes associated with the earthquake cycle along the complex fault network of the Southern San Andreas system. This activity supports several of the SCEC5 science questions including: How are faults loaded across temporal and spatial scales? What is the role of off-fault inelastic deformation on strain accumulation, dynamic rupture, and radiated seismic energy? The Tectonic Geodesy group also plays a role in earthquake monitoring and response, from tracking surface deformation changes that may precede or accompany induced seismicity, to measuring coseismic displacements and postseismic transients, either in near-real time as part of earthquake early warning, or as part of a coordinated post-earthquake rapid response.

In addition, the group is tasked with developing a Community Geodetic Model (CGM) for use by the SCEC community in system-level analyses of earthquake processes over the full range of length and timescales. The CGM is built on the complementary strengths of temporally dense GPS data and spatially dense InSAR data. Much of the SCEC4 activity was focused on the assembly and testing of GPS and InSAR data sets for measuring secular motions and comparing geodetically inferred fault slip rates with geological rates based on paleoseismic studies (e.g. UCERF3). The quality and quantity of both GPS and InSAR data is rapidly improving to enable a breakthrough in the spatial and temporal resolution of the CGM. In particular, reprocessing of long GPS time series has provided high accuracy vertical measurements that reveal a wide range of new hydrologic and tectonic signals. In addition, two new C-band InSAR satellites (Sentinel-1A and B) are providing highly accurate systematic coverage of the entire SCEC region every 12 days from two look directions. Developing methods to integrate and update these dense spatiotemporal datasets will be a major task in SCEC5.

4.2.2. Research Strategies

These advances motivate the following strategies:

- Develop vector time series of crustal deformation at ~1 km spatial resolution and better than seasonal temporal resolution.
- Increase vertical precision of multi-decadal GPS time series.
- Develop methods to robustly estimate spatial and temporal uncertainties in GPS/InSAR/combined time series.
- Provide derived geodetic data products such as strain rate maps, displacement fields, common mode signals, seasonal signals, and noise assessments.
- Develop methods to constrain the extent of permanent, off-fault deformation, and its contribution to geodetic fault slip-rate estimates.
- Improve methods for characterizing transient deformation, including episodic aseismic creep, the effects of surface hydrology and anthropogenic activity, and both short- and long-term postseismic deformation transients, and for decomposing geodetic time series into secular and transient components.
- Develop and test mechanistic models of the crustal deformation associated with hydrology and/or anthropogenic activities, with a view to gaining insight into the processes associated with induced seismicity.
- Improve techniques for inferring fault rupture parameters from time-limited geodetic data.
- Work with the initial findings of the Community Rheology Model (CRM) to understand the importance of spatial variations in rheology on geodetic inversions for fault slip and crustal strain.
- Use these data in combination with other SCEC Community Models, as well as physical models, to address the major SCEC science questions.

4.2.3 Research Priorities

The major research priorities this year are:

- ***Community Geodetic Model (CGM) secular velocities.*** Produce a consensus secular velocity InSAR product using the full archive of SAR data (ERS, Envisat, ALOS-1) for the SCEC region. Coordination between participating groups in this effort is encouraged. Continue to develop methods to improve error characterization and/or reduction in secular geodetic velocity estimates, e.g. by refined analysis of campaign GPS data in combination with large-area InSAR analyses, by developing improved noise models, or by improving methods for mitigating temporally or spatially correlated noise.
- ***Community Geodetic Model (CGM) time series.*** Produce a consensus time series GPS product integrating both continuous and campaign data. Coordination between participating groups in this effort is encouraged. Develop methods for processing, updating and integrating InSAR time series

in near-real time, using the latest generation of SAR satellites (e.g. Sentinel-1, ALOS-2). Continue to develop methods for GPS/InSAR time series integration for the SCEC region, including methods that combine multiple InSAR data sets with different viewing geometries and temporal sampling rates.

- ***Research pertaining to other community models.*** Foster the development of 4D models of the earthquake cycle that include spatial variations in crustal rheology. Work with other SCEC scientists to develop the Community Stress Model as well as an improved understanding of how stress varies from the earthquake cycle timescale to the mountain building timescale (see SDOT).
- ***GPS data collection and preparation for earthquake rapid response.*** Collect campaign GPS data in areas of sparse GPS coverage and poor InSAR correlation. Develop a coordinated rapid response GPS capability, including updating GPS site coordinates in the vicinity of major faults, in preparation for a major event.
- ***Community Outreach.*** Work with the SCEC Communication, Education & Outreach group to highlight the importance of geodetic measurements for improving earthquake forecasting.

4.3 Earthquake Geology

4.3.1 Research Objectives

The Earthquake Geology working group promotes studies of the geologic record of the Southern California natural laboratory that advance SCEC science. Its primary focus is on the Late Quaternary record of faulting and ground motion, including data gathering in response to major earthquakes. Earthquake Geology also fosters research activities motivated by outstanding seismic hazard issues, understanding of the structural framework and earthquake history of faults in southern California, and contributes significant information to the statewide Unified Structural Representation and the Community Rheology Model (CRM). Collaborative proposals that cut across disciplinary boundaries are encouraged.

4.3.2. Research Strategies

- Paleoseismic documentation of earthquake ages and displacements, with emphasis on long paleoseismic histories, coordinated slip-per-event and incremental slip-rates, and system-level behavior (seismic supercycles).
- Gathering well-constrained slip-rates on the southern California fault system, with emphasis on major structures, along-strike variations, quantification of uncertainties, and comparison with geodetic observations and fault-loading models.
- Mapping and analysis of fault-zone geometries, mechanical properties, compositions, and fluid histories in regions where the seismogenic zone, the brittle-ductile transition or the ductile roots of major fault zones have been exhumed.
- Quantifying variations in fault roughness, complexity, strain localization, and damage in relation to the rupture propagation processes, including the extent, magnitude, and mechanisms of off-fault deformation and potential indicators of paleoseismic rupture direction.
- Improving the statewide community fault model in areas of inadequate fault representations or where new data is available, such as using high-resolution topographic data sets to better define fault traces, spatial uncertainty, and stochastic heterogeneity of fault geometry, and the addition of new fault geometries based on geophysical data.
- Validating ground motion prediction through analysis and dating of precariously balanced rocks and other fragile geomorphic features.

- Developing a geologic framework for the Community Rheology Model (CRM) that is consistent with existing and emerging geologic and geophysical observations, and the tectonic history of southern California.

4.3.3 Research Priorities

- Development of a paleoseismic event model to facilitate regional correlation with paleoclimate and other proxy records, document record completeness, and to enhance comparison of event history with the outcomes of earthquake simulations.
- Link fault representations within the statewide community fault model to slip rate information used to develop the Uniform California Earthquake Rupture Forecast, and alternative sources, where appropriate, in order to enhance utility of the model for simulations.
- Develop a research strategy for the "Earthquake Gates" initiative (see SAFS for definition).
- Foster an interdisciplinary workshop focused on the topic of 'Beyond Elasticity.'
- Establish a Technical Activity Group (TAG) to develop a geologic framework for the Community Rheology Model (CRM), as outlined in the 2016 CRM workshop report.
- Document earthquake sources and geomorphic constraints on extreme ground motions in the southern Sierra Nevada in support of the Central California Seismic Project.
- Revise empirical constraints on fault-rupture hazard (magnitude-displacement scaling) specific to the California plate boundary fault system.
- Develop methods or models for estimating fault displacements at the surface and at depth for the evaluation of risk to large distributed infrastructures (as relevant for EEII). Consider primary fault displacement (main fault trace), secondary fault displacement (distributed deformation zones in the near-field are around faults) as well as vertical tectonic shift which would cause tilt in distributed infrastructure.

4.3.4 Geochronology Infrastructure

The shared geochronology infrastructure supports C-14 and cosmogenic dating for SCEC-sponsored research. The purpose of shared geochronology infrastructure is to allow flexibility in the number and type of dates applied to each SCEC funded project as investigations proceed. Investigators requesting geochronology support should clearly state in their proposal an estimate of the number and type of dates required. For C-14, specify if sample preparation will take place at a location other than the designated laboratory. For cosmogenic dating, investigators are required to arrange for sample preparation and include these costs in the proposal budget. Investigators are encouraged to contact the investigators at the collaborating laboratories prior to proposal submission. Currently, SCEC geochronology has established relationships with the laboratories listed in table below for C-14 and cosmogenic dating.

