A Vision for the Next Earthquake Center

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Earthquake science is associated at its core with ***unsolved scientific*** problems. This is manifested by the lack of an equation of motion for material under brittle deformation (in contrast to elasticity and fluid dynamics), lack of ability to forecast earthquakes, and even lack of agreement on whether earthquake dynamics should be modeled with continuum or discrete (or hybrid) frameworks (e.g., *Ben-Zion*, 2008). At the same time, earthquakes can have enormous societal impact and have led in the past to collapse of societies (e.g., *Nur and Burgess*, 2008; *Bilham*, 2009). It is therefore important to be engaged vigorously at national and international levels in efforts to improve the understanding of earthquake and fault processes and mitigation of seismic hazard.

The Southern California Earthquake Center (SCEC) has made significant progress in basic and applied aspects of earthquake science, and in developing effective modes of coordinating broad activities on data collection, theoretical studies, computer simulations, and synthesis of results in community models and system science products. Nevertheless, the basic earthquake problems ***remain unsolved*** and should be the subject of increased research. The next earthquake center should develop further, in a geographically broader natural laboratory, activities with high potential for significant impact such as near-fault studies, community models, forecasting, and research computing, while embracing more fully additional problems such as induced seismicity, landslides and crustal hydrology, and moving some services and facilities such as data archives and instrument pools to other centers.

SCEC's significant success in advancing earthquake science can be attributed largely to the following: (i) Facilitating focused observational, theoretical and computational research on PI-driven topics, which evolve to reflect new knowledge, and cover numerous topics ranging from dynamics of individual earthquakes and fault structures to collective behavior of seismicity and the crust. These activities benefitted significantly from the excellent exposure of faults and rupture zones in SoCal to detailed field observations. (ii) Integrating observational results obtained by the focused PI-driven studies in consensus community models (e.g., *Shaw et al.*, 2015). These activities benefitted strongly from contributions of software developers. (iii) Building diverse software toolboxes for calculations of ground motion and simulations of dynamic ruptures, sequences of slip events on faults, and crustal deformation, accompanied by community code verifications (e.g., *Harris et al*., 2018; *Erickson et al.*, 2020) and validation of model results against observations. (iv) Developing system science frameworks such as those associated with the Uniform California Earthquake Rupture Forecast (UCERF) and CyberShake, which utilize the evolving state-of-the-art results from the focused PI-driven research and community models and provide integrative results for hazard mitigation (e.g., *Graves et al.*, 2011; *Field et al.*, 2017). Activities in categories (iii) and (iv) benefitted significantly from the involvements of computer scientists and engineers in the SCEC collaboration. (v) Working on earthquake predictability and establishing the Collaboratory for the Study of Earthquake Predictability (CSEP) to test objectively forecasting models (e.g., *Michael and Werner*, 2018). These activities benefitted strongly from the involvement of statisticians in SCEC. (vi) Major involvement in several post-earthquake responses to moderate and large events (1992 Landers, 1994 Northridge, 1999 Hector-Mine, 2010 El Mayor-Cucapah, 2019 Ridgecrest). These activities benefitted significantly from the direct field access to faults and rupture zones. (vii) Outstanding education and outreach activities that address a very broad audience ranging from interns to the general population and nurture the SCEC community.

The next earthquake center should build on and strengthen the multi-disciplinary data collection efforts, fundamental theoretical studies, integration of results in a system science approach, estimations of seismic hazard with increasing realism, and broad dissemination of knowledge that have been hallmarks of SCEC. The following activities can lead to transformative research in earthquake science, significant contributions to mitigation of hazard, and improved training of scientists and the public:

(1) The next earthquake center should have an extended natural laboratory covering the ***entire San Andreas system*** from the Gulf of California to Cape Mendocino. This will encompass appropriate natural

boundaries for the natural laboratory, with increasing types of faults and slip modes, and increased population that can benefit directly from the research. The center should continue to ***refine results and products in SoCal*** (e.g. community models, CyberShake simulations), and conduct corresponding studies that start from and improve on ***current knowledge in other parts of the San Andreas system***.

(2) The next center should augment typical seismological and geodetic observations, which have been done from the far field since the beginning of instrumental geophysics, with ***near-fault recordings***. Such observations can close critical data gaps (e.g., *Ben-Zion*, 2019) and provide a wealth of new small-scale high-frequency results, which are not observed in the far field and are not incorporated in current models used to understand and predict earthquake and fault processes. Example results that will be enriched by near-field observations range from basic earthquake properties (e.g., rupture width and velocity, slip velocity, full dynamic strain field during rupture propagation including possible tensile components, dynamic/static strain/stress drops, ground motion measures within and around rupture zones) to evolving near-fault processes before and after large earthquakes (e.g., evolving localization of deformation and temporal changes of seismic properties and surface strain rates). The near-fault recordings will also allow the development of detailed characterizations of fault zones, which will improve the accuracy of regional far field data inversions, will provide baselines for quantifying possible preparation processes before large events and post-earthquake processes, and will contribute to early warning and ShakeAlert studies.

(3) The next earthquake center should have increased efforts on ***forecasting large earthquakes***. This is a very old, much plagued and unsolved topic, which is nevertheless highly important and worthy of additional studies. The UCERF platform provides the best current regional forecasting methodology. However, UCERF is an evolving framework that should be improved, e.g., by utilizing better community models, better on/off-fault deformation data, and better earthquake simulators. UCERF should also be tested, e.g., by comparing *declustered* UCERF and observed seismicity (raw catalogs cannot be used since observed catalogs cover very short time intervals and are highly non-stationary), comparing UCERF surface velocities with geodetic data, and conducting a suite of tests using the CSEP framework. Additional promising research directions on forecasting should also be pursued. Examples motivated by recent experiments, model simulations and analyses of geophysical data include signals reflecting growing slow slip events (e.g., *Socquet et al*., 2017), evolving localization of deformation (e.g., *Ben-Zion and Zaliapin*, 2020), and temporal changes of seismic velocities at depth (e.g., *Niu et al.*, 2008; *Brenguier et al.*, 2019). Automated analyses of geodetic and seismic data for such signals, using AI algorithms and improved networks of sensors (including new near-fault data), can increase the ability to forecast large earthquakes. These and other proposed forecasting methods should be subjected to objective testing by CSEP, which itself should continue to be developed further in the next earthquake center.

(4) The next earthquake center should have an increased focused on ***properties and dynamics of the top crust***, which are poorly understood despite their great importance to the vast near-surface infrastructure, observed seismic motion, crustal hydrology and numerous other applications. Detailed imaging of the top crust will allow velocity and attenuation models to be developed essentially up to the surface, where they may be combined with information derived from geological mapping, geodetic measurements and boreholes. This will enable ***CyberShake simulations*** to provide realistic results at frequencies ≥ 10 Hz important for many structures, which may be used in turn to develop improved building codes.

(5) The next center should conduct ***CyberShake simulations at frequencies extending to 10 Hz or more***, for regions that have high-resolution velocity models with realistic small-scale information relevant for such frequencies, and with appropriate nonlinear response at the subsurface and near faults. This will require developing better velocity and rheological models for the subsurface and fault zones in the extended natural laboratory, and considerable HPC resources. To have sustained research in these and other activities, the next center should receive funding also from the CISE and ENG Directorates of NSF.

(6) The next center should have an increased focus on ***induced seismicity, crustal hydrology and landslides***. Faults are barriers to fluid flow and often bound water aquifers and oil reservoirs (e.g. *Hauksson et al.* 2015, Fig. 1). Earthquakes change the permeability of rocks and tend to trigger landslides. The transform plate-boundary in California has high hazard from tectonic deformation, human activities involving oil/gas exploration and geothermal energy extraction, and landslides. Induced seismicity can

have negative hazard impact, but also offers possibilities for conducting crustal-scale experiments. The next center should coordinate such experiments, improve the ability to distinguish between natural and induced seismicity (e.g. through refined data analyses and experiments), work on improved understanding of interactions between induced and (potentially larger triggered) natural earthquakes, conduct research on interactions of faults' activity with crustal hydrology and landslides, and work on improved hazard mitigation procedures associated with these topics.

(7) The next center should coordinate ***post-earthquake scientific responses*** following large earthquakes in the enlarged natural laboratory. Most sections of the San Andreas system are overdue for large earthquakes, and large events on some sections may trigger others, so the next decade may have an increased rate of large events, and some may affect large population centers. The next earthquake center should have plans (and drills) for post-earthquake responses that engage different science working groups, broad community participation and outreach activities. Pre-existing agreements on required funds and equipment should be in place to facilitate effective and rapid post-earthquake responses.

(8) The next earthquake center should continue to emphasize communication, education and outreach, with increasing training of early career researchers, workshops for established researchers, and general education that ensure significant, broad impact of the continuing and new research in earthquake science.

(9) The next earthquake center can forgo its pools of sensors for surface deployments along with its data archives, and develop instead agreements with the GAGE and SAGE facilities to obtain needed sensors (with top priority for rapid post-earthquake responses) and archival services.

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