SCEC
AN NSF+USGS CENTER

Southern California Earthquake Center
2023 Science Plan

Proposals Due: December 1, 2022

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1. New This Year

The SCEC Science Plan (aka RFP) reflects the research priorities first articulated in the SCEC5 proposal and approved by the National Science Foundation and the U.S. Geological Survey. The 2023 Science Plan, with its updated priorities, is an extension of the SCEC5 research program to a 7th year (February 1, 2023 - January 31, 2024). It builds on SCEC's strengths in coordinating fundamental PI-driven research and integrating results into state-of-the-art community models, software and other products that advance our understanding of earthquake processes. The SCEC Science Plan detailed in this document is provisional pending final budget authorization by sponsoring agencies. The Southern California Earthquake Center is committed to providing a safe, productive, and welcoming environment for all participants.

Substantial changes have been made to the RFP since last year. We strongly encourage researchers to read this document carefully and in its entirety.

In March of 2022, SCEC submitted a proposal to NSF to transition to a "Statewide California Earthquake Center." As of October 2022, that proposal is still pending. For the period covered by this Science Plan, we will not have the benefit of NSF funding to support the core research program. The reduced funding means we will remain attentive to the long-term health and sustainability of all community models. The 2023 Science Plan continues the trend emphasizing (1) artificial intelligence, machine learning and other emerging techniques in computational and observational studies across the full disciplinary spectrum of earthquake science; (2) near-fault studies for testing and developing further models of earthquake processes; and (3) enhancements to SCEC research computing, cyberinfrastructure, and information technology.

- 2023 is an extended year of the SCEC5 research program. Our overarching mission remains focused on reaching SCEC5 goals. Proposals for new projects must make a compelling case for how they will contribute to these goals within the 1-year period.
- The continuing COVID pandemic impacted the ability of some SCEC investigators to complete work as initially planned. We recognize this adversity and encourage investigators to document such hardship, where appropriate, in their prior results. PIs may want to also consider contingencies in their proposed work plan should the pandemic continue and a project period extension is not possible. We will communicate with SCEC investigators of any future changes in guidance.
- Funded SCEC projects will have an effective performance period from February 1, 2023 to January 31, 2024. Funded workshops must be scheduled between February 1, 2023 and December 31, 2023.
- Proposal guidelines outlined in Section 3.3.4 will be strictly enforced. Proposals that do not comply with the guidelines will be returned without review.
- The Ridgecrest earthquake sequence provides important new data and research opportunities across the SCEC collaboration, including, but not limited to: constraints on the stress field, earthquake interaction, ground motion prediction, and the community rheology model.
- The San Diego Supercomputer Center (SDSC), a new SCEC core institution, provides the SCEC community with access to approximately 1 million core hours of computing time each year on SDSC systems. SCEC researchers may request access to SDSC computer resources in their proposals. Investigators that anticipate use of research computing and/or cyberinfrastructure support through SCEC should follow the process described in section 4.4.2. Prior to proposal submission, investigators should contact Philip Maechling (maechlin@usc.edu) to ascertain the relevant SCEC capabilities and SDSC computing resources available to SCEC researchers that may contribute to the proposed project, as well as guidance on the software developer level of effort needed. Estimates of developer time requested should be entered in the online budget form as noted in the "budget justification" section below.
- There is a renewed call to develop methodologies to validate ground motion simulations based on dynamic rupture simulations, for systematic assessment of aleatory variability and epistemic uncertainty in simulated

ground motions, and for the development of methodologies to validate and calibrate estimates of permanent displacements.

- The “Earthquake Gates” focus area was started in the first year of SCEC5. This initiative is designed to foster multidisciplinary studies of the factors that lead earthquakes to start or stop (as at a gate). To organize this initiative the SCEC community held an incubator workshop in March 2017 and solicited proposals to establish Earthquake Gate Areas. The Cajon Pass Region was selected as the first and only Earthquake Gate of SCEC5. We do not plan to initialize any additional Earthquake Gate Areas in SCEC5. Refer to section 5.5 SAFS for more information on the Earthquake Gates Initiative and the Cajon Pass Earthquake Gate Integrated Science Plan.
- The geochronology infrastructure supports Accelerator Mass Spectrometer analysis of 14C, 10Be, 26Al, and 36Cl through collaboration with Lawrence Livermore National Laboratory and the University of California, Irvine (14C only). Luminescence dating (OSL, pIR-IRSL) will be supported through regular proposal budgets, through an arrangement with a luminescence laboratory (see Earthquake Geology section for suggestions).
- See Tectonic Geodesy section for new opportunities related to off-fault deformation, behavior of the shallow crust, and upcoming EMIT and NISAR missions.
- Investigators proposing projects that include undergraduate student support are encouraged to explore funding for the student(s) with SCEC’s Assistant Director for Experiential Learning and Career Advancement, Gabriela Noriega (gnoriega@usc.edu).
- We will consider workshops that focus more effort on training the next generation of users in the use of SCEC software, SCEC datasets, other data access and visualization tools, and software best practices. The workshop budget may include allocation for a researcher/instructor/programmer team to develop and lead the course and to facilitate online instruction, up to a maximum total budget of $25,000-$30,000.
- We will also consider field trips paired with synthesis workshops. The workshop budget should include field trip expenses, as well as expenses for the development of “virtual field trip guide” to allow for enhanced accessibility for workshop participants and a synthesis report or publication. The virtual field trip guides will be made available and hosted online as educational resources for the broader community through SCEC’s Communication, Education, and Outreach program.
- SCEC takes pride in fostering a diverse and inclusive SCEC community, and therefore expects all participants to abide by the SCEC Activities Code of Conduct, as approved by the SCEC Board of Directors.

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 was extended for another 5-year period, effective 1 February 2017 to 31 January 2022 (USGS SCEC5) and 1 May 2017 to 30 April 2022 (NSF SCEC5). NSF extended SCEC5 for a 6th year and the USGS has funded a separate “bridge period” proposal to span the 2-year time period for the start of a potential new earthquake center. This Science Plan covers the second year of the bridge period, with funding from the USGS, but not from NSF.

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 the earthquake source to infrastructure performance and risk.

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 Science 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 (described in section 2.2.2).

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 and fluid migration). 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. Develop an integrated quasi-static modeling framework incorporating information in the community models, and apply it to estimate the stress field and its uncertainties, to be updated periodically. (SDOT, CXM, FARM, 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. Quantify stress heterogeneity on faults at different spatial scales, with various techniques including ML analyses of fault maps and topographic and imagery data, and model their influence on rupture initiation, propagation, and arrest. (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 inelasticity 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. Determine how off fault deformation 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 artificial intelligence (AI), machine learning (ML) and other emerging approaches to represent the effects of nonlinearity that would allow the continued use of linear wave propagation as an effective approximation. (GM, CS, Seismology)

P2.c Constrain the properties of rock damage in fault-zones and in the subsurface, as well as the factors, such as initial properties, loading conditions and pore fluid pressure, that are likely to influence it. (FARM, CS, GM, Seismology)

P2.d. Understand how inelastic strain and changes of elastic moduli within and around faults influences rupture propagation, seismic radiation, and scaling of earthquake source parameters. (CS, FARM, Seismology)