Investigators may request support for geochronology outside of the infrastructure program for methods not listed here or if justified on a cost-basis. These requests must be included in the individual proposal budget, and will normally involve a collaborative proposal with the participating geochronologist. This includes OSL, pIR-IRSL and U-series dating, each of which are techniques that require that the geochronologist work closely with the project PI. Several investigators and laboratories, listed below, are available for collaboration on SCEC projects.

	Method	Laboratory	Contact	Email
Geochronology Infrastructure	C-14	University of California at Irvine	John Southon	jsouthon@uci.edu
		Lawrence Livermore National Lab	Tom Guilderson	tguilderson@llnl.gov
	Cosmogenic	Lawrence Livermore National Lab	Susan Zimmerman	zimmerman17@llnl.gov
Individual Collaborative Proposals	OSL / pIR-IRSL	University of Cincinnati	Lewis Owen	lewis.owen@uc.edu
		Utah State University	Tammy Rittenour	tammy.rittenour@usu.edu
		Desert Research Institute	Amanda Keen-Zebert	akz@dri.edu
	U-Series	Berkeley Geochronology Laboratory	Warren Sharp	wsharp@bgc.org

Student participation in lab analysis is strongly encouraged by SCEC and by all participating geochronology laboratories. Please direct questions regarding geochronology infrastructure to the Earthquake Geology group leader, Mike Oskin (meoskin@ucdavis.edu).

Data Reporting Requirements. Funded investigators are required to provide full reporting of their geochronology samples, including raw data, interpreted age, and geographic/stratigraphic/geomorphic context (what was dated?) before samples are submitted for analysis.

4.4 Computational Science (CS)

4.4.1 Research Objectives

The Computational Science working group promotes the use of advanced numerical modeling techniques, data intensive (big-data) computing, and high performance computing (HPC) to address the emerging needs of SCEC users and the application community on a variety of computer systems, including HPC platforms. The group works with SCEC scientists across a wide range of topics to take advantage of rapidly changing computer architectures and algorithms. We engage and coordinate with national HPC labs, centers, and service providers in crosscutting efforts to enable large-scale and data-intensive computing milestones. The group encourages research using national supercomputing resources, and supports students from both geoscience and computer science backgrounds to develop their skills in the area. Projects listing Computational Science as their primary area should involve significant software-based processing, big-data synthesis, or HPC in some way. Proposed research with the potential to be transferred to data intensive and HPC applications should make this explicit and include Computational Science as a secondary focus area. Research utilizing standard desktop computing should list the most relevant non-Computational Science working group as the primary area.

Computational Requirements. If your proposed research requires substantial SCEC computing resources or allocations, your proposal to SCEC should detail the computational requirements and include the following information:

1. The scientific goal of your computational research.
2. The scientific software you plan to use or develop.
3. A list of computations you plan to run.
4. The estimated computing time that will be required.
5. The computer resources you plan to use to perform your simulations.

Investigators on proposals that anticipate use of SCEC computational resources and/or help from SCEC software developers should consult with SCEC IT leadership for budget time support estimates and coordination planning.

Note that researchers may request startup allocations from NSF's Extreme Science and Engineering Discovery Environment (XSEDE) at https://www.xsede.org/allocations.

4.4.2. Research Strategies

- Reengineer and optimize HPC codes, required to reach SCEC research goals, for CPU-based and/or GPU-based supercomputers, with emphasis on issues such as performance, portability, interoperability, power efficiency, and reliability.
- Develop novel algorithms and implementation of more realistic models for earthquake simulation, particularly those that improve efficiency and accuracy or expand the class of problems that can be solved (see SCEC5 Thematic Areas).
- Optimize earthquake cycle simulators that can resolve fault processes across the range of scales required to investigate stress-mediated fault interaction, including those caused by dynamic wave propagation, or that combine coseismic dynamic rupture and multi-cycle simulators; generate synthetic seismicity catalogs; and assess the viability of earthquake rupture forecasts.
- Develop tools and algorithms for uncertainty quantification in large-scale inversion and forward-modeling studies, for managing I/O, data repositories, workflow, advanced seismic data format, visualization, and end-to-end approaches.
- Develop data-intensive computing tools, including but not limited to, InSAR and geodesy, lidar and structure-from-motion, 3D tomography, cross-correlation algorithms used in ambient noise seismology, and other signal processing techniques used, for example, to search for tectonic tremor and repeating events.
- Develop application programming interfaces (APIs) that contribute to integration of SCEC community models (CXM) with HPC applications for modeling and simulation; with emphasis in accelerating model creation (meshing and gridding), visualization of models, flexible integration of new datasets; and community software for CXM development (see SCEC Community Models Research Priorities).

4.4.3 Research Priorities

- Seismic wave propagation
    - Develop tools and implement procedures to validate SCEC community fault and seismic velocity models as applied in inverse and forward problems.
    - Develop and improve existing software tools and algorithms with application to HPC that accelerates and advances high-frequency simulation methods, while contributing to solve standing research problems as stated in the Ground Motions working group priorities.
    - Develop software tools and algorithms to incorporate more realistic constitutive material models and material model representation with application in wave propagation HPC codes. Examples include, but are not limited to, developing efficient tools and algorithms for modeling inelastic deformation, scattering by small-scale heterogeneities, and topography.
- Tomography
    - Develop new or adapt existing forward modeling software to solve full 3D tomography (F3DT) problems using HPC resources. Computational Science research in this area should help diversify current dependency on existing software and provide alternatives for SGT and F3DT verification, as done in dynamic rupture and forward ground motion simulation.

    - Develop efficient and sustainable computational procedures to facilitate the assimilation of regional waveform data in the SCEC community velocity models (CVMs); and integrate F3DT and inversion results into existing CVMs.
- Rupture dynamics
    - Develop computational codes that incorporate more sophisticated and realistic descriptions of fault weakening processes, complex fault geometry, and material heterogeneity and inelastic response in large-scale earthquake simulations, ideally with minimal impact on computational efficiency. This might require novel numerical approaches like adaptive mesh refinement.
    - Develop computational codes that merge single event rupture models with earthquake cycle models.
- Scenario earthquake modeling
    - Develop software processing tools such as workflows that can facilitate modeling a suite of scenario ruptures, incorporating material properties and fault geometries from SCEC community models, and investigate the sensitivity of simulations to models and modeling parameters.
    - Isolate causes of amplified ground motion using adjoint-based sensitivity methods.
- Data-intensive computing
    - Develop computational tools for advanced signal processing algorithms, such as those used in ambient noise seismology and tomography as well as InSAR and other forms of geodesy.
    - Integrate Big Data analytics techniques involving software stacks such as Hadoop/Spark, fault recovery, data format, generation, partitioning, abstraction, and mining.
- Engineering applications
    - Develop computational tools to investigate the implications of ground motion simulation results by integrating observed and simulated ground motions with engineering-based building response models; and to validate the results by comparison to observed building responses.
    - Develop and advance existing computational platforms that will facilitate end-to-end "ruptures-to-rafters" modeling capabilities that can help transform earthquake risk management into a cyberinfrastructure science and engineering discipline.

5. Research by Interdisciplinary Working Groups

SCEC coordinates earthquake system science through interdisciplinary working groups including: Fault and Rupture Mechanics (FARM), Stress and Deformation Over Time (SDOT), Earthquake Forecasting and Predictability (EFP), and Ground Motions (GM). The Southern San Andreas Fault Evaluation (SoSAFE) group has evolved into the San Andreas Fault System (SAFS) working group for SCEC5. This group coordinates research on the San Andreas and the San Jacinto master faults. Also new in SCEC5 is the SCEC Community Models (CXM) working group, focused on developing, refining and integrating community models that describe a wide range of features of the southern California lithosphere and asthenosphere. Seismic hazard and risk analysis research continues to be coordinated by the Earthquake Engineering Implementation Interface working group. Their activities include educational as well as research partnerships with practicing engineers, geotechnical consultants, building officials, emergency managers, financial institutions, and insurers.

