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TITLE OF PROPOSED PROJECT **Southern California Earthquake Center**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 17,500,000	60 months	02/01/07	

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PI/PD DEPARTMENT

Earth Sciences

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Proposal Summary

The Southern California Earthquake Center was created as a Science & Technology Center in 1991 by NSF and the USGS. SCEC was renewed in 2002, and its size has since expanded to 54 institutions involving over 560 scientists. The core institutions, currently 15, are committed to SCEC's mission and offer sustained support for its programs; the participating institutions, currently 39, are self-nominated through their members' participation.

The Center is open to any credible scientist from any research institution interested in collaborating on the problems of earthquake science. However, its program is structured to achieve prioritized science objectives within the Southern California Natural Laboratory, and resources are allocated accordingly. Research projects are supported on a year-to-year basis by a competitive, collaboration-building process that involves extensive interactions among 14 working groups, a Joint Planning Committee with the USGS, the SCEC Board of Directors, and an External Advisory Council. In 2005, SCEC will sponsor 123 projects by 156 principal investigators at 51 institutions. The overall program includes a number of additional USGS investigators, as well as many collaborators supported by SCEC's partner organizations.

<u>Science Goal and Mission</u>. SCEC's basic science goal is to understand the physics of the Southern California fault system and encode this understanding in a system-level model that can predict salient aspects of earthquake behavior. Southern California's network of several hundred active faults forms a superb natural laboratory for the study of earthquake physics. Its seismic, geodetic, and geologic data are among the best in the world. Moreover, Southern California contains 23 million people, so that high seismic hazard translates to nearly one-half of the national earthquake risk.

The Center's tripartite mission statement emphasizes the connections between information gathering, knowledge formulation through physics-based modeling, and public communication of hazard and risk. An important part of SCEC's mission is to increase the diversity of its scientific workforce; it values diversity in all aspects of its activities.

Mission Statement

- Gather data on earthquakes in Southern California
- Integrate this and other information into a comprehensive, physics-based understanding of earthquake phenomena
- Communicate this understanding to the community at large as useful knowledge for reducing earthquake risk

<u>Intellectual Merit of the Proposed Research</u>. Earthquakes are one of the great unsolved puzzles of science. The study of earthquakes concerns the two basic geophysical problems: (a) the *dynamics of fault rupture*—what happens on a time scale of seconds to minutes when a single fault breaks during a given earthquake—and (b) the *dynamics of fault systems*—what happens within a fault network on a time scale of hours to centuries to generate a sequence of earthquakes. These highly nonlinear problems are coupled to one another through the complex processes of brittle and ductile deformation. No theory adequately describes the basic features of dynamic rupture, nor is one available that fully explains the dynamical interactions among faults, because we do not yet understand the physics of how matter and energy interact during the extreme conditions of rock failure. The major research issues of earthquake science are true *system-level problems*—they require an interdisciplinary, multi-institutional approach that considers the nonlinear interactions among many fault-system elements. SCEC will advance earthquake science through a comprehensive program of system-specific studies in Southern California.

<u>Broader Implications of the Proposed Research</u>. Earthquakes pose the greatest natural threat to the built environment of California and other seismically active regions. Probabilistic seismic hazard analysis (PSHA) is the primary methodology used to ensure the public's seismic safety. SCEC research will incorporate physics-based methods into PSHA, which will provide better earthquake forecasts and better estimates of strong ground motions. The Center will extend this research beyond Southern California through its national and international research collaborations. Through partnerships with earthquake engineers, it will also generalize the natural system under consideration to include built structures, thereby extending its seismic hazard analysis to earthquake risk. Through its Communication, Education & Outreach (CEO) Program, it will provide society at large with useful knowledge for reducing earthquake risk.

Accomplishments

SCEC scientists engaged in data collection have come together with theoreticians and numerical modelers in a collaborative process that has greatly accelerated the understanding of seismic hazards in Southern California and elsewhere. The results have been incorporated into practical products, including the National Seismic Hazard Maps of 2002 and the new seismic attenuation relations developed by the Next Generation Attenuation Project. SCEC's achievements contributed to the launching of NSF's EarthScope initiative in 2003. For example, the Center developed the 250-station

Southern California Integrated GPS Network (SCIGN), the largest outside of Japan, which has served as a prototype for EarthScope's Plate Boundary Observatory.