P2.e Describe how fault geometry and rock damage 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,paleoseismic chronologies, and other near-fault observations. (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 macroscale of plate tectonics to the microscale of asperity contacts on a fault surface in highly damaged rocks that are fluid-filled and chemically reactive. Many questions about the evolving, multi-scale 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 some recent 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. Conversely, 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. Assess the roles of transient volumetric changes before, during and after ruptures by: analyzing near-fault seismic and geodetic data, conducting geological studies of signatures of tensile failures (e.g., pulverization), performing related laboratory experiments, and through numerical modeling. (CXM, Seismology, Geodesy, Geology, SAFS)

P3.b. Constrain 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.c. Assess how shear resistance and dilatational effects depend on the maturity of the fault system, and how these and different products of energy dissipation on and off-faults are expressed geologically. (FARM, SDOT, Geology)

P3.d. Determine how damage zones, crack healing and cementation, fault zone mineralogy, and off-fault damage govern the degree of strain localization, the state and stability of slip (e.g., creeping vs. locked, seismic vs aseismic), 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, FARM, 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 reconciling geodetic and seismological estimates of fault slip at depth with fault offset 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: Realistic physics-based predictions of strong ground motions are among the highest long-term priorities of SCEC; comparing them with data is essential to testing our understanding of source and wave dynamics, and to connect the basic science of earthquakes to the practical applications of seismic hazard analysis. Ground-motion simulations have become useful in performance-based engineering (for nonlinear building response analyses, for example), in operational earthquake forecasting, and in 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 empirical databases.

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 had 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 and its associated computational benefits while integrating off-fault and shallow crustal plasticity, Cybershake hazard computations would need to be constrained to perfectly linearly elastic media; near-fault inelasticity would need to be built into the rupture model as a source effect; and near-surface inelasticity would need to be built into the wave propagation simulations in the form of a-posteriori imposed site correction factors.

In SCEC5, we are moving away from the classical trichotomy of source, path, and site effects as decoupled processes by a new paradigm. Under this new paradigm, in which the surface ground motions are modeled as the nonlinear response of a dynamical system where these effects are coupled. As the CyberShake example above indicates, identifying approaches that preserve the computational efficiency enabled by reciprocity and superposition, but approximating the inelastic response of rocks and soils from source to surface will be a major challenge. 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, shallow crust nonlinearities and ground surface topography in controlling and bounding ground motions. (GM, Seismology, FARM, EEII)

P4.b. Develop multi-scale velocity models, with high-resolution information around faults and near the surface embedded in the regional models, and validate the merged multi-scale models. (GM, Seismology, EEII)

P4.c. Perform elastic ground-motion simulations for anticipated large events suitable for probabilistic seismic hazard and risk analysis, using the multi-scale velocity models up to frequencies justified by the small-scale information included in the models. (CS, GM, EEII)

P4.d. Develop ML techniques to modify linear ground-motion simulations to fit observed ground motion generated by moderate and large earthquakes at various sites. (CS, GM, EEII)

P4.e. Communicate the impact of physics-based seismic hazard analysis to earthquake engineers, emergency responders, and the 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 conditional predictions 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 of 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 physics including off-fault yielding and 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 not 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 and material properties, 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 and usability of the SCEC Community Models, including the model uncertainties. Community thermal and rheological models will be updated.
- 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 interseismic earthquake simulators to achieve a multi-cycle simulation capability that can account for slip history, inertial effects, fault-zone complexity, realistic fault geometry, and realistic loading.
- Ground Motion Simulation. We will validate ground-motion simulations, improve their accuracy by incorporating nonlinear rock and soil response in the shallow crust, and integrate dynamic rupture models with wave-scattering and attenuation models. We will expand our simulation capabilities to capture the frequency band of engineering interest, 0.1-10 Hz. In collaboration with geotechnical engineers and engineering geologists, we will develop or implement nonlinear rheological models of near-surface rock and soil layers tailored to the computational constraints and parameter scarcity of full-physics earthquake simulations and calibrated against observed site responses from recordings.
- 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.
- 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.
- Velocity and Rheology of Basin Sediments. In collaboration with geotechnical engineers, we will advance the understanding of site effects by incorporating refined soil stratigraphies and nonlinear rheological models of near-surface rock, sediment, and soil layers into full-physics earthquake simulations.

2.3 Management of the SCEC Research Program

The SCEC Science Planning Committee (SPC) 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 SPC is responsible for formulating the Center's science plan, conducting proposal reviews, and recommending projects to the Board of Directors for SCEC funding. Its members play key roles in implementing the SCEC5 science plan.

The SPC is chaired by the SCEC Co-Director (Greg Beroza), who is assisted by a Vice-Chair (Judi Chester). The SPC comprises the leaders of the SCEC science working groups—disciplinary committees and focus groups. The Center Director (Yehuda Ben-Zion) and the Associate Directors for Science Operations (Tran Huynh), and CEO (Mark Benthien) serve as ex officio members to the SPC.

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 investigations outside southern California may be considered, provided the proposed research demonstrates direct relevance to SCEC5 goals that are not achievable within the southern California natural laboratory.

3.1 Investigator Eligibility and Responsibilities

3.1.1 Who May Submit Proposals

Any person eligible to serve as a Principal Investigator (PI) at a U.S. academic institution or private corporation based in the U.S. may submit a proposal to SCEC. Recipients of SCEC funds from Federal sources must be able to demonstrate their ability to comply fully with the requirements specified in 2 CFR § 200, Uniform Administrative Requirements, Cost Principles, and Audit Requirements for Federal Awards.

Collaborative proposals involving non-U.S. participants will be considered provided the proposal (1) clearly states how the investigator from the non-U.S. institution is critical to the project and (2) the requested budget for the international participant only includes direct costs (e.g. travel support). The funding for research requested on such projects should only be for the U.S. portion of the collaborative effort.

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

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 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 models).

Code of Conduct. The Southern California Earthquake Center is committed to providing a safe, productive, and welcoming environment for all participants. We take pride in fostering a diverse and inclusive SCEC community, and therefore expect all participants to abide by the SCEC Activities Code of Conduct (https://www.scec.org/meetings/code-of-conduct).

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

Workshop Awards. A report of 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 45 days after the project period end date. Projects that have been extended for any reason must still have an interim technical report on file by the original deadline, to be replaced with a final report no later than 45 days after the extended deadline. 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 or in education and/or outreach activities.

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, complete and up-to-date current and pending support statements) must be included in the proposal submission. Note that funding for Collaborative Proposals will 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. In the past, 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, 2023 and December 31, 2023 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 or SCEC Annual Meeting are limited in number and may have further constraints due to space and time availability.

B. ***Supplemental Funding for Undergraduate Students.*** Investigators proposing projects that include undergraduate student support are encouraged to also explore funding opportunities with SCEC's Assistant Director for Experiential Learning and Career Advancement, Gabriela Noriega (gnoriega@usc.edu).

3.3 Guidelines for Proposal Submission

3.3.1 Proposal Due Date

The deadline date is December 1, 2022 (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. SCEC does not require that proposals be formally signed by institutional representatives at this stage; however, official documents including a signed letter of intent will be required within 30 days of award notification.

3.3.3 Project Duration

The proposed project period should be 1-year duration (starting February 1, 2023 and ending January 31, 2024).