5.1 Fault and Rupture Mechanics (FARM)

5.1.1 Research Objectives

The Fault and Rupture Mechanics (FARM) working group develops (1) constraints on the properties, conditions and physical processes that control faulting in the lithosphere over the entire range of pre-, co-, and post-seismic periods using field, laboratory, and theoretical studies; and (2) physics-based fault models applicable to various spatial and temporal scales, such as nucleation, propagation and arrest of dynamic rupture or long-term earthquake sequence simulations. This fundamental research aims to develop physics-based understanding of earthquakes in the Southern California fault system and contribute to SCEC hazards estimates such as the Uniform California Earthquake Rupture Forecast (UCERF) and physics-based ground motion predictions.

5.1.2. Research Strategies

Observational constraints on earthquake physics come from a range of sources, including seismology, geodesy, field geology, borehole geophysics, heat flow, hydrology, and gravity. Insights into earthquake physics are obtained by targeted laboratory fault and rock mechanics experiments and theoretical studies. Numerical modeling is used for understanding, analyzing, and relating theories, laboratory findings, and observations as well as exploring the implications of the findings. FARM supports fundamental research using these and related approaches. FARM research strategies include:

- Field, laboratory, and theoretical studies to determine spatial (including depth-dependent) and temporal variations in evolving fault strength and the effect of various relevant factors such as temperature, composition, pore pressure, degree of shear localization, and damage, including the variations and heterogeneity of relevant fault and rock properties.
- Theoretical and laboratory studies of nucleation, propagation, and arrest of seismic and aseismic fault slip.
- Seismological, geodetic, geophysical, laboratory and theoretical determinations of earthquake triggering, including triggering by static and dynamic stressing, fluid injection (induced earthquakes), and aseismic deformation.
- Geologic descriptions of fault complexity and shear zone structure, their relation to fault-scale and system-scale structural complexity, and representations suitable for inclusion in physics-based models.
- Characterization of fault damage zones and their evolution over both seismic and interseismic periods using seismological, geodetic, geologic, laboratory, and numerical experiments.
- Inferences and measurements of fault zone pore pressure, fluid flow, and their temporal and spatial variation.
- Development of improved numerical approaches to interrogate various temporal and spatial scales of faulting, including long-terms simulations of fault slip that incorporate inertial effects during earthquakes and geologic/fault system scale earthquake simulations (simulators) for the next generation of seismic hazard estimates ('beyond PSHA').

5.1.3 Research Priorities

- Constrain how absolute stress, fault strength and rheology vary with depth on faults.
- Determine the mechanisms dominant in coseismic (dynamic) fault resistance, including the relative importance of various potential dynamic weakening mechanisms and off-fault processes, and their compatibility with observational constraints such as stress drops and temperature measurements.

- Investigate the effect of fine-scale processes on the nucleation and dynamic rupture of large earthquakes and the resulting ground shaking, including whether the fine-scale processes can be suitably coarse-grained at the system scale.
- Investigate the relation between material, geometrical, and dynamic (deformation-induced) on- and off-fault heterogeneity, its effect on rupture initiation, propagation, and arrest, and implications for radiated energy, slip and rupture speed distributions, their scaling, and ground motion.
- Investigate how inelastic strain associated with fault roughness and discontinuities influences rupture propagation, seismic radiation, and scaling of earthquake source parameters.
- Determine how damage zones, crack healing and cementation, fault zone mineralogy, and off-fault yielding govern strain localization, slip stability, interseismic strength recovery, and rupture propagation.
- Determine how much off-fault inelasticity contributes to strain accumulation and what fraction of strain is relaxed by aseismic processes.
- Describe how fault complexity and inelastic deformation interact to determine the probability of rupture propagation through structural complexities.
- Assess how shear resistance and energy dissipation depend on the maturity of the fault system, and how these are expressed geologically.
- Constrain the active geometry and rheology of the vicinity of brittle-ductile transition - including frictional sliding stability transition zone - and ductile roots of fault zones, and determine their implications for depth limits of large earthquakes, overlap of seismic and aseismic slip, geodetic estimates of fault locking, and transition from frictional sliding to visco-plastic flow.
- Study the mechanical and chemical effects of fluid flow, both natural and anthropogenic, on faulting and earthquake occurrence, and how they vary throughout the earthquake cycle.
- Determine how seismic and aseismic deformation processes interact, and how that interaction affects long-term fault behavior, by developing numerical simulations that incorporate both seismic and interseismic periods and a combination of relevant physical factors, e.g., establishing the long-term effect of off-fault damage during earthquakes and off-fault healing during the interseismic periods exploring how slow slip and microseismicity redistributes stress for the following large events, and determining how large events can rupture into interseismically stable fault regions due to coseismic weakening.
- Study the implications of earthquake physics findings on earthquake hazard by developing physics-based long-term simulations of earthquake sequences on fault systems (earthquake simulators).
- Use numerical models to investigate which fault properties are compatible with paleoseismic findings, including average recurrence, slip rate, coefficient of variation of earthquake recurrence, and the possibility of system-wide “supercycles,” e.g. periods of several large earthquakes followed by periods of their absence; determine whether such behavior can be compatible with the currently observed statistics of smaller-magnitude events.
- Exploit anthropogenic (induced) seismicity as experiments in earthquake physics and earthquake predictability.

5.2 Stress and Deformation Over Time (SDOT)

5.2.1 Research Objectives

The focus of Stress and Deformation Over Time (SDOT) working group is to improve our understanding of how faults in the crust are loaded in the context of the wider lithospheric system. SDOT studies lithospheric processes on timescales from tens of millions of years to tens of years using the structure, geological history, and physical state of the southern California lithosphere as a natural laboratory. One objective is to characterize the present-day state of stress and deformation on crustal-scale faults and the lithosphere as a whole, and to tie this stress state to the long-term evolution of the lithospheric architecture through geodynamic modeling. Another central goal is to contribute to the development of a physics-based, probabilistic seismic hazard analysis for southern California by developing and applying system-wide deformation models.

5.2.2. Research Strategies

Addressing the SDOT research objectives requires a better understanding of fundamental quantities including lithospheric driving forces, the relevant rock rheology for processes acting over a wide range of time scales, fault constitutive laws, and the spatial distribution of absolute deviatoric stress. Tied in with this is a quest for better structural constraints, such as on density, rock type, Moho depths, thickness of the seismogenic layer, the geometry of lithosphere-asthenosphere boundary, as well as basin depths, rock type, temperature, water content, and seismic velocity and anisotropy. These quantities are constrained by a wide range of observables from disciplines including geodesy, geology, and geophysics.

Specific SDOT strategies include:

- Seismological imaging of the crust, lithosphere and upper mantle using interface and transmission methods.
- Examinations of geologic inheritance and evolution, on faults and off, and its relation to the three-dimensional (3D) structure and physical properties of the present-day crust and lithosphere.
- Development of models of interseismic, earthquake cycle and long-term deformation
- Development of models using approaches that may include analytical or semi-analytical methods, spectral approaches, boundary, finite, or distinct element methods.

5.2.3 Research Priorities

- Characterize the 3D distribution of isotropic and anisotropic wave speed variations. Assemble 3D lithological models of the crust, lithosphere, and mantle based on active- and passive-source seismic data, potential field data, and surface geology.
- Contribute to the development of the geologic framework for the Community Rheology Model (CRM).
- Advance research into averaging, simplification, and coarse-graining approaches in numerical models across spatio-temporal scales, addressing questions such as the appropriate scale for capturing fault interactions, the adequate representation of frictional behavior and dynamic processes in long-term interaction models, fault roughness, structure, complexity and uncertainty.
- Develop models to estimate slip rates on southern California faults, fault geometries at depth, and spatial distribution of slip or moment deficits on faults. Incorporate rheological and geometric complexities in such models and exploration of mechanical averaging properties. Assess potential discrepancies of models based on geodetic, geologic, and seismic data. Provide informative slip rates for fault representations defined by the Community Fault Model (CFM) for usage in earthquake simulator activities.
- Develop deformation models (fault slip rates and locking depths, off-fault deformation rates) in support of earthquake rupture forecasting.
- Develop improved estimates of spatio-temporal variations of stress based on inversions of earthquake focal mechanisms.
- 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.