This proposal highlights scientific accomplishments in six problem areas central to the earthquake system science.

Fault mechanics. New types of laboratory experiments have elucidated on the frictional resistance during high-speed coseismic slip, and these data have been combined with field studies on exhumed faults to develop better models of dynamic rupture.

Earthquake Rupture Dynamics. Codes for 3D dynamic rupture simulation have been validated by cross-comparison exercises; they are being verified by comparisons with laboratory experiments and real earthquakes and coupled with anelastic wave propagation models to investigate strong ground motions.

Structural Representation. The Community Velocity Model (CVM) has been improved by extending and refining its 3D elastic structure and incorporating attenuation parameters; a new Community Fault Model (CFM) representing more than 140 active faults has been developed and extended to a Community Block Model (CBM), and a prototype Unified Structural Representation (USR) is merging the CVM into the CBM structural framework.

Fault Systems. New deformation signals have been discovered by InSAR and GPS, and new data from SCIGN and GPS campaigns have been incorporated into the Crustal Motion Map (CMM). The geologic record of fault-system behavior has been significantly expanded; tectonic block models have been created for physics-based earthquake forecasting, and finite-element codes have been developed for a new CBM-based deformation model that will assimilate the CMM and geologic data.

Earthquake Forecasting. New paleoseismic data and data-synthesis techniques have been used to constrain earthquake recurrence intervals, event clustering, and interactions among faults. Relocated seismicity has mapped new seismogenic structures and provided better tests of earthquake triggering models. Regional earthquake likelihood models have been formulated for use in PSHA and earthquake predictability experiments, and they are being tested for prediction skill using a rigorous methodology.

Ground Motion Prediction. Earthquake ground motions have been simulated using the CVM, realistic source models, and validated wave-physics codes; high-frequency stochastic methods have been combined with low-frequency deterministic methods to attain a broadband (0-10 Hz) simulation capability; broadband predictions have been tested against precarious-rock data; and simulations have been used to improve attenuation relationships and create realistic earthquake scenarios.

The CEO program has expanded SCEC partnerships in science, engineering, risk management, government, business, and education; increased earthquake knowledge and science literacy at all educational levels; worked with partners to improve earthquake hazard and risk assessments; and promoted earthquake preparedness, mitigation, and planning. An *Implementation Interface* has been constructed to integrate physics-based SHA into earthquake engineering research and practice through collaborations with PEER, CUREE, and the Next Generation Attenuation (NGA) Project; it has provided a flexible computational framework for system-level hazard and risk analysis through the OpenSHA platform, and it is developing an interface between SCEC and the NSF Network for Earthquake Engineering Simulation (NEES).

CEO highlights include a very successful new intern program Undergraduate Studies in Earthquake Information Technology (USEIT); the development of the *Electronic Encyclopedia of Earthquakes* as part of the NSF National Science Digital Library; the establishment of the Earthquake Country Alliance to present consistent earthquake information to the public; and a new edition of *Putting Down Roots in Earthquake Country* in both English and Spanish.

Science Plan

The SCEC3 Science Plan is articulated in terms of four basic science problems that organize the most pressing issues of earthquake system science.

A. Earthquake Source Physics: to discover the physics of fault failure and dynamic rupture that will improve predictions of strong ground motions and the understanding of earthquake predictability.

B. Fault System Dynamics: to develop representations of the postseismic and interseismic evolution of stress, strain, and rheology that can predict fault system behaviors.

C. Earthquake Forecasting and Predictability: to improve earthquake forecasts by understanding the physical basis for earthquake predictability.

D. Ground Motion Prediction: to predict the ground motions using realistic earthquake simulations at frequencies up to 10 Hz for all sites in Southern California.

In each problem area, we state the research issues, identify specific objectives, and assess the requisite research activities and capabilities. Based on this assessment, we formulate a new working-group structure to enact the Science Plan.

The SCEC3 Science Plan motivates eight initiatives that will augment the basic research program.

1. Networks as Research Tools: to foster innovations in network deployments and data collection that can provide researchers with new information on earthquake phenomena. Plans include a real-time demonstration project in seismic early warning in partnership with CISN.

2. Southern San Andreas Fault: to mobilize a major effort on the collection and interpretation of geologic data to understand the earthquake history of the SSAF system.