SCEC involves over 1,000 scientists at more than 60 institutions in its research program. The SCEC research program is investigator-driven and open to anyone who is willing to submit a qualified project plan for peer review. The core resources are allocated through an annual planning process, so the roster changes constantly as new people and institutions become involved in the SCEC research collaboration. This annual review of the research program (and associated subcontracts) allows SCEC to drive and change the direction of research as needed to meet the program goals. The fact that this is done on an annual basis with so many people and institutions involved is a unique characteristic of SCEC. Therefore, every effort is made to ensure projects funded through the annual process are for 1-year duration only.

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 required information, to be considered complete**. Incomplete proposals will 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).

2. Project Plan. In 5 pages maximum (including all 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. The Project Plan section of the proposal should follow NSF guidelines for *Proposal Font, Spacing and Margin Requirements*, namely:

- Use one of the following fonts identified below:
  - Arial (not Arial Narrow), Courier New, or Palatino Linotype at a font size of 10 points or larger;
  - Times New Roman at a font size of 11 points or larger; or
  - Computer Modern family of fonts at a font size of 11 points or larger.
- A font size of less than 10 points may be used for mathematical formulas or equations, figures, tables or diagram captions.
- No more than six lines of text within a vertical space of one inch.
- Margins, in all directions, must be at least an inch. No proposer-supplied information may appear in the margins.
- Paper size must be no larger than standard letter paper size (8.5 by 11").

Other considerations to include in the Project Plan:

- Previous Support or Multiple Proposals. Every proposal must include a section reporting on the PI(s) research results from projects previously-funded by SCEC, and/or how concurrent proposal submissions are related to or complement each other, if applicable. This section should emphasize how such efforts relate to, or distinguish themselves from, the current proposal. This section counts toward 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. This 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.
- 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.

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. The budget and budget justification do not count toward the 5-page limit of the Project Plan. Budget and budget justification for each organization must be included in the single PDF version of the proposal submitted through the online system. This is in addition to (and does not replace) the budget information that is input into the online forms. Proposals without a complete budget and budget justification will be rejected and returned without review.

- 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.
- Field Research. Field investigations outside southern California may be considered, provided the proposed research clearly demonstrates direct relevance to SCEC5 goals that are not achievable within the southern California natural laboratory.
- Uniformity of Budget Information. For each organization requesting funding, the complete 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. While the SCEC Science Planning Committee evaluates all budget requests based on the standard NSF budget categories, funded proposals may be contracted on other bases (e.g., fixed-price milestones, direct stipend support, etc).
- 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. Research faculty (or similar personnel) whose salary is funded solely from external grants are exempted from this maximum 1-month funding rule.
- SCEC Research Computing and Cyberinfrastructure Support. The San Diego Supercomputer Center (SDSC) provides the SCEC community with access to approximately 1 million core hours of computing time each year on SDSC systems. SCEC researchers may request access to SDSC computer resources in their proposals. Investigators that anticipate use of research computing and/or cyberinfrastructure support through SCEC should follow the process described in section 4.4.2. Prior to proposal submission, investigators should contact Philip Maechling (maechlin@usc.edu) to ascertain the relevant SCEC capabilities and SDSC computing resources available to SCEC researchers that may contribute to the proposed project, as well as guidance on the software developer level of effort needed. Estimates of developer time requested (in terms of days, weeks or months of developer time) should be entered in the online budget form.
- International Travel Funding Support. Funding for international travel to participate in the SCEC activities 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. The requested international funding support should not exceed $1,500 per person in the proposed budget.
- Unallowable Direct Expenses. Under guidelines of the SCEC Cooperative Agreements and Uniform Guidance, secretarial support, general office supplies and refreshments for intramural meetings are not allowable as direct expenses.
- Indirect Costs. Proposal budgets should include appropriate Indirect Costs, using the institution's federally Negotiated Indirect Cost Rate Agreement (NICRA). It is the investigator's responsibility to ensure their submitted budget conforms to their organization's applicable rates and internal guidelines. If no NICRA is available, investigators should contact proposals@scec.org to determine if they qualify for funding from SCEC.

4. Current and Pending Support. Accurate and up-to-date statements of current and pending support must be included for each Principal Investigator requesting funding on the proposal. The current and pending support do not count toward the 5-page limit of the Project Plan. Current and pending support must be included in the single PDF version of the proposal submitted through the online system. This is in addition to (and does not replace) the current and pending support information that should also be input in the online forms. Proposals without a complete current and pending support statement will be rejected and returned without review.

- Each investigator requesting funding must enter their current and pending support information through the online submission system. **This information must also be included in the PDF uploaded at the time of proposal submission**.

- If identical or closely related work is also proposed to another institution (e.g., National Science Foundation, U.S. Geological Survey) for funding, an explanation of the relationship of such work to this proposal should be provided through the online system, as well as in the submitted PDF.
- Exception for Workshop Proposals. Current and pending support information is not required from investigators on workshop proposals.

3.4 Proposal Review Process

The annual budget cycle begins with a SCEC Leadership Meeting in early May, where the Board, Science Planning Committee (SPC), Executive Committee of the Center, and agency representatives discuss SCEC research priorities. Based on these discussions, the SPC drafts an annual SCEC Science Plan, which is presented to the SCEC community at the Annual Meeting in early September. The SPC uses the feedback received at the meeting to finalize the Annual Science Plan, and a project solicitation released in October. SCEC participants submit proposals in response to this solicitation in November. All proposals are independently reviewed by the Director, the Co-Director, Vice-Chair of the SPC, and the leaders of at least three relevant science working groups. Reviews are assigned to avoid conflicts of interest.

The SPC meets in January to review all proposals and construct an Annual Collaboration Plan. The plan's objective is a coherent science program, consistent with SCEC's basic mission, institutional composition, and budget that achieves the Center's short-term objectives and long-term goals, as expressed in the Annual Science Plan. The PC Chair submits the recommended Annual Collaboration Plan to the Board of Directors for approval. The annual budget approved by the Board and the Center Director is submitted to the sponsoring agencies for final approval and funding. Upon approval by the agencies, notifications are sent out to the investigators.

To construct the Annual Collaboration Plan, proposals submitted in response to the annual solicitation are evaluated based on: (a) scientific merit of the proposed research; (b) competence, diversity, career level, and performance of the investigators; (c) priority of the proposed project for short-term SCEC objectives; (d) promise of the proposed project for contributing to long-term SCEC goals; (e) commitment of the principal investigator and institution to the SCEC mission; (f) value of the proposed research relative to its cost; and (g) the need to achieve a balanced budget while maintaining a reasonable level of scientific continuity given funding limitations. With respect to criterion (b), improving the diversity of the SCEC community and supporting early-career scientists is a major goal of the Center. It is important to note that a proposal that receives a low rating or no funding does not necessarily imply it is scientifically inferior. Rather, these proposals may be downgraded because they may not meet other criteria noted above.

It should be also noted that SCEC maintains close alignment with the USGS Earthquake Hazards Program through three mechanisms: (1) reporting and accountability required by USGS funding of SCEC, (2) liaison memberships on the Board of Directors by the three USGS offices now enrolled as SCEC core institutions, and (3) a Joint SCEC/USGS Planning Committee (JPC). The JPC augments the SCEC Science Planning Committee with a group of program leaders designated by the USGS who participate in the construction of the Annual Collaboration Plan. If requested, the SPC chair will continue to sit on the Southern California Proposal Review Panel for the USGS External Research Program.