- Develop interseismic and long-term deformation models that incorporate inelastic deformation. Develop that can predict the relative proportions of elastic, recoverable strain associated with the earthquake cycle and permanent, distributed strain in the crust.
- Apply stress and deformation measurements at various time scales for hypothesis testing of issues pertaining to postseismic deformation, fault friction, rheology of the lithosphere, seismic efficiency, the heat flow paradox, stress and strain transients, stress complexities at earthquake gates and fault system evolution. Improved constraints on the active geometry and rheology of ductile roots of fault zones.
- Contribute to the Community Stress Model (CSM). Development of spatio-temporal (4D) representations of the stress tensor in the southern California lithosphere using diverse stress constraints (e.g. from borehole or anisotropy measurements) and geodynamic models of stress.
- Contribute to the Community Thermal Model (CTM) and Community Rheology Model (CRM) (see Community Models Research Priorities). Test provisional rheology models with numerical models and geodetic, seismic, and geologic data. Assess sensitivity of stress and deformation patterns to parameter variations to facilitate determining what level of detail is needed in the CRM and CTM.
- Develop vertical deformation models (interseismic and multi-earthquake cycle) that incorporate improved vertical constraints from the Community Geodetic Model (CGM). Improve analyses of model sensitivity to non-tectonic vertical motion signals.
- Develop earthquake cycle stress models consistent with paleoseismic chronologies (slip estimates and event dates) that investigate stress accumulation and stress drop sequences over multiple earthquake cycles.

5.3 Earthquake Forecasting and Predictability (EFP)

5.3.1 Research Objectives

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

5.3.2. Research Strategies

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

We encourage researchers to consider how their proposals may further the objectives of special project working groups focussing on earthquake predictability and forecasting: the Collaboratory for Interseismic Simulation and Modelling (CISM, section 6.5), the Collaboratory for the Study of Earthquake Predictability (CSEP, section 6.2), and the Working Group on California Earthquake Probabilities (WGCEP, section 6.1).

5.3.3 Research Priorities

- Enhance methodology for evaluating forecasts of finite-size earthquake ruptures against past and/or future observations, including geological, geodetic, and seismological data.

- Enhance statistical methods of analyzing spatio-temporal patterns of seismicity, including cluster identification and declustering methods, in connection with understanding the physical basis of earthquake predictability.
- 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.
- Place useful geologic bounds on the character and frequency of multi-segment and multi-fault ruptures of extreme magnitude.
- 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.
- Develop earthquake simulators that encode the current understanding of earthquake physics for elucidating predictability.
- Test the hypothesis that “seismic supercycles’’ seen in earthquake simulators actually exist in nature and explore the implications for earthquake predictability.
- 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.
- Constrain the extent of permanent, off-fault deformation, and its contribution to geologic and geodetic fault slip-rate estimates.
- 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.
- Assess the predictive power of the Coulomb stress hypothesis by testing physics-based clustering models against multiple earthquake sequences across various tectonic settings.
- Exploit anthropogenic (induced) seismicity as experiments in earthquake predictability. Proposals that align with USGS priorities are particularly welcome (see, e.g., p. 40-43 of the Open File Report on “Incorporating Induced Seismicity into the US National Seismic Hazard Model”, http://pubs.usgs.gov/of/2015/1070/pdf/ofr2015-1070.pdf).
- 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.
- Strengthen testing methodology that accounts for epistemic uncertainties, dependence and observational errors in seismicity and rupture forecasts.
- Support government agencies in their efforts to deploy Operational Earthquake Forecasting (OEF) systems by developing real-time forecasting tools and protocols, including estimates of real-time data uncertainty and ensemble modelling techniques.
- Connect earthquake early warning algorithms with short-term earthquake forecast models to produce ground motion forecasts that span a range of timescales.

5.4 Ground Motions (GM)

5.4.1 Research Objectives

The primary goal of the Ground Motions (GM) interdisciplinary working group is to study the characteristics of ground motion data; understand and model the complex wave propagation mechanisms that give rise to these characteristics (e.g. nonlinearity, scattering effects); implement these models in physics-based ground motion simulation methodologies to predict strong-motion broadband waveforms and their effects (e.g.

constitutive models for off-fault plasticity and permanent ground deformation); and validate the simulated time-series using ground motion data and their statistics.

Both source and path characterization play a vital role in ground-motion prediction and are important areas of research for this group. An important focus for SCEC5 is the development of methodologies for validation of ground-motion simulations against observed data, and the implementation and testing of these methodologies. Another important focus of SCEC5 is to investigate the role of nonlinear material deformation and material failure on simulated ground motions. The GM focus group seeks to understand and simulate the conditions under which nonlinear effects reduce the ground surface shaking; the conditions which cause amplification due to impedance contrasts between stiff and soft crustal layers accentuated by material yielding; and the more dramatic effects of ground failure such as liquefaction and landslides. Our overarching goal is to produce simulated ground motions that are valid across a range of magnitudes, distances, and frequency bands, but especially for large magnitudes at close distances.

Given the emphasis of SCEC5 on nonlinear phenomena, which manifest in the vicinity of the fault as well as in the near-surface, the Geotechnical Layer (GTL) is conceptually eliminated, and the sedimentary deposits (soil) are heretofore considered integral constituents of the path. In turn, to incorporate off-fault and near-surface nonlinear effects in physics-based simulations, the GM focus group seeks proposals that develop and implement rheological models for each of these materials. These models should also account for the computational and modeling challenges of large-scale simulations as outlined by the Computational Science (CS) Working Group and by the SCEC Community Models (CXM) Focus Group (see pertinent sections); and enable predictions of phenomena that govern the risk of infrastructure systems, as outlined research priorities of the Earthquake Engineering Implementation Interface (EEII) Focus Group and of some of the Special Projects.

5.4.2. Research Strategies

- Analyze ground motion data and develop models that capture the observed characteristics of recorded data, such as how the frequency content, amplitude, duration and their spatio-temporal variability scale with magnitude and distance.
- Develop 3D rheology models (velocity, anelastic attenuation, nonlinear properties) of rock and soil layers of the crust, for integration in physics-based nonlinear wave propagation simulations.
- Validate ground motion simulations through development and testing of algorithms that trace the predictability and uncertainties of the simulated ground motions across frequency ranges.
- Continue development of the SCEC Broadband Platform.
- Coordinate efforts across the working groups, possibly via the formation of Technical Activity Groups (TAGs). Example of a TAG that would benefit the GM group would focus on the modeling, integration and simulation of nonlinear phenomena in the near-surface soft sediments (effort cuts across CS, EEII, CXM and GM).

5.4.3 Research Priorities

- Gather and develop novel data sets to be used as ground motion data for application to any of the research priorities. This may include, but certainly not limited to different sources (i.e., small magnitude earthquakes, tremor/low-frequency earthquakes, ambient noise), new instrumentation types (cell-phone accelerometers, strainmeter data, etc), or large data sets.
- Use observed ground-motion data to infer physical understanding of the controls on ground motion, to aid in the development of ground-motion simulations. Determine the relative roles of fault geometry, heterogeneous frictional resistance, wavefield scattering, intrinsic attenuation, and near-surface nonlinearities in controlling ground motions.

- Develop constitutive models to capture nonlinear phenomena such as off-fault plasticity, permanent ground deformation and earthquake triggered ground failure in physics-based simulations, especially in the near-field, where there is paucity of recorded data.
- Develop rheology models (velocity, anelastic attenuation, nonlinear properties) of the rock and soil layers of the crust to capture nonlinear phenomena such as off-fault plasticity, permanent ground deformation and earthquake triggered ground failure phenomena in physics-based simulation (especially in the near-field, where there is paucity of recorded data). Use available borehole measurements, near-surface material stiffness proxies (e.g., Vs30, topography) and/or empirical correlations to estimate input parameters necessary for the physics-based nonlinear ground motion simulations. This effort should be coordinated with the research priorities and activities of the SCEC Community Models (CXM), to ensure that the sedimentary models are properly constrained by the rheological properties of the deeper Community Velocity Model structure (including the 3D geometry of sedimentary basins), and avoid spurious reflections from fictitious impedance contrasts that could emerge from improper integration of the sedimentary layers with the underlying rock basement.
- Quantify the epistemic and parametric uncertainties of these models; and develop protocols on how to map material proxies (such as Vs30, or velocity profiles where available) and empirical estimates of the nonlinear soil and rock parameters (e.g., friction angle as a function of confining pressure) on the input parameters. Coordinate with research priorities and activities of the SCEC Community Models (CXM) (especially the velocity and rheology models); of the Fault and Rupture Mechanics (FARM) group with respect to the development and implementation of consistent material models for fault-zone and off-fault plasticity of rocks; and of the Computational Science (CS) group for the integration of these models in large-scale simulations.
- Develop statistical models of the sedimentary layers for stochastic media realizations, intended to capture scattering attenuation for the SCEC Broadband Platform (BBP) and for 3D physics-based simulations (see Community Models Research Priorities). Consider anisotropy in mapping the differences between lateral and vertical heterogeneities. Compare simulated ground motions from rough faults propagating through realistic heterogeneous media to simulated ground motions representing scattering via anelastic frequency dependent attenuation and to historical data.
- Develop, in collaboration with the Computational Science (CS) group, computationally efficient methodologies of integrating topographic amplification in 3D simulations, and study the effects of scattering and focusing by the geometric irregularities, as well as the coupling between wave amplification effects in the near-surface damaged rock layers and topography effects.
- Explore approximations to represent the effects of non-linearity in computational efficient reciprocity-based simulations, especially for SCEC products that entail very large numbers of simulations such as Cybershake. Distinguish between near-field and far-field nonlinear effects.
- Conduct systematic verification (comparison against theoretical predictions) of the simulation methodologies with the objective to develop robust and transparent simulation capabilities that incorporate consistent and accurate representations of the earthquake source and three-dimensional velocity structure.
- Conduct systematic validation of ground-motion simulation methodologies to appropriate observed historical ground-motion data. Trace the modeling and parametric uncertainties of the simulated ground motions. Conduct validation across frequency ranges (each representative of the scale of the model input parameters and source models). Compare synthetic ground motions from deterministic and stochastic approaches to data for overlapping bandwidths. Validate specific elements, such as source, path or site components, of the complex physics-based simulation models to identify topics where improvement is necessary. Coordinate with Earthquake Engineering Implementation Interface (EEII), to work on validation for engineering applications.