3. Working Group on California Earthquake Probabilities: to develop in partnership with the USGS and CGS a uniform California earthquake rupture forecast by combining new information with the best available methodologies for time-dependent forecasting.

4. Next Generation Attenuation Program: to produce in partnership with PEER-Lifeline and the USGS more reliable ground motion attenuation models that are based on physics as well as data.

5. "Rupture to Rafters": to develop in partnership with earthquake engineers a capability for the end-to-end simulation of earthquake processes, including embedding built structures in geologic models. This analysis will be used in new types of risk assessment.

6. Collaboratory for the Study of Earthquake Predictability: to provide a stable environment for registering earthquake predictions and conducting long-term predictability experiments that are properly characterized and can be properly evaluated.

7. National Collaborations Through EarthScope: to apply SCEC's system-level approach to other fault systems in the United States and collaborate on a national scale in comparative studies of fault system dynamics and earthquake behavior.

8. International Collaborations: to develop multinational partnerships that will promote comparative studies of fault systems and international cooperation in earthquake system science.

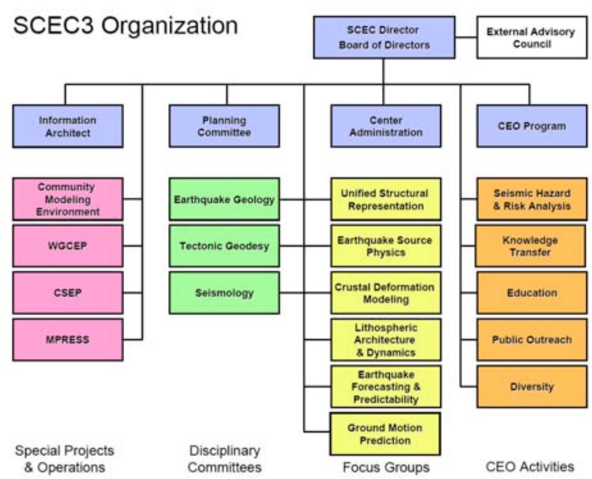
We outline the objectives of each initiative, its resource requirements, the participants and organizational partners, and the mechanisms that we will pursue to obtain additional resources. The latter is critical, because the ambitious research program proposed for SCEC3, particularly in the realm of applied studies, will require other sources of funding than the Center base budget proposed here.

The CEO program is an essential component of the Science Plan through its management of external partnerships that foster new research opportunities and its delivery of research and educational products to society at large.

In SCEC3, the Center will expand its CEO activities through partnerships with new groups, such as the EarthScope Education & Outreach Program and the NEES Education, Outreach & Training Program. The CEO focus areas will include partnerships in seismic hazard & risk analysis, primarily with research engineers; knowledge transfer partnerships and programs for technical professionals and government officials; education programs and products for students and educators; and public outreach to the general public, civic and preparedness groups, and the news media. As in SCEC2, CEO will organize community development programs for SCEC participants.

Management Plan

SCEC3 will continue to operate under the lean, flexible, and very successful management structure developed for SCEC2. However, to implement the Science Plan, we will make significant changes in the organization of the working groups, as shown on the SCEC3 organization chart.



Recognizing that diversity is a long-term issue that requires continuing assessments and constant attention by the leadership, the Center has taken a number of concrete steps to assess the diversity of its workforce and to develop policies for increasing diversity. Tangible progress has been made in populating SCEC leadership positions with outstanding women and minority scientists, and a long-term plan has been enacted to make further improvements. A key pipeline strategy is to recruit minority students into the SCEC intern programs and encourage them to pursue research careers at SCEC institutions. These recruitment and retention activities will be expanded in SCEC3.