3.5 Award Procedure

The Southern California Earthquake Center is funded by the NSF and USGS through cooperative agreements with the University of Southern California (USC). Additional funding for the annual SCEC research program may be provided by other external sources. Each funding source has constraints on how funds can be spent. Altogether, funding to SCEC supports earthquake research in Southern California that engages an interdisciplinary community of over 1,000 active participants.

The SCEC research program supported over 100 projects in the past year, but we anticipate that will be reduced in the coming year due to overall budgetary constraints. Science funding includes (a) smaller grants for individual scientists working in Center focus areas and collaborations, (b) larger grants for scientists and collaborative teams collecting new data on major Center projects or performing data integration and advanced modeling, and (c) workshops that bring all interested scientists together to focus on specific research initiatives.

Funding received from all sources is considered for the purposes of building the overall Annual Collaboration Plan. Each research award is funded via a subcontract between USC and the Investigators' institution. Multiple awards from the same funding source at the same institution might be included in a single contract. Multiple awards at the same institution might be set up from different funding sources as separate contracts. When SCEC funding becomes available to investigators depends on (1) how soon SCEC/USC receives Center funding from the prime sponsors, and (2) how quickly contracts are negotiated between USC and the subrecipient institution. Participant support award expenditures are managed through the master SCEC account at USC. For investigators at USC, the project expenses are also charged directly to the master SCEC account.

For project proposals approved for funding, the investigators submit formal requests for a subaward through their research offices with a final statement of work (SOW), final budget, and budget justification. The formal requests are carefully reviewed at SCEC to ensure that the SOW and budget reflect the approved research. Historically, most budgets include salary funds for the investigator, postdocs, and students (including tuition), materials and supplies to accomplish the research objectives, travel to the SCEC annual meeting to present research results, and indirect costs per the subrecipient institution's federally negotiated rate. SCEC very rarely funds requests for equipment. Budget formats are comparable to normal NSF proposal submission and verified by the submitting organization that they reflect current salaries and costs for other items. Before the final subaward can be established, the formal request and the original informal submission is submitted to the prime sponsoring agency's SCEC program officers for approval.

Once a subaward is made, the SCEC Science Planning Committee and working group leaders monitor the scientific and technical progress of SCEC-funded projects through (1) investigator presentations at the SCEC Annual Meeting, workshops, working group meetings, and/or other national meetings; (2) written project reports submitted to SCEC (www.scec.org/reports/projects); and registration of publications to the SCEC database (www.scec.org/reports/publications). Funded investigators are also required to contribute data and results to the appropriate SCEC resource (e.g., Southern California Earthquake Data Center, database, community models). This information feeds into the annual review of the SCEC program, and allows SCEC to drive and change the direction of research as needed to meet the Center's goals, milestones, and metrics. The Annual Science Plan will be adapted based on the progress by the SCEC community of researchers.

With respect to financial monitoring on the subawards, the SCEC administration team reviews every invoice (a) to ensure expenses are within the approved scope of work, (b) to determine funds spent are reasonable and expensed in a timely manner, and (c) to track who is receiving funds and their level of effort. Any change in scope or major change in budget categories requires approval by the SCEC Director. Detailed documentation will be requested from the investigators when an invoice significantly deviates from the approved budget. The summary financial report submitted by investigators at the end of the budget period also provides critical information for the Center's budget planning for following budget years.

If an investigator submits a successful proposal to SCEC the following year, their subcontract is usually amended to add on the new year of funding. Alternatively, investigators may not be funded in consecutive years if (1) they do not submit a proposal or (2) their submitted proposal is unsuccessful. This process means that the roster of participating investigators changes each year as new people and institutions become involved in the SCEC research collaboration. This annual review of the SCEC program (and associated subawards) allows SCEC to drive and change the direction of research as needed to meet the Center's goals, milestones, and metrics. The fact that this is done on an annual basis with so many people and institutions involved is a unique characteristic of SCEC, and very different from how other research centers typically operate.

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 earthquake 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 SPC 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. Kate Scharer, 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 disciplinary group gathers data on the range of seismic phenomena observed in southern California, develops improved techniques for extracting detailed and 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. Understand and reduce the variability and uncertainty of source parameters (such as stress drop), and work to resolve

discrepancies reported between various methods of estimation, particularly through collaborative, community based research.

- 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 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 regional network operators.
- Investigate near-fault crustal properties, evaluate fault structural complexity, and develop constraints on crustal structures and state of stress.
- Improve the knowledge on properties of subsurface materials, and their evolving susceptibility to failure in relation to motion generated by various ongoing sources, by analyzing seismic, strain, pore pressure and other signals.
- 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 (including using Distributed Acoustic Sensing, aka DAS), 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 recorded seismic data.

4.1.3 Research Priorities

- **New and low-cost seismic network data utilization and archiving.** New seismic networks utilizing low-cost MEMS accelerometers and new recording capabilities using Distributed Acoustic Sensing (DAS) are currently being developed. We seek proposals on innovative algorithms to utilize data from these sources, develop metadata and archiving models, and make the data and products available to the user community.
- **The shallow crust.** Seismic properties in the top 100-1000 m of the crust have strong effects on ground motion, but are generally not well understood or constrained. Deriving detailed local and regional images of seismic velocities and attenuation coefficients that expand the SCEC community models (CXM) to the inelastic material response regime of the shallow crust is among the research priorities of the Seismology group. Another priority is to improve the quantitative treatment of nonlinear behavior of shallow crustal materials.
- **Small earthquakes.** Reducing the magnitude of completeness of detected earthquakes can increase the amount of available information for many studies. We welcome proposals on improved detection of small earthquakes and separation of small events from other sources of weak ground motion.
- **Tremor and related signals.** Tremor has been observed on several faults in California. Although we will continue to consider proposals aiming to detect and analyze tremor in southern California, and to distinguish tremor from other sources that may produce similar signals, such proposals should be mindful of the limited success of similar endeavors to date.

- **Earthquake ruptures.** In-situ observational constraints on earthquake ruptures are very limited. We welcome proposals to determine rupture velocity, fracture energy and other properties of natural earthquakes. Rupture directivity can have strong influence on ground motion but it is not clear if earthquake directivities on given fault sections are systematic or random. We seek proposals on robust estimations of 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.
- **Earthquake preparation and short term predictability.** We seek proposals to provide in-situ observational results on the earthquake preparation process using seismic waveforms and catalogs, and 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 of structural properties and seismotectonics in southern California, especially those identified as "Earthquake Gates" (see SAFS for definition).
- **Collaborative Earthquake Stress Drop and Source Study.** We seek proposals towards collaborative work to understand when and why different methods to estimate stress drop or other source parameters agree or disagree; to reduce the variability and uncertainty of stress drop; and to resolve discrepancies reported between various methods of estimation. This is specifically encouraged through participation in the community study using the 2019 Ridgecrest earthquake sequence.