- Incorporate new effects and features in the SCEC Broadband Platform such as multi-segment rupture; nonlinear amplification factors; spatial variability of crustal properties; 3D basins and their on ensemble averaged long-period ground motions (e.g., by comparing ensemble averages of long-period (<~1Hz) ground motions computed in 1D and 3D crustal models for events included in the GMSV). Develop and implement methods for computing and storing 3D Green's functions, both source- and site-based, (see CXM section for related efforts).
- Develop frequency-dependent amplification factors for the SCEC BBP (preferably based on Fourier-spectral ratios, for both amplitude and phase) parameterized in terms of simple site parameters such as Vs30, basin depth, and/or the near surface soil-velocity gradient.

5.5 San Andreas Fault System (SAFS)

5.5.1 Research Objectives

The San Andreas Fault System (SAFS) group will develop projects within SCEC that are focused on the occurrence of large earthquakes on the San Andreas Fault system, seeking (1) projects that continue data collection on the timing and size of large earthquakes on the SAF and (2) projects that investigate the features of the fault system that may halt or permit continued rupture. This second class of projects falls under a new SCEC5 initiative called "**Earthquake Gates**" and will be organized in Year 1 through an incubator workshop to be held in the Winter/Spring of 2017.

5.5.2. Research Strategies

A. Research on the timing and size of large earthquakes on the San Andreas Fault System are encouraged which utilize
- High-resolution imaging of ground deformation (in trenches or recorded in the geomorphology)
- Data collection and analysis of vertical deformation associated with coseismic land-level changes on reverse faults and coastal faults
- Modern geochronologic techniques, or exploration of uncertainties in paleoearthquake or geomorphic event dating

B. The Earthquake Gates initiative is designed to bring together groups of collaborators across multiple disciplines to investigate the features that promote or arrest large earthquakes on the San Andreas Fault System. The goal is to study features that may conditionally arrest ruptures so that at some times the gate is 'closed' while at other times the gate is 'open' in order to better forecast earthquake behavior. Earthquake Gates projects may be location-specific, for example investigating a subregion in southern California in which subsurface data such as paleoseismic or geophysical data can be combined with modeling approaches to study the size of ruptures in that region, or may be more generalized, for example addressing large earthquakes that rupture below the base of the seismogenic zone and affect Mmax.

Like the Special Fault Study Areas of SCEC4, the number of Earthquake Gates projects will be limited so that the research aims of the community are focused on a subset of tractable areas or problems. To accomplish this, in Year 1 of the Earthquake Gates Initiative, an incubator workshop will be held to bring investigators together to discuss the best locations or questions to tackle in SCEC5. **The workshop will be open to all members of the community, but individuals (or groups) should prepare short (2 page) idea papers that identify the research questions and purpose of a possible Earthquake Gates Special Fault Study Area**. A call for the idea papers will be released with the incubator workshop announcement in the Fall of 2016.

5.5.3 Research Priorities

- Basic research on the occurrence of large earthquakes on the San Andreas Fault System. This includes studies of the factors that lead to occurrence and preservation of ground rupture and offsets, as well as improved dating and correlation techniques for development of fault rupture histories.
- Hold an incubator workshop for the Earthquake Gates initiative.Prior to the workshop, attendees must submit (individually or as groups) 2-page idea papers that describe an Earthquake Gate of interest to the investigator(s), specifying the research questions, data, and modeling that would be needed to pursue research on a specific Gate. The workshop will use these idea papers to (1) further discussion and foster ideas on the most promising Earthquake Gates to investigate and (2) promote organization of individual investigators into leading an Earthquake Gates project and begin development of Earthquake Gates. The Earthquake Gates incubator workshop will be held in Winter/Spring 2017 and an announcement will be sent to the SCEC community in the Fall of 2016.

5.6 SCEC Community Models (CXM)

5.6.1 Research Objectives

The SCEC CXM working group develops, refines and integrates community models describing a wide range of features of the southern California lithosphere and asthenosphere. These features include: elastic and attenuation properties (Community Velocity Model, CVM), temperature (Community Thermal Model, CTM), rheology (Community Rheology Model, CRM), stress and stressing rate (Community Stress Model, CSM), deformation rate (Community Geodetic Model, CGM), and fault geometry (Community Fault Model, CFM). Our goal is to provide an internally consistent suite of models that can be used to simulate the seismic behavior in southern California.

SCEC5 research goals involve continued refinement of existing community models (CFM, CVM, CSM, CGM), development of new community models (CTM and CRM), and integration of the models into a self-consistent suite. Objectives also include quantification of uncertainties and development of techniques for propagating uncertainties from observations through community model development to simulation predictions.

5.6.2. Research Strategies

- Develop and apply inversion techniques to populate and refine the community models.
- Collect additional observations to improve resolution of a community model and/or resolve discrepancies among competing models.
- Develop viable alternative community models that facilitate representation of the epistemic uncertainty.
- Develop methods to characterize uncertainty in each of the community models.
- Validate individual community models and verify consistency across multiple community models (e.g., consistency of stress predictions from the CTM and CRM with the CSM).
- Use community models in simulations to forecast behavior, including estimates of the uncertainties in predicted values.
- Expand community participation in model development, validation, and application through workshops, tutorials, and participation in and/or collaboration with related efforts (e.g., EarthCube).

5.6.3 Research Priorities

- ***Science integration***. Convene a workshop focused on guiding community model development towards self-consistent and well-integrated community models.
- ***Information technology integration***. In collaboration with the Community Modeling Environment (CME) and the CXM developer- and user-communities, develop detailed documentation defining standard user-interface(s) and storage formats for the community models. Design goals include: ease of use, computational efficiency, and common interfaces and storage for each class of model (e.g., grid-based or object-based). The documentation should include complete specification of user-interfaces as well as appropriate use cases for each community model. Emphasis is on defining long-lasting, effective standards.
- ***Training.*** Provide virtual or in-person hands-on training in how to use the existing community models in research applications. Training should target user needs (e.g., from surveys of the community). Training should be archived for on-demand access.
- ***Small scale features***. Develop methods to represent smaller scale features in the CXMs, such as stochastic variations in elastic properties, attenuation, stress, temperature, rheology, and fault strike and dip.
- ***Validation***. Develop and apply procedures (i.e., goodness-of-fit measures) for evaluating updated CXMs against observations (e.g., seismic waveforms, gravity, etc) to discriminate among alternatives and quantify model uncertainties.
- ***Community Fault Model (CFM)***
    - Improve and evaluate the CFM, placing emphasis on defining the geometry of major faults that are incompletely, or inaccurately, represented in the current model, and on faults of particular concern, such as those that are located close to critical facilities.
    - Refine representations of the linkages among major fault systems.
    - Generate maps of geologic surfaces compatible with the CFM that may serve as strain markers in crustal deformation modeling and/or property boundaries in future iterations.
    - Collaborate with developers of related data products to improve consistency in the organization and naming scheme (e.g., USGS Fault and Fold database).
- ***Community Velocity Model (CVM)***
    - Integrate new data (especially the Salton Sea Imaging Project) into the existing CVMs with validation of improvements in the CVMs for ground-motion prediction.
    - Quantify uncertainty in the CVM structure and its impact on simulated ground motions.
    - Develop efficient and sustainable computational procedures to facilitate the assimilation of regional waveform data into the CVMs (see Computational Science Research Priorities).
- ***Community Stress Model (CSM)***
    - Assess sensitivity of stress and deformation patterns to parameter variations to facilitate determining what level of detail is needed in the CRM and CTM.
    - Compile diverse constraints on stress (e.g. from borehole or anisotropy measurements) and evaluate the accuracy of the CSM (see Stress and Deformation Over Time Research Priorities).
- ***Community Geodetic Model (CGM)***
    - See Tectonic Geodesy Research Priorities.
- ***Community Thermal Model (CTM)***
    - Deliver a preliminary CTM that provides temperatures throughout the southern California lithosphere and asthenosphere consistent with radiogenic heat production.