PROPOSAL TO THE NSF AND USGS FOR SUPPORT OF

The Southern California Earthquake Center

February 1, 2007 – January 31, 2012

This proposal is organized into six parts. The **Introduction** describes the *Southern California Natural Laboratory*, gives an *Overview of the Center*, and presents two assessments: *Intellectual Merit of the Proposed Research*, which highlights the Center's goals in system-level geoscience, and *Broader Impacts of the Proposed Research*, which shows how basic research by the SCEC community will be transformed into practical knowledge. **Accomplishments** includes a brief summary of the *Principal Achievements of SCEC1* and more detailed descriptions of the *SCEC2 Science Accomplishments* and its *Communication, Education and Outreach* (CEO) program. The heart of the proposal is the **Science Plan**, organized into three sections: *Basic Research Problems*, which lays out the Center's scientific objectives and evaluates the required resources, *Research Initiatives*, which proposes a new set of Center-based activities, and its *CEO Plan*. The **Management Plan** outlines the Center's revised *Organizational Structure*, its *Budgeting Process*, and its *Operations Following a Major Earthquake*. The final part describes the **Facilities and Resources** available to the Center, including the new *SCEC Headquarters* at the University of Southern California, the substantial *Resources of the Core and Participating Institutions*, and the advanced cyberinfrastructure now available from SCEC's *Community Modeling Environment*. The **Supplemental Materials** to this proposal include *Supporting Letters* from partnering organizations, and a variety of electronic resources, including the SCEC2 proposal, the SCEC Annual Reports, Advisory Council Reports, CME project evaluations, and demographic assessments.

Table of Contents

I. Introduction

The Southern California Earthquake Center (SCEC) was created as a Science & Technology Center (STC) on February 1, 1991, with joint funding by the National Science Foundation (NSF) and the U. S. Geological Survey (USGS). SCEC graduated from the STC Program in 2002, and was renewed as a stand-alone center (SCEC2) under NSF Cooperative Agreement EAR-0106924 and USGS Cooperative Agreement 02HQAG0008. This proposal requests an extension of those cooperative agreements for the 5-year period from February 1, 2007 to January 31, 2012 (SCEC3).

SCEC is a *consortium of institutions* that coordinates and supports research in earthquake science on a larger scale than would be possible for individual researchers or institutions. Enormous efficiencies are achieved through shared resources and enhanced communication. The Center's working groups, workshops, field activities, and annual meeting have been very successful in promoting the cross-fertilization of ideas and accelerating progress toward scientific goals.

More generally, SCEC is a *community of scientists* from many disciplines, institutions, and levels of experience who cooperate to identify the most important problems of earthquake science and collaborate to solve them. In their assessments of the Center, participants who have joined SCEC in recent years have emphasized the benefits they derive, not primarily from the limited research dollars, but from the opportunity to learn from their peers and work together in addressing fundamental scientific problems with societal relevance. SCEC organizes this collaboration around physics-based, system-level earthquake research in the Southern California Natural Laboratory.

A. Southern California—a Natural Laboratory for Earthquake Physics

Southern California is a superb natural laboratory for the study of earthquake physics. This tectonically diverse stretch of the Pacific-North America plate boundary contains a network of several hundred active faults organized around the right-lateral San Andreas master fault (Fig. 1.1). Its geographic dimensions are well suited to system-level earthquake studies: big enough to contain the largest (M8) San Andreas events, which set the system's outer scale, but small enough for detailed surveys of seismicity and fault interactions. The entire fault network is seismically active, making the region one of the most data-rich—and hazardous—in the nation.

The seismographic and geodetic data from Southern California are among the best in the world. The Southern California Seismic Network (SCSN) has instrumentally located more than 400,000 earthquakes in its 73 years of operation; short-period digital recordings have been acquired since the late 1970s, and the California Integrated Seismographic Network (CISN) now operates more than 170 broadband/strong-motion stations, 125 short-period stations, and more than 600 strong-motion sensors south of 37°N. CISN routinely locates all events above M_L 2 throughout most of the region. Since 1975, laser strainmeters have been used to measure local interseismic deformations at the nanostrain level. Long-term measurements that can resolve 100 nanostrain across the plate boundary began with electronic distance measurements (EDM) in the 1970s, intermittent Global Positioning System (GPS) measurements in 1985, and continuously recording GPS stations in 1990. The 250-station Southern California Integrated GPS Network (SCIGN) was completed by a SCEC/USGS/JPL consortium in 2001.