4.2 Tectonic Geodesy

4.2.1 Research Objectives

The Tectonic Geodesy disciplinary 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 SAR satellites (Sentinel-1A and B) are providing highly accurate systematic coverage of the entire SCEC region every 12 days from two look directions and the ALOS-2 SAR satellite has provided L-band data since 2015. More than a decade of archival airborne L-band InSAR data from the NASA UAVSAR mission and the full archive, spanning two decades, of the ERS and Envisat C-band InSAR satellites is also available. Developing methods to integrate and update these dense spatio-temporal 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 estimate robustly 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 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.
- Develop block models and earthquake cycle models that contribute to and utilize the emerging 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.** Devise strategies for estimating the geodetic deformation field at high resolution in three dimensions, using a combination of GNSS and InSAR data. Develop and refine methods that can improve the density of measurements that have sensitivity to N-S motions using InSAR data. Integrate data from multiple spacecraft and airborne SAR. Coordination between participating groups in these efforts is encouraged. Continue to develop methods to improve error characterization and/or reduction in secular geodetic velocity estimates, e.g. through explicit consideration of temporal correlations in time series or spatial correlations in noise, or by improving methods for mitigating temporally or spatially correlated noise.
- **Community Geodetic Model (CGM) time series.** Produce a consensus time series GNSS product integrating both continuous and survey data. Produce consensus Sentinel-1 InSAR time series, with corresponding uncertainties, across the SCEC region of interest. Update both GNSS and InSAR time series to include robust characterization of both the coseismic offset during, and the postseismic deformation transient following, the 2019 Ridgecrest earthquakes, and develop strategies to automate such updates in case of future earthquakes and transients. Coordination between participating groups in these efforts is encouraged. Continue to develop methods for GNSS/InSAR time series integration for southern California, including methods that apply similar corrections (e.g. for tropospheric/ionospheric noise, solid Earth tides, ocean tidal loading, hydrological loading, plate motions, dielectric changes) to both data types, and devise strategies to place InSAR deformation time series within a common, GNSS-based reference frame.

- **Community Geodetic Model (CGM) strain rates.** Develop and compare methods to estimate, and to update estimates of, temporally-variable strain rates across the SCEC region. Both observation-based and model-based approaches are of interest. Coordination between participating groups in these efforts is encouraged.
- **New Opportunities in Tectonic Geodesy**. Taking advantage of high-quality geodetic data sets provided by the CGM, there are opportunities to address novel research targets. These include constraining the proportion of the southern California deformation budget that is not accommodated by the major faults. Detection of localization of deformation in geodetic data and other transients that might occur before large earthquakes. Geodetic signals involving volumetric / fault-normal deformation. Geodetic signals related to rock damage, liquefaction, slope failures, subsidence, and crustal hydrology. Seasonal signals that can be used to infer processes in the lower crust (e.g. viscous flow) and in the shallow crust (e.g., groundwater level changes that can be related to variations of sub-surface seismic velocities). Correlations between geodetic signals, surface geology and seismic properties of sub-surface rock in anticipation of future NiSAR and EMIT data. Proposals for a workshop focused on utilization of space geodetic data to enhance research on these topics are welcome.
- **Research pertaining to other community models.** Foster the development of models that include spatial variations in crustal rheology, including 4D models of the earthquake cycle, and models of contemporary crustal strain and/or fault slip rates, to motivate development of the Community Rheology Model. Work with other SCEC scientists to further 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).
- **GNSS data collection and preparation for earthquake rapid response.** Collect campaign GNSS data in areas of sparse GNSS coverage and poor InSAR correlation. Develop a coordinated rapid response GNSS capability, including updating GPS site coordinates in the vicinity of major faults, and training in the setup and operation of GNSS apparatus, 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 disciplinary 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 (e.g. seismic supercycles, fault evolution or slip rate variability).
- 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. This may include analysis of relevant samples from outside of southern California, though fieldwork to collect new samples cannot be supported.

- Quantifying variations in fault slip, 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 are 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.
- Analysis and dating of precariously balanced rocks and other fragile geologic features to evaluate ground motion hazard and inform seismic hazard methodologies.
- 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.
- Re-evaluate key slip-rate sites with modern techniques to reduce uncertainty.
- 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.
- Data synthesis and new data gathering targeted at understanding fault behavior through the Cajon Pass Earthquake Gate Area (see SAFS for definition).
- Improve constraints on fault-rupture hazard (magnitude-displacement scaling) specific to the California plate boundary fault system.
- Develop community guidelines for post-earthquake field reconnaissance activities.
- Develop techniques for documenting, dating, and fragility analysis of fragile geologic features.
- Develop methods or models for estimating fault displacement hazard at the surface and at depth for the evaluation of risk to infrastructure (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 motion.
- Data synthesis and new data gathering aimed at developing and refining 3D long-wavelength geologic models of the lithotectonic provinces defined for the CRM.

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 the 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	Bruce Buchholz	buchholz2@llnl.gov
	Cosmogenic	Lawrence Livermore National Lab	Susan Zimmerman	zimmerman17@llnl.gov
Individual Collaborative Proposals	OSL / pIR-IRSL	North Carolina State University	Lewis Owen	lewis.owen@ncsu.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 metadata for their geochronology samples, including sample preparation, and geographic/stratigraphic/geomorphic context (what was dated?) before samples are submitted for analysis. Contact the Earthquake Geology group leader, Mike Oskin (meoskin@ucdavis.edu), to arrange for analysis and a link and spreadsheet for metadata submission.

4.4 Computational Science (CS)

4.4.1 Research Objectives

The Computational Science disciplinary group promotes the use of advanced numerical modeling techniques, data intensive (big-data) computing, high performance computing (HPC), and emerging computational and algorithmic methods such as artificial intelligence or machine learning, to address the needs of SCEC users and the scientific community on a variety of computer systems, including but not limited to HPC platforms. The group works with SCEC scientists across a wide range of topics to take advantage of the rapidly changing computer architectures, software development, numerical methods and algorithms. A significant effort of this group is targeted to engage and coordinate with national HPC labs, centers, and service providers in crosscutting efforts to enable large-scale and data-intensive computing milestones. In that sense, 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. In recent years, the group has promoted the growth of emerging techniques based on artificial intelligence, machine learning and other techniques that can help accelerate earthquake science. Projects listing Computational Science as their primary area should involve significant software-based processing, big-data synthesis, HPC, data-intensive computing, or emerging numerical methods and algorithms including artificial intelligence and machine learning. 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.

4.4.2 Shared SCEC Research Computing and Cyberinfrastructure

SCEC researchers make extensive use of research computing resources and tools including high-performance and cloud computing, observational and simulated data, community earth models, open-source scientific community software, and complex research computing software stacks. A growing number of research projects also require improved information sharing, data access and data delivery tools;. The purpose of the shared SCEC research computing (RC) and cyberinfrastructure (CI) is to identify and properly allocate the available SCEC capabilities and resources in terms of software developer time and/or computing resources to support projects funded through the annual SCEC science collaboration process that have RC/CI needs. During the proposal submission, investigators requesting SCEC's shared RC/CI resources/capabilities must identify and select the Computational Science (CS) disciplinary group in the options for suggested reviewers to facilitate identifying the proposal accordingly for review.

Please direct questions regarding the shared SCEC research computing and cyberinfrastructure to the Computational Science group leaders, Ricardo Taborda (rtaborda@eafit.edu.co) and Ahmed Elbanna (elbanna2@illinois.edu).

SCEC Software Developer Support. Investigators requesting SCEC software developer support should clearly state in their proposal an estimate of the level of effort (in terms of days, weeks or months of developer time) required. If known, specify the capabilities and SCEC software and developer(s) needed to achieve the proposed project plans (see table below). Prior to proposal submission, investigators should contact SCEC Associate Director for IT, Philip Maechling (maechlin@usc.edu) to ascertain the relevant SCEC capabilities that may contribute to the proposed project, as well as guidance on the developer level of effort needed.

SCEC Software	Capabilities
SCEC Community Models	Data access, delivery and management for SCEC community models (e.g., CFM, CVM, CGM, CSM, CRM, CTM, UCVM)
Community Information System	Project websites; data access, delivery and management for SCEC research projects
Collaboratory for the Study of Earthquake Predictability	Delivery and maintenance of versioned, documented code for making and evaluating forecasts including intercomparisons to evaluate predictive skills; software support to allow individual researchers and groups to participate in prediction experiments
Broadband Platform	Provides a verified, validated, and user-friendly computational environment for generating broadband (0-100Hz) ground motions
CyberShake Platform	Provides physics-based probabilistic seismic hazard curves and maps using seismic reciprocity to generate large ensembles of ground motion simulations (> 10^8)
OpenSHA Platform	Used to analyze and evaluate CyberShake hazard model results; includes reference implementations the UCERF2 and UCERF3

Computing Time at SDSC. The San Diego Supercomputer Center (SDSC), a SCEC core institution, provides the SCEC community with access to approximately 1 million core hours of computing time each year on SDSC systems. Investigators may apply for SDSC computing resources by including a description of their computational research goals and the amount of requested computing time in core hours in their SCEC proposals. If your research would benefit from access to SDSC computer resources, we strongly encourage you to first contact SCEC Associate Director for IT, Philip Maechling (maechlin@usc.edu), to determine which SDSC computer resources most appropriate for the project, which may include both CPU and GPU resources.

The SCEC Science Planning Committee will evaluate all proposals based on the criteria stated in Section 3.4. The SPC has the final responsibility for approving access and allocation of SCEC's shared computing resources. The amount of computing time and developer time available to individual research projects will depend on the overall amount requested by the community.

4.4.3 Research Strategies

- Reengineer and optimize existing HPC codes for CPU-based, GPU-based, and manycore-based (e.g. Xeon Phi) supercomputers; or adapt existing or develop new HPC codes using emerging supercomputer hardware architectures; with emphasis on issues such as performance, portability, interoperability, power efficiency, and reliability; and focusing on software elements that can contribute to reaching SCEC research goals.

- Develop software tools needed to support large-scale simulations, such as software tools for building simulation meshes, data management tools for distributing simulation results, or visualization tools for improving analysis and presentation of large-scale simulation results.
- 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). The development of new algorithms and methods may include the use of emerging numerical and computational techniques in artificial intelligence and machine learning.
- 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, workflows, advanced seismic data format, visualization, and end-to-end approaches.
- Develop data-intensive computing tools for the analysis of very large data sets for applications such as: 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 new or adapt existing software architectures and application programming interfaces (APIs) that can contribute to building new, or integrating existing SCEC community models (CXMs), and how these can be used with HPC applications for modeling and simulation; with emphasis in software development for accelerating model creation, data synthesis, manipulation and integration, and model building (meshing and gridding) and visualization, (see also SCEC Community Models Research Priorities).
- Develop and adapt emerging numerical methods and algorithms with the potential of accelerating or improving data assimilation, processing and analysis; fault, earthquake, and ground motion modeling and simulation; earthquake forecasting and predictability; using computational tools of scalable potential.

4.4.4 Research Priorities

- SCEC Community Models (CXMs)
    - Develop tools that can accelerate community building of new (or existing) community models. These may include but are not limited to the design of versatile data-structures and application libraries (software elements) for data manipulation and integration, meshing and gridding, and visualization of community models.
    - Develop tools that can help integrate different community models between themselves and/or with simulation software. These may include but are not limited to the design of software interfaces capable of connecting in efficient manners HPC simulation codes with community models.
- 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 interdisciplinary 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 and/or multi-scale velocity models into 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, physics-informed machine learning, or consistent coupling of different existing numerical schemes.
    - Develop computational codes that merge single event rupture models with earthquake cycle models to consistently model sequences of seismic and aseismic slip.
- 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.
    - Develop alternative methods using emerging techniques (e.g., artificial intelligence, machine learning) that could potentially accelerate or optimize use of HPC resources in physics-based earthquake hazard calculations.
    - 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.
    - Evaluate alternative computational methods to determine the tradeoffs between the scientific effectiveness and the computational costs of these alternatives.
    - Develop surrogate models, using machine learning or other emerging techniques, that emulate high fidelity physics-based models of small scale processes, in order to accelerate computation and enable bridging scales in earthquake science.
- 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 modeling capabilities that can help transform earthquake risk management into a cyberinfrastructure science and engineering discipline.

- Develop workshops to focus effort on training the next generation of users in the use of SCEC software, SCEC datasets, other data access and visualization tools, and software best practices through support for an instructor/programmer/researcher to develop and lead the course, and to facilitate online instruction.

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) interdisciplinary 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 fragile geological units such as the top crust, along with 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-term 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.
- Determination of the scaling with magnitude of seismic source parameters, such as radiated energy or stress drop. Understanding and reducing the variability and uncertainty of these parameters, and working to resolve discrepancies reported between various methods of estimation, so that these source parameters can be accurately incorporated into ground motion studies and numerical and rheological models. In particular, we encourage collaborative, community based work on this topic (see Seismology Research Priorities 4.1.3.)
- Investigate the effect of fine-scale processes on the nucleation and dynamic rupture of large earthquakes and the resulting ground shaking, including whether 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, degree of localization 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 conducting laboratory experiments at the appropriate temperatures and stress conditions, and 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.
- Develop methodologies to validate ground motion simulations and surface displacements based on dynamic rupture simulations, with the goal of defining input parameters for events that have not yet been observed, so as to generate ground motion times series and displacement maps for engineering applications. See Section 5.7.3 under Earthquake Engineering Implementation Interface (EEII).

5.2 Stress and Deformation Over Time (SDOT)

5.2.1 Research Objectives

The focus of the Stress and Deformation Over Time (SDOT) interdisciplinary 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 rock type and density, Moho depths, thickness of the seismogenic layer, the geometry of the lithosphere-asthenosphere boundary, as well as basin depths, 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.
- Examination 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 coseismic, postseismic, interseismic, 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

- Contribute to the Community Stress Model (CSM). Compile diverse stress constraints (e.g., in situ stress from borehole breakouts or anisotropy measurements) and evaluate the accuracy of the CSM. Develop spatio-temporal (4D) representations of the stress tensor in the southern California lithosphere using stress constraints and geodynamic models of stress.
- Contribute to the development of 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 improved estimates of spatio-temporal variations of stress based on inversions of earthquake focal mechanisms.
- 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.
- Apply stress and deformation measurements at various time scales for hypothesis testing of issues pertaining to postseismic deformation, fault friction, isotropic and anisotropic rheology of the lithosphere, seismic efficiency, the heat flow paradox, stress and strain transients, stress complexities at earthquake gates and fault system evolution. Improve constraints on the active geometry and rheology of ductile roots of fault zones, including slow earthquake phenomena such as triggered slip, tremor, and slow slip.
- Develop deformation models (fault slip and moment accumulation rates, locking depths, and off-fault deformation rates) in support of earthquake rupture forecasting.
- Develop models of vertical deformation (interseismic and multi-earthquake cycle) that incorporate improved vertical constraints from the Community Geodetic Model (CGM) and geomorphology. Assess the sensitivity of vertical deformation to spatially variable rheologic assumptions. Improve analyses of model sensitivity to non-tectonic vertical motion signals.
- Develop more comprehensive models for understanding the role of fluids on 3D and time-dependent deformation. Improve our usage and application of geodetic data that are heavily influenced by hydrologic processes within the crust.
- Develop interseismic and long-term deformation models that incorporate inelastic deformation. Develop models that can predict the relative proportions of elastic, recoverable strain associated with the earthquake cycle and permanent, distributed strain in the crust.
- Advance research into averaging, simplification, and coarse-graining approaches in numerical models across spatio-temporal scales. Address 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, 3D structure and its influence on dynamics and faulting behavior, complexity, and uncertainty.
- Assess the relative importance of basal tractions, plate motions and gravitational potential driving forces, and develop appropriate boundary conditions for plate-boundary scale deformation models.

5.3 Earthquake Forecasting and Predictability (EFP)

5.3.1 Research Objectives

The Earthquake Forecasting and Predictability (EFP) interdisciplinary working group coordinates five broad types of research projects: (1) the development of earthquake forecast methods, (2) the development of methods 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 the Collaboratory for the Study of Earthquake Predictability (CSEP) and the Working Group on California Earthquake Probabilities (WGCEP). CSEP is 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.

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.
- Develop strategies for validating results of earthquake simulators and rupture forecasts with observational data.
- 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 USGS 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.
- Establish benchmark data sets, benchmark models, and scoring metrics for machine learning efforts to predict seismicity rates.
- 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 damage 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 regional nonlinear effects can be captured by models that have been developed for site response problems (such as site correction factors, one-dimensional site response analyses, three-dimensional soil constitutive models); the conditions that cause amplification due to complex wave propagation phenomena related to 3D basin structure and surface waves; and the more dramatic effects of ground failure such as liquefaction and landslides. The 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 shallow crust (soils and rocks, previously known as the Geotechnical Layer or GTL) is a constituent of the path. In turn, to incorporate near-surface nonlinear effects in physics-based simulations, the GM focus group seeks proposals that develop and implement time-series correction factors to account for nonlinear site response; as well as three-dimensional rheological models for the materials that comprise the shallow crust. These models should 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). These shallow crust inelastic models should lastly enable predictions of phenomena that govern the risk of infrastructure systems, as outlined research priorities of the Earthquake Engineering Implementation Interface (EEII) Focus Group.

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, distance, and site conditions.
- Develop 3D rheology models (velocity, anelastic attenuation, nonlinear properties) of rock and soil materials of the shallow crust, for integration in physics-based nonlinear wave propagation simulations. Due to large uncertainties, regions for which such models are especially needed include the Imperial Valley and the Central Valley regions of California.
- Develop deterministic and stochastic approaches to model wave propagation in heterogeneous structures, intended to improve representation of wave propagation scattering due to structural complexities in deterministic broadband ground motion 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, and as needed, calibrate the simulations to better represent observed features of ground motions (site response, path effects, dispersion) from past earthquakes
- Continue development of the SCEC Broadband Platform.

5.4.3 Research Priorities

- Gather and develop novel data sets to be used as ground motion data for application in any of the research priorities. This may include, but is 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 subsurface properties and wave propagation processes that will improve ground-motion simulations. Determine the relative roles of fault geometry, heterogeneous frictional resistance, directivity, wavefield scattering, intrinsic attenuation, and near-surface nonlinearities in controlling ground motions.
- Understand and reduce variability and uncertainty of earthquake source parameters, so that they can be accurately incorporated as predictive source information into ground motion models. In particular, we encourage collaborative, community based work on this topic (see Seismology Research Priorities 4.1.3.).
- Develop three-dimensional 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 a paucity of recorded data.
- Develop a rheology model for the shallow crust (including anelastic attenuation, nonlinear properties, heterogeneity, etc.) to capture nonlinear phenomena in physics-based simulations. Use available borehole

measurements, near-surface material stiffness proxies (e.g., Vs30, topography) and/or empirical correlations to estimate pertinent input parameters. Quantify the epistemic and parametric uncertainties of these models. This effort should be coordinated with the research priorities and activities of the SCEC Community Models (CXM) (especially the Velocity, CVM, and Rheology Models, CRM); the Fault and Rupture Mechanics (FARM) group with respect to the development and implementation of consistent material models for fault-zone and off-fault damage of rocks; the Computational Science (CS) group for the integration of these models in large-scale simulations; and the technical activity group (TAG) for the simulation of nonlinear effects in the shallow crust.

- 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.
- Develop methods for better representation of wave scattering due to structural complexities in deterministic broadband and 3D physics-based ground motion simulations. Develop methods for the parameterization of the correlation functions used in statistical representation of small-scale velocity variations that vary with geology and depth, and can handle velocity discontinuities at layer boundaries with strong velocity contrast. Conduct systematic verification (comparison against theoretical predictions) to ensure that the above methods can incorporate consistent and accurate representations of the earthquake source, three-dimensional velocity structure and shallow nonlinear effects in a robust and transparent manner.
- Conduct systematic validation of ground-motion simulation methodologies (broadband and three-dimensional), including those from dynamic ruptures, against appropriate observed historical ground-motion data for the median and standard deviation(s) of ground motions. 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.
- Develop validation techniques and criteria for new metrics such as smoothed Fourier Amplitude Spectra, duration, inter-frequency correlation (Fourier or response), and spatial correlation of ground motions.
- Perform systematic assessments of aleatory variability and epistemic uncertainty in both observed and simulated ground motions from any type of model or platform, and attribute to various parts of the models, including but not limited to those for source, path and site.
- 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 of different sizes/geometries and their ensemble averaged long-period ground motions. Combine earthquake recordings and ground response simulations and develop appropriate models for Fourier amplitude and phase ordinates. Develop and implement methods for computing and storing 3D Green's functions, both source- and site-based, (see CXM section for related efforts).

5.5 San Andreas Fault System (SAFS)

5.5.1 Research Objectives

The San Andreas Fault System (SAFS) interdisciplinary working group develops projects within SCEC that are focused on the occurrence of large earthquakes along the San Andreas Fault system, seeking (1) projects that collect and analyze data on the timing and size of large earthquakes on the SAFS 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” for multidisciplinary study of conditional earthquake rupture. The Cajon Pass region has been selected as an earthquake gate area for SCEC5. Research proposals to study earthquake gate behavior, sections of faults where ruptures pass through depending on the conditions of the segment, in other regions or settings within southern California are welcome. We are particularly interested in work along the active faults of the Salton Trough as well as the creeping-to-locked transition near Parkfield to develop insights that complement those from Cajon Pass into conditions that promote or inhibit earthquake rupture propagation.

5.5.2. Research Strategies

A. Research on the timing and size of large earthquakes on the San Andreas Fault System is encouraged that utilizes

- High-resolution imaging and documentation of ground deformation (in trenches or preserved in topography)
- 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 along the San Andreas Fault System. The goal is to study features that may conditionally modulate 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. The Cajon Pass Region has been selected as an Earthquake Gate for SCEC5 and has a specific Integrated Science Plan (www.scec.org/research/ega).

5.5.3 Research Priorities

- Basic research on the occurrence of large earthquakes on the San Andreas Fault System. This includes study of the many 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. In addition, dynamic models that consider San Andreas fault loading, geometry and rheology can be integrated with rupture histories to inform ground rupture conditions.
- Cajon Pass Earthquake Gate Area
  - Synthesize data that characterizes evidence of relative rates of fault slip, off-fault deformation, stressing rates, paleoearthquakes, and related ground shaking using methods such as tectonic geomorphology, analysis of high resolution topography, geologic mapping, paleoseismology, InSAR/GPS, precariously balanced rocks, and well data. Emphasis in the last year of SCEC 5 is on synthesis of data that inform rupture propagation through zones of fault complexity or improve earthquake rupture forecasts. Any new data collection efforts should target critical data gaps.
  - Synthesize geophysical, seismological and well data to characterize subsurface conditions related to geology, material properties (e.g. damage, crustal velocities, and fault strength), material interfaces as well as stress state and style of faulting. Material properties and stress state information will interface with Community Model (CRM and CSM) efforts and will be included within modeling efforts
  - Evaluate and improve the Community Fault Model 3D fault representations in the Cajon Pass area using improved 3D velocity models, relocated seismicity, geophysical constraints and insights from kinematic and mechanical models as well as the available data from passive portable seismic array, refraction microtremor and ambient noise studies.
  - Calibrate results from models (e.g., forward crustal deformation models, geodetic inversions and dynamic rupture) with geologic and geophysical data from within the EGA. Determine how model-based hypotheses about fault interaction through zones of complexity can be tested by

observations of geodetically-determined straining, accumulated slip, and paleoseismic chronologies.

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). The goal of the CXM working group is to provide an internally consistent suite of models that can be used to simulate seismic phenomena in southern California.

SCEC5 research goals involve continued refinement of existing community models (CFM, CVM, CSM, CGM), continuing development of newer 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 and/or test individual community models against independent data and/or 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).
- Begin the process of geographically expanding the community models beyond southern California.

5.6.3 Research Priorities

- **IT tools.** Assess practicality of using existing software and/or computational procedures to integrate community models with deformation and other physical simulation codes. Produce a web-based SCEC Community Models Viewer (SCMV) where users can directly compare and query various CXM components while simultaneously enhancing accessibility to individual components, especially UCVM and CGM.
- **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.
- **Validation and quantifying uncertainty.** 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. Develop alternative versions of CXM's where the diversity of reasonable interpretations is not currently represented.

- **Expand the target region.** Extend the geographical scope of all CXM models south to the Gulf of California and north to the latitude of the Mendocino Triple Junction area.
- **Formally release CXM models that have recent updates.** SCEC5 has invested into improvements to various CXMs that may be currently unreleased. For this final year of SCEC5, we encourage CXM groups to formally release their current models as products of the SCEC5 collaboration. To facilitate wide usage, formal CXM releases should be accompanied by documentation, a doi, and updates to the appropriate scec.org CXM webpages.
- **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, and/or are poorly studied.
    - 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 Quaternary Fault database).
    - Develop tools to assist users in visualizing and using the CFM in a range of computational models.
    - Develop the data, metadata, and tools necessary for expanding the current CFM statewide.
    - Organize a community workshop with partners (e.g., USGS/CGS) to evaluate the current state of statewide 3D fault knowledge and to prioritize regions needing additional data constraints..
    - Test and apply new methodologies for generating CFM fault models. Methods that can be partially or wholly automated and/or provide uncertainties are encouraged.
- **Community Velocity Model (CVM)**
    - Integrate new data (especially from the Salton Sea Imaging Project and other high-resolution datasets) 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).
    - Improve web-based tools for accessing and querying the CVMs.
- **Community Stress Model (CSM)**
    - Generate/integrate new stress and stressing rate estimates for the CSM, including updates of existing products and new measurements based on borehole or anisotropy. (See Stress and Deformation Over Time Research Priorities). Use these and/or other updates to generate and release an updated version of the CSM including a doi and scec.org website updates.
    - Work with SCEC IT and CXM leaders to develop expanded capabilities for the CSM website, including tools for interactive visualization and comparing different CSM's.

- Investigate stress changes from the 2019 Ridgecrest and other earthquakes, through modeling and observation, and utilize these to constrain absolute stress level and stress heterogeneity.
- Perform quantitative testing of the CSM using independent data and/or methods.

- **Community Geodetic Model (CGM)**
  - See Tectonic Geodesy Research Priorities.
  - In coordination with SCEC and the CXM group leaders, generate a SCEC-hosted CGM website with CGM products (including uncertainties) and an interactive web-based query tool.
  - Formally release the combined GNSS and InSAR CGM model complete with a doi and scec.org website updates.
- **Community Thermal Model (CTM)**
  - Update the CTM to include thermal diffusion in 3D, and reconcile region boundary segments with geometries of other CXM components (e.g. GF provinces and major CFM faults).
  - Provide alternative temperature models of the region. In coordination with SCEC and the CXM group leaders, share updates and alternative models via the CTM web page and possibly a formal release of an updated CTM version.
- **Community Rheology Model (CRM)**
  - Compare predicted seismic velocities for GF rocks with the SCEC CVM, and utilize velocity structure to extend the GF to a fully three-dimensional representation of crustal composition and infer the depth of the BPT throughout southern California.
  - Broaden the range of rheological parameters provided by the CRM to include diffusion creep and elasticity
  - Use deformation models to evaluate CRM effective viscosities against postseismic deformation CGM surface velocities, and the CSM.
  - Add representations of shear zones and fault rocks to the CRM.
  - Develop strategy and workflow for implementing strain-dependent viscosity, shear zone grain size evolution, and shear zone width evolution in 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 results to parameters in the science models.

- Develop tools and approaches that facilitate the transfer of 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. Identify specific areas of misfit between simulations and observations to guide the improvement of ground motion simulation tools.
- Develop methodologies to validate and use SCEC CyberShake and high-frequency ground motion simulations for developing probabilistic and deterministic hazard maps for building codes and other engineering applications. Investigations of observed versus simulated region-specific path and site 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, so that simulation models and/or algorithms might be improved to better represent ground motion features of interest.
- Quantify and evaluate spatial variation in amplitudes, and the associated seismic response, 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.
- Quantify the role of source, path and site modeling in simulated ground motions as they compare to recorded ground motions using techniques relevant to engineering ground motion hazard analysis (mixed-effects, Bayesian regression, etc.).
- 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.
- Develop methodologies to validate and calibrate permanent displacements computed from simulations (kinematic and/or dynamic rupture models).

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. Communication, Education, and Outreach Activities

SCEC's Communication, Education, and Outreach (CEO) program addresses the final element of the Center's mission: Communicate understanding 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*** preparing people and organizations to make informed decisions (split-second as well as long-term) that reduce loss improve safety, and advance overall prosperity and welfare, and also preparing the next generation of scientists via research opportunities and support through career transitions. SCEC CEO is organized into two interconnected focus areas:

1. **Public Education and Preparedness** informs broad audiences about earthquakes and how to improve resilience through the *Great ShakeOut Earthquake Drills*; the *Earthquake Country Alliance*; and *Science, and Risk and Crisis Communication* activities.
2. **Experiential Learning and Career Advancement** program will provide research opportunities, networking, and other resources to encourage and sustain careers in STEM fields.

The long-term outcomes of these focus areas are to: improve application of earthquake system science in policy and practice; reduce loss of life, property, and recovery time; increase science literacy; and increase diversity, retention, and career success in the scientific workforce.

Investigators interested in contributing to CEO activities are strongly encouraged to coordinate with Mark Benthien (benthien@usc.edu) before submitting a proposal. Alternative approaches may be more appropriate.