- Improve/interpolate surface heat flow maps. Search for additional heat flow and thermal property data in areas with poor coverage.

- ***Community Rheology Model (CRM)***
    - Establish a Technical Activity Group (TAG) to develop a geologic framework for the Community Rheology Model (see Earthquake Geology Research Priorities).
    - Construct a provisional rheology model based upon a simplified geologic framework. The model should provide constitutive relations for ductile, plastic and brittle material in rock and in shear zones.
    - Develop mixing laws for polymineralic rocks of the CRM.

5.7 Earthquake Engineering Implementation Interface (EEII)

5.7.1 Research Objectives

The purpose of the Earthquake Engineering Implementation Interface (EEII) is to create and maintain collaborations with research and practicing engineers. These activities may include ground motion simulation validation, as well as the end-to-end analysis of structures and infrastructure systems. Our goal of impacting engineering practice and large-scale risk assessments requires partnerships with the engineering and risk-modeling communities, which motivates the following activities.

5.7.2. Research Strategies

Example strategies to achieve these objectives include:

- Perform engineering and risk analysis using SCEC research products related to hazards and ground motions, in order to determine the impact of research insights on engineering decisions, and sensitivity of engineering-related result to parameters in the science models.
- Develop tools and approaches that facilitate the transfer or SCEC science products to the research community.
- Form groups to reach consensus on methods to validate and utilize simulated ground motions, simulation-based hazard maps, and other SCEC science products of relevance to engineers and risk analysts.

5.7.3 Research Priorities

Ground motion simulation validation and utilization

- Develop, coordinate and vet methods for validating simulations of ground motions for engineering use.
- Demonstrate ground motion simulation validation methodologies with existing simulated ground motions.
- Develop methodologies to validate and use SCEC CyberShake ground motion simulations for developing probabilistic and deterministic hazard maps for building codes and other engineering applications seismic hazard applications. Investigations of observed versus simulated region-specific path effects for small-magnitude earthquakes in Southern California are encouraged.
- Develop data, products or tools that enable physics-based hazard calculations or ground motions to be utilized by engineers and risk modelers.
- Identify or demonstrate links between ground motion metrics or structural response parameters and ground motion simulation features, such that simulation algorithms might be improved to better represent ground motion features of interest.

- Quantify and evaluate spatial variation in amplitudes from regional ground motion simulations, for the purpose of validating simulations versus observations from empirical networks, and for quantifying the role of geological features in the observed variation.

Collaboration in engineering and risk analysis

- Assess the performance of distributed infrastructure systems using simulated ground motions. Evaluate the potential impact of basin effects, rupture directivity, spatial distribution of ground motion, or other phenomena on risk to infrastructure systems.
- Enhance the reliability of simulations of long period ground motions in the Los Angeles region using refinements in source characterization and seismic velocity models, and evaluate the impacts of these ground motions on tall buildings and other long-period structures (e.g., bridges, waterfront structures).
- Identify the sensitivity of structural response to ground motion parameters and structural parameters through end-to-end simulation. Buildings of particular interest include non-ductile concrete frame buildings.
- Perform detailed assessments of the results of ground motion simulation scenarios, as they relate to the relationship between ground motion characteristics and structural response and damage.
- Develop improved site/facility-specific and portfolio/regional risk analysis (or loss estimation) techniques and tools, and implement them in software tools.
- Identify earthquake source and ground motion characteristics that control damage and financial loss estimates.
- Evaluate the spatio-temporal correlation of ground motions at regional scales from recordings and using CyberShake data. Compare and validate CyberShake results with empirical correlations.
- Develop methods or models for estimating fault displacements at the surface and at depth for the evaluation of risk to large distributed infrastructures. Consider primary fault displacement (main fault trace), secondary fault displacement (distributed deformation zones in the near-field are around faults) as well as vertical tectonic shift which would cause tilt in distributed infrastructure.

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

6. Research by Special Projects Working Groups

Special Projects are organized around large-scale projects funded through special grants outside of the NSF-USGS cooperative agreements that support the SCEC base program, but have synergistic goals and are aligned with the overall SCEC research program priorities. The current Special Projects teams include Working Group on California Earthquake Probabilities (WGCEP), the Collaboratory for the Study of Earthquake Predictability (CSEP), the Community Modeling Environment (CME), the Central California Seismic Project (CCSP), Collaboratory for Interseismic Simulation and Modeling (CISM), and Mining Seismic Wavefields.

6.1 Working Group on California Earthquake Probabilities (WGCEP)

The Working Group on California Earthquake Probabilities (WGCEP) is a collaboration between SCEC, the U.S. Geological Survey, and California Geological Survey aimed at developing official earthquake-rupture-forecast models for California. The project is closely coordinated with the USGS National Seismic Hazard Mapping Program, and has received financial support from the California Earthquake Authority (CEA). The WGCEP has completed the time-independent UCERF3 model

(UCERF3-TI, which relaxes segmentation and includes multi-fault ruptures) and the long-term, time-dependent model (UCERF3-TD, which includes elastic-rebound effects). More recently, we are working to add spatiotemporal clustering (UCERF3-ETAS) to account for the fact that triggered events can be large and damaging. As the latter will require robust interoperability with real-time seismicity information, UCERF3-ETAS will bring us into the realm of operational earthquake forecasting (OEF). We are also starting to plan for UCERF4, which we anticipate will utilize physics-based simulators to a greater degree (see last bullet below).

The following research activities would contribute to WGCEP goals:

- Evaluate fault models in terms of the overall fault connectivity at depth (important for understanding the likelihood of multi-fault ruptures) and the extent to which faults represent a well-define surface versus a proxy for a braided deformation zone.
- Evaluate existing deformation models, or develop new ones, in terms of applicability of GPS constraints, categorical slip-rate assignments (based on “similar” faults), applicability of back-slip methods, and other assumptions. Of particular interest is the extent to which slip rates taper at the ends of faults and at fault connections.
- Evaluate the UCERF3 finding that 30% to 60% of off-fault deformation may be aseismic.
- Help determine the average along-strike slip distribution of large earthquakes, especially where multiple faults are involved (e.g., is there reduced slip at fault connections?).
- Help determine the average down-dip slip distribution of large earthquakes (the ultimate source of existing discrepancies in magnitude-area relationships). Are surface slip measurements biased with respect to slips at depth?
- Develop a better understanding of the distribution of creeping processes and their influence on both rupture dimension and seismogenic slip rate.
- Contribute to the compilation and interpretation of mean recurrence-interval estimates (including uncertainties) from paleoseismic data and/or develop site-specific models for the probability of events going undetected at a paleoseismic site.
- Develop ways to constrain the spatial distribution of maximum magnitude for background seismicity (for earthquakes occurring off of the explicitly modeled faults).
- Address the question of whether small volumes of space exhibit a Gutenberg Richter distribution of nucleations (even on faults).
- Develop improved estimates (including uncertainties) of the total long-term rates of observed earthquakes for different sized volumes of space.
- Refine our magnitude completeness estimates (as a function of time, space, and magnitude). Develop such models for real-time applications (as will be needed in operational earthquake forecasting).
- Develop methods for quantifying elastic-rebound based probabilities in un-segmented fault models.
- Help quantify the amount of slip in the last event, and/or average slip over multiple events, on any major faults in California (including variations along strike).
- Develop models for fault-to-fault rupture probabilities, especially given uncertainties in fault endpoints.
- Determine the extent to which seismicity rates vary over the course of historical and instrumental observations (the so-called Empirical Model of previous WGCEPs), and the extent to which this is explained by decaying aftershock sequences.
- Determine the applicability of higher-resolution smoothed-seismicity maps for predicting the location of larger, more damaging events.
- Explore the UCERF3 “Grand Inversion” with respect to: possible plausibility filters, relaxing the UCERF2 constraints, not over-fitting data, alternative equation-set weights, applying a

characteristic-slip model, and applicability of the Gutenberg Richter hypothesis on faults (see report at www.WGCEP.org).

- Develop methods for combining spatiotemporal clustering with long-term forecast models.
- Are sequence-specific parameters for aftershock sequences warranted?
- Determine if there is a physical difference between a multi-fault rupture and a separate event that was triggered quickly.
- Develop more objective ways of setting logic-tree branch weights, especially where there are either known or unknown correlations between branches.
- Develop easily computable hazard or loss metrics that can be used to evaluate and perhaps trim logic- tree branches.
- Develop techniques for down-sampling event sets to enable more efficient hazard and loss calculations.
- Because all models will be wrong at some level, develop valuation metrics that allow one to quantify the benefit of potential model improvements in the context of specific uses.
- Develop novel ways of testing UCERF3, especially ones that can be integrated with CSEP. For example, UCERF3-ETAS could be tested against historic ruptures that have occurred in the state.
- Address the extent to which large triggered events can or cannot nucleate from within the rupture area of a main shock (the answer has an important influence on UCERF3-ETAS results).
- Help constrain the distance decay of triggered earthquakes, especially in light of a finite seismogenic thickness and a depth-dependent rate of earthquake nucleation.
- Compile global datasets of large-event triggering, and compare with the more robust statistics available for smaller events. Also try to quantify the extent of spatial overlap between large main shocks and large triggered events (an important metric that could be used to tune models like UCERF3).
- Study and test the behavior of computational earthquake-cycle simulators, envisioning that they could become essential ingredients in future UCERF projects and a cornerstone of SCEC5. The goal is to develop the capability of simulators to be able to contribute meaningfully to hazard estimates. Important tasks include:
  - Study and test, using code verification exercises and more than one code, the sensitivity of simulator results to input details including fault-system geometry, stress-drop values, tapering of slip, methods of encouraging rupture jumps from fault to fault, cell size, etc.
  - Develop physically realistic ways of simulating off-fault seismicity.
  - Add additional physics into simulators, for example, the inclusion of high-speed frictional weakening and of off-fault viscoelastic and heterogeneous elastic properties.
  - Develop alternate methods of driving fault slip besides “back-slip”.
  - Make access to existing simulators easy for new users, including adequate documentation and version numbers, examples of input and output files for initial testing, and access to analysis tools. Publicize availability.
  - Develop new approaches to designing simulators and/or of making them more computationally efficient, including the use of better algorithms, point source Green’s functions, and GPUs.
  - Develop validation tools for simulators, utilize existing UCERF data comparison tools with them, and develop capabilities for simulators to interact with UCERF infrastructure.
  - Develop the capability of simulators to deal with UCERF and SCEC CFM fault geometries, both for rectangular and triangular cell representations.
  - Create statewide synthetic earthquake catalogs spanning 100 My using as many different simulators as possible, in order to generate statistically significant behavior on even slow-slipping faults. Use small time-steps to permit evaluation of short-term clustering.

- Use these catalogs as synthetic laboratories for CSEP testing as described under CSEP.
- Data-mine these catalogs for statistically significant patterns of behavior. Evaluate whether much-shorter observed catalogs are statistically distinguishable from simulated catalogs. Consider and explore what revisions in simulators would make simulated catalogs indistinguishable from observed catalogs.
- Develop and test a variety of statistical methods for determining the predictability of earthquakes in these simulated catalogs, especially with respect to large triggered earthquakes.
- Compute other data types such as gravity changes, surface deformation, InSAR images, in order to allow additional comparisons between simulated results and observations.

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

6.2 Collaboratory for the Study of Earthquake Predictability (CSEP)

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

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

6.2.1. Priorities for CSEP

- ***Develop retrospective and prospective tests of UCERF3-ETAS.*** This new WGCEP model combines fault-based long-term time-dependence with short-term earthquake clustering and specifies forecasts as a set of simulated catalogs. New strategies for retrospective and prospective testing are required to evaluate the model.
- **Develop forensic tools** for understanding what aspects of a model dominate CSEP results.
- ***Evaluate the Coulomb stress hypothesis.*** Assess the predictive skill of forecast models based on Coulomb stress through retrospective and prospective experiments on multiple earthquake sequences. For example, build on the retrospective evaluation of physics-based and statistical forecasting models during the 2010-12 Canterbury, New Zealand, earthquake sequence by applying these models to other earthquake sequences in different tectonic settings.
- ***Global experiments.*** Develop and test global high-resolution models that (i) encode fundamental hypotheses about earthquake occurrence at a global scale for faster evaluation, and (ii) elucidate differences in the predictability of earthquakes across tectonic settings.
- ***Strengthening evaluation methodologies.*** Develop computationally efficient performance metrics of forecasts and predictions that can account for epistemic uncertainties and evaluate forecasts specified as sets of simulated catalogs (e.g., simulation-based ETAS models or UCERF3-ETAS).
- ***Supporting Operational Earthquake Forecasting (OEF).*** (i) Developing forecasting methods that address real-time data deficiencies, (ii) update forecasts on an event basis and evaluating forecasts with overlapping time-windows or on an event basis, (iii) improve short-term forecasting models, (iv) develop prospective and retrospective experiments to evaluate OEF candidate models.

- ***Earthquake rupture simulators.*** Develop experiments to evaluate the predictive skills of earthquake rupture simulators, against both synthetic (simulated) and observed data (see also the WGCEP and CISM sections), with specific focus on how to automate the identification of a large earthquake with a modeled fault.
- ***External Forecasts and Predictions.*** Develop and refine experiments to evaluate forecasts and predictions generated outside of CSEP, including operational forecasts by official agencies and prediction algorithms based on seismic and electromagnetic data;
- ***Induced seismicity.*** Develop models and experiments to test forecasts of induced seismicity, e.g. in California or Oklahoma. Proposals that align with USGS priorities are particularly welcome (see, e.g., p. 40-43 of the Open File Report on "Incorporating Induced Seismicity into the US National Seismic Hazard Model", http://pubs.usgs.gov/of/2015/1070/pdf/ofr2015-1070.pdf).
- ***Hybrid/ensemble modeling.*** Develop methods for forming optimal hybrid and ensemble models from multiple probability-based or alarm-based forecasting models;
- ***Evaluating hazard models.*** Develop methodologies for prospectively evaluating seismic hazard models and their components (e.g., ground motion models).
- ***Forecasting focal mechanisms.*** Develop methodology to forecast focal mechanisms and evaluating the skill of such forecasts.
- ***Paleo-based forecasts.*** Develop experiments to test the fault rupture and earthquake probabilities implied by paleoseismic investigations of California faults (e.g., testing probabilities of future ruptures at paleoseismic sites where numerous ruptures have been documented, the relative effectiveness of proposed fault segment boundaries at stopping ruptures, and the relative frequency of on-fault and off-fault ruptures in California) (see also the WGCEP and SoSafe sections).

6.2.2 General Contributions

- Establish rigorous procedures in controlled environments (testing centers) for registering prediction procedures, which include the delivery and maintenance of versioned, documented code for making and evaluating forecasts including intercomparisons to evaluate predictive skills.
- Construct community-endorsed standards for testing and evaluating probability-based, alarm-based, fault-based, and event-based predictions.
- Develop hardware facilities and software support to allow individual researchers and groups to participate in prediction experiments.
- Design and develop programmatic interfaces that provide access to earthquake forecasts and forecast evaluations.
- Provide prediction experiments with access to data sets and monitoring products, authorized by the agencies that produce them, for use in calibrating and testing algorithms.
- Characterize the influence of limitations and uncertainties of such data sets (e.g., completeness magnitudes, source parameters, real-time vs post-processed data uncertainties).
- Conduct workshops to facilitate international collaboratories.