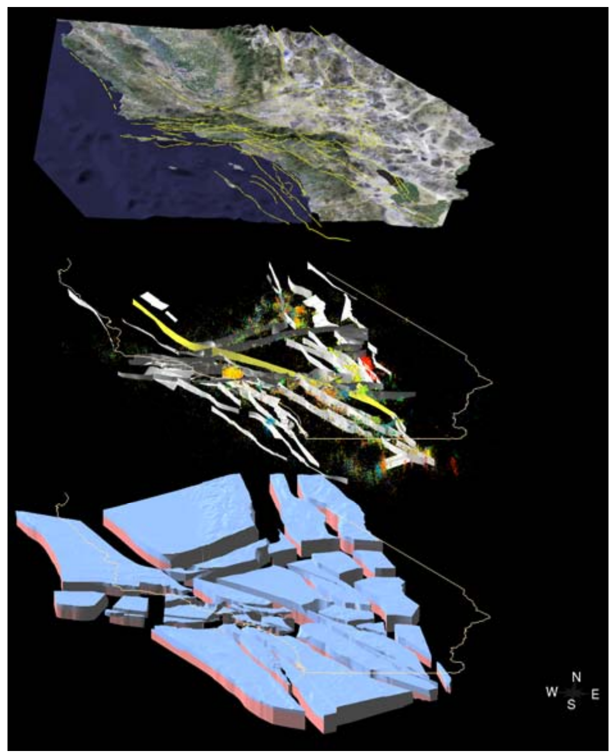


Fig. 1.1. An exploded, oblique view of the Southern California fault system, showing **(top)** the surface traces of active faults in the National Fold and Fault Database superposed on a digital elevation model and Landsat 7 imagery, **(middle)** a subsurface representation of the faults from the SCEC Community Fault Model (Plesch et al., 2005) and relocated seismicity (Hauksson & Shearer, 2005), and **(bottom)** the block surfaces defined in the SCEC Community Block Model (J. Shaw et al, 2004).

Southern California's arid climate and sparse vegetation expose its geology to plain view, and its favorable environment facilitates field studies. Geologists have mapped the region's active fault traces and neotectonic features, and they have probed its near-surface structure by geophysical surveying and deep drilling (primarily for hydrocarbons). They have combined these data with precise hypocenters to infer the geometry of fault surfaces throughout the seismogenic crust (Fig. 1.1). The surface ruptures and secondary effects of recent large earthquakes have been carefully mapped on the ground and by remote-sensing methods, including multi-spectral imaging, lidar, and interferometric synthetic aperture radar (InSAR). Ancient events have been excavated by paleoseismologists at hundreds of trenching sites, extending the large-earthquake catalog on some major faults for thousands of years into the past. These data have revealed patterns of clustering and quiescence that suggest millennium-scale interactions across the fault system.

B. Overview of the Center

SCEC has played a central role in coordinating regional earthquake research since 1991. By promoting access to instrumental networks, field areas, and regional data collections, the Center has established the Southern California Natural Laboratory as an interdisciplinary research facility on earthquake behavior. In the last three years, SCEC has augmented the natural laboratory with a collaboratory for model-based earthquake research.

1. *Science Goal and Mission*

SCEC's basic science goal is to understand the physics of the Southern California fault system and encode this understanding into a system-level "master model" that can predict salient aspects of earthquake behavior (Aki, 2002). SCEC1 focused on improving data-gathering capabilities in seismology, tectonic geodesy, and earthquake geology, setting up data centers, producing high-level data products and community models, and synthesizing an empirical master model of the regional seismic hazard—all with great success. The results were incorporated into practical products, including the USGS National Seismic Hazard Maps of 1996 and 2002. Its achievements in basic research, as well as its organizational capabilities, contributed to the launching of NSF's EarthScope initiative in 2003.

SCEC2 has built on the success of SCEC1, capitalizing upon the Center's expertise in earthquake simulation and system-level modeling, expanding its Communication, Education & Outreach (CEO) program, and broadening its partnerships with other organizations. It has particularly invested its resources in the physics-based modeling of earthquakes to promote interdisciplinary synthesis, creating a large, diverse collaboration dedicated to understanding earthquakes through system-level research.

Box 1.1. SCEC Mission

- Gather data on earthquakes in Southern California
- Integrate this and other information into a comprehensive, physics-based understanding of earthquake phenomena
- Communicate this understanding to the community at large as useful knowledge for reducing earthquake risk

The Center's motto of *basic research for practical purpose* is reflected in its tripartite mission statement (Box 1.1), which emphasizes the connections between information gathering by sensor networks, fieldwork, and laboratory experiments, knowledge formulation through physics-based modeling, and public communication of hazard and risk. This mission statement will continue to guide SCEC during its next five years.

Table 1.1. SCEC Member Institution (February 1, 2005).