6.3 Community Modeling Environment (CME)

The Community Modeling Environment (CME) is a SCEC special project that develops improved ground motion forecasts by integrating physics-based earthquake simulation software, observational data, and earth structural models using advanced computational techniques including high performance computing (HPC). CME is developing ground motion simulations that produce broadband seismograms and often use results, and integrate work, from various SCEC activities. The simulation tools used in CME activities include rupture generators (dynamic and kinematic), wave propagation models (low and high frequency), nonlinear site response modules, and validation capabilities (including assembled observational strong motion data sets and waveform-matching goodness of fit algorithms and information displays).

6.3.1 SCEC Computational Platforms

The SCEC community can contribute research activities to CME by providing scientific or computational capability that can improve ground motion forecasts for any of the activities described below.

Broadband Platform. The open-source Broadband Platform (BBP) provides a verified, validated, and user-friendly computational environment for generating broadband (0-100Hz) ground motions. The BBP includes a suite of kinematic source models, wave propagation codes and site response modules to calculate suites of synthetic seismograms from user-specified rupture sets, structural models, and station sets.

High-F Platform. The High-F platform comprises source and wave propagation codes (kinematic ruptures with the AWP-ODC wave propagation code and Hercules for both) used by SCEC researchers to push earthquake simulations to higher frequencies (> 1Hz). High-F activities aim at including more realistic physics while improving the upper frequency limits of physics-based ground motions. Physics models currently tested in the High-F platform include those for fault roughness, near-fault plasticity, frequency-dependent attenuation, topography, small-scale near-surface heterogeneities, and near-surface nonlinearities.

CyberShake Platform. The CyberShake Platform provides physics-based probabilistic seismic hazard curves and maps using seismic reciprocity to generate large ensembles of ground motion simulations (> 10^8). CyberShake combines an earthquake rupture forecast (currently UCERF2) with a kinematic source generator (Graves and Pitarka) and a wave propagation code (AWP-ODC) to provide rates of exceedance of ground motions.

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. F3DT can invert both earthquake waveforms and ambient-field correlograms for high-resolution crustal models, and it can refine the centroid moment tensors of earthquakes by matching observed waveforms with 3D synthetics.

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. UCVM is used as a repository and delivery system for Community Velocity Models (CVMs) developed by SCEC researchers. UCVM allows the generation of large simulation meshes which can be used for High-F and CyberShake simulations.

6.3.2 Research Priorities

In addition to specific priorities described in the Ground Motions section, the Planning Committee is seeking proposals to:

- Provide codes to be included in an upcoming dynamic rupture platform, DynaShake. DynaShake is intended to operate in a fashion similar to the BBP, where independent codes are to be integrated to run simulation problems and go through validation exercises for realistic applications. Dynamic rupture code developers must be willing to work under an open source license. Preference will be given to codes that have been verified under the Dynamic Rupture Code Verification Technical Activity Group and to codes that have been parallelized or are in the process of being parallelized to run on multiple core systems (clusters and HPC).

- Improve and integrate models for source generation, wave propagation, and site effects into any of CME's simulation platforms. This can include the development of scientific software that simulates one or more physical processes from the source to the surface.
- Improve our ability to extend ground motion simulations to higher frequencies and to improve the accuracy of such models through the integration of better physics. Proposals can be targeted to any of the ground motion simulations platforms, but are most relevant in the context of High-F.
- Develop the computational and integration frameworks to extend 3D structural modeling capabilities to the BBP.
- Develop or improve ground motion simulation validation computational and organizational tools. Research in this area would contribute to the efforts under the ground motion simulation validation (GMSV) technical activity group and the EEII. Validation of ground motions and models is important for any and all of the simulation platforms under CME.
- Improve the accuracy of community velocity models (CVMs), through the development of techniques that may involve, for example, the development of 3D tomography codes as well as the integration of geology constraints into CVMs. Proposals are also sought to improve the methodologies used for integration of models from different sources and scales within UCVM.
- Develop tools for decimating the UCERF3 model for use within CyberShake for specific regions (Southern and Central California) and accounting for the loss of precision and accuracy from the simplified model.
- Evaluate the spatio-temporal correlation of ground motions at regional scales from recordings and using CyberShake data. Compare and validate CyberShake results with empirical correlations.

6.4 Central California Seismic Project (CCSP)

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

A pilot project focused on the central coast of California was initiated in 2015 and continued through 2016. The goal of the CCSP is to assess the effectiveness of physics-based ground motion modeling in reducing path-effect uncertainties.

6.4.1 Research Strategies

Currently planned objectives of the program are fourfold:

- Analyze the existing seismic, geophysical, and geologic data for constraints on the 3D crustal structure of Central California. The seismic constraints include earthquake waveforms and ambient-field correlograms; the geologic constraints include surface and subsurface data on basin, fault, and basement structure.
- Invert the seismic and geologic constraints to improve models of Central California crustal structure. Priority will be given to full-3D tomographic methods that can account for 3D wave propagation and the nonlinearity of the structural inverse problem.
- Deploy an array of temporary seismic stations in Central California to collect new earthquake and ambient-field data. Assess the efficacy of these data in reducing path-effect uncertainties and validating model-based uncertainty reductions. Both ground and ocean bottom seismometer (OBS) array deployments will be considered.

- Compute large ensembles of earthquake simulations for central California sites that are suitable for probabilistic seismic hazard analysis (PSHA). Compare the simulation results with those from ground motion prediction equations (GMPEs). Use this modeling to understand the aleatory variability encoded by the GMPEs and to assess the epistemic uncertainties in the simulation-based PSHA.

6.4.2 Research Priorities

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

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

6.5 Collaboratory for Interseismic Simulation and Modeling (CISM)

The Collaboratory for Interseismic Simulation and Modeling (CISM) is an effort to forge physics-based models into comprehensive earthquake forecasts using California as its primary test bed. Short-term forecasts of seismic sequences, in combination with consistent long-term forecasts, are critical for reducing risks and enhancing preparedness. CISM involves multiple specialties and groups, including those from WGCEP and CSEP and those involved with earthquake simulators. The Planning Committee is welcoming proposals that support CISM in its mission to improve predictability by combining rupture simulators that account for the physics of rupture nucleation and stress transfer with ground-motion simulators that account for wave excitation and propagation. CISM forecasting models will be tested against observed earthquake behaviors within the existing CSEP. Detailed research priorities associated with CISM include the use and calibration of earthquake simulators and priorities listed under the WGCEP and CSEP sections.

6.6 Mining Seismic Wavefields (MSW)

The Mining Seismic Wavefields (MSW) project was initiated in 2016 to develop and deploy cyberinfrastructure for mining seismic wavefields through data intensive computing techniques to extend similarity search for earthquake detection to massive data sets. Similarity search has been used to understand the mechanics of tectonic tremor, transform our understanding of the depth dependence of faulting, illuminate diffusion within aftershock seismicity, and reveal new insights into induced earthquakes. These results were achieved with modest data volumes – from ~ 10 seismic stations spanning ~ 10 km – yet they increased the number of detected earthquakes by a factor of 10 to 100. This project will develop the cyberinfrastructure required to enable high-sensitivity studies of earthquake processes through the discovery of previously undetected seismic events within massive data volumes. The Planning Committee welcomes proposals that support the Mining Seismic Wavefields project. Key priorities can be found in the Seismology section. In addition, we encourage proposals to develop and apply data-intensive computing techniques, e.g. for long seismic time series (large-T) or dense seismic instrumentation (large-N) analysis, to earthquake science and engineering research problems.

7. Communication, Education, and Outreach Activities

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 in SCEC5 is *Partner Globally, Prepare Locally*. Our geographic reach has been expanded far beyond the Golden State. Our 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. In SCEC5, the CEO program will manage and expand activities within four CEO focus areas:

1. ***Knowledge Implementation*** connects SCEC scientists and research results with practicing engineers, government officials, business risk managers, and other professionals active in the application of earthquake science.
2. 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.
3. 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.
4. Finally, the ***Experiential Learning and Career Advancement*** program will provide research opportunities, networking, and other resources to encourage and sustain careers in STEM fields.

Investigators interested in contributing to CEO activities are strongly advised to contact Mark Benthien (213-740-0323; benthien@usc.edu) before submitting a proposal since alternative approaches may be more appropriate.