Core Institutions (15)	Participating Institutions (39)
California Institute of Technology Columbia University Harvard University Massachusetts Institute of Technology San Diego State University Stanford University U.S. Geological Survey, Golden U.S. Geological Survey, Menlo Park U.S. Geological Survey, Pasadena University of California, Los Angeles University of California, Riverside University of California, San Diego University of California, Santa Barbara University of Nevada, Reno University of Southern California (lead)	Arizona State University; Boston University; Brown University; Cal-State, Fullerton; Cal-State, Northridge; Cal-State, San Bernardino; California Geological Survey; Carnegie Mellon University; Case Western Reserve University; Central Washington University; CICESE (Mexico); ETH (Switzerland); Institute of Earth Sciences of Academia Sinica (Taiwan); Jet Propulsion Laboratory; Lawrence Livermore National Laboratory; National Chung Cheng University (Taiwan); National Taiwan University (Taiwan); National Central University (Taiwan); Oregon State University; Pennsylvania State University; Rensselaer Polytechnic University; Rice University; SUNY Stony Brook; Texas A&M University; UC, Berkeley; UC, Davis; UC, Irvine; UC, Santa Cruz; University of Colorado; University of Kentucky; University of Massachusetts; University of New Mexico; University of Oregon; University of Utah; University of Western Ontario (Canada); URS Corporation; Utah State University; Whittier College; Woods Hole Oceanographic Institution

2. *The SCEC Organization*

SCEC is an institution-based center, composed of core and participating institutions (Table 1.1). The core institutions (currently 15) are committed to SCEC's mission and offer sustained support for its programs; the participating institutions (currently 39) are self-nominated through their members' participation and approved by the SCEC Board of Directors. There are many ways to measure the size of the SCEC community, but a few of the most useful are the number of people on the Center's email list (796 on January 1, 2005), active SCEC participants (565), and the registrants at the SCEC annual meeting (398 in 2004). A graph of the meeting registrations for SCEC's entire 14 year history is shown in Fig. 1.2.[1]

[1] To put participation in perspective, the 2004 SCEC annual meeting in September was slightly larger than the national meeting of Seismological Society of

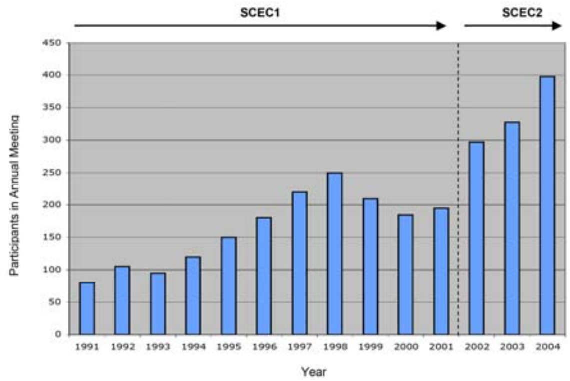


Fig. 1.2. Registrants at SCEC Annual Meetings, 1991-2004. It is notable that the Center's base funding in the year of SCEC1 peak attendance, 1998, was $5.00M compared to its base funding of $3.86M in 2004.

The Center is open to any credible scientist from any research institution interested in collaborating on the problems of earthquake science. However, its program is structured to achieve prioritized science objectives, and resources are allocated accordingly. Research projects are supported on a year-to-year basis by a competitive, collaboration-building process. In 2005, SCEC will sponsor 123 projects involving 156 principal investigators at 51 institutions. There are a number of additional investigators from the USGS, as well as many collaborators supported by SCEC's many partner organizations (Fig. 1.3).

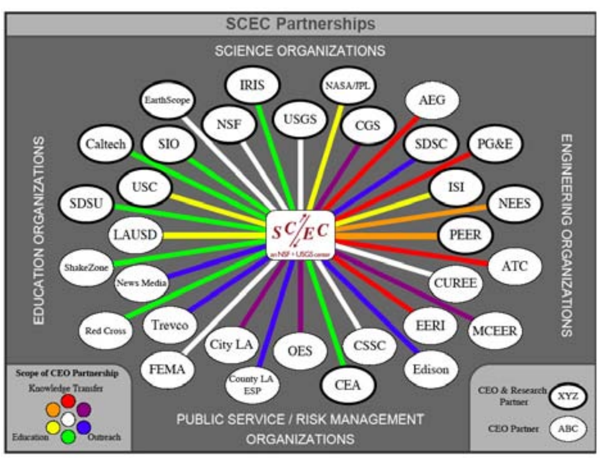


Fig. 1.3. SCEC's active partnerships with other organizations, positioned according to their mission. The connections are color coded by the type of partnership; e.g., a white connector means SCEC and its partner collaborate in all three areas—knowledge transfer, education, and outreach. Research partners are indicated by bold black borders.

America (390), which was hosted by SCEC at the same facility in April, 2004.

In particular, SCEC2 has successfully connected earthquake science with earthquake engineering through partnerships that involve major earthquake engineering organizations, including the Consortium of Universities for Research in Earthquake Engineering (CUREE), the Pacific Earthquake Engineering Research (PEER) Center, and the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). Supporting letters from these and other partner organizations are attached to this proposal. We propose to build on these new relationships in SCEC3.

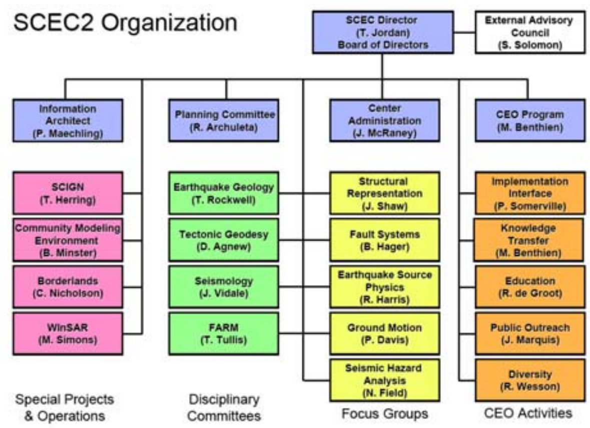


Fig. 1.4. The current SCEC organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects & operations (pink), CEO activities (orange), management offices (blue), and its external advisory council (white). Names in parentheses are current group leaders, committee chairs, or principal staff members.

SCEC is organized to accomplish its mission (Fig. 1.4). It sustains disciplinary science and related data-gathering activities through standing committees in *Seismology*, *Tectonic Geodesy*, *Earthquake Geology*, and *Fault and Rock Mechanics*. Interdisciplinary research is organized into five science focus areas: *Structural Representation*, *Fault Systems*, *Earthquake Source Physics*, *Ground Motion*, and *Seismic Hazard Analysis*. The Center manages several special research projects, including the Southern California Integrated GPS Network (SCIGN), the Western InSAR Consortium (WInSAR), the Borderland Working Group, and a large NSF/ITR project to develop its Community Modeling Environment (CME). It maintains an active set of partnerships with earthquake engineering and emergency management organizations through its *Implementation Interface*, which is part of its Communication, Education and Outreach (CEO) program. CEO is the main engine for broadening SCEC's impact outside of geoscience, and its extensive program is described in §II.C of this proposal.

SCEC is led by a Center Director (T. Jordan, USC), who chairs its *Board of Director*s, and a Deputy Director (R. Archuleta, UCSB), who chairs its *Planning Committee*. The Board members are representatives appointed by each core institution plus two at-large members elected from the participating institutions. The Planning Committee comprises the 14 working group leaders; it is responsible for reviewing the internal proposals and formulating an Annual Collaboration Plan for distributing resources to projects within the working groups. This plan is reviewed, modified, and approved by the Board at its February meeting.

The SCEC leadership is committed to increasing the diversity of its scientific community. It considers diversity in all aspects of Center activities. In particular, it has charged a *Diversity Working Group* to formulate concrete steps for improving diversity within the SCEC community. The progress and plans in this area are discussed in §IV.C.

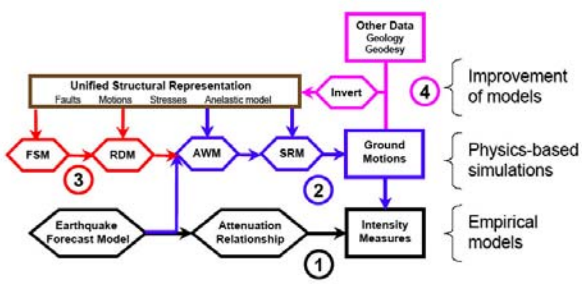


Fig. 1.5. Computational pathways facilitated by the SCEC/CME Project (Jordan & Maechling, 2003). (1) Current methodology for probabilistic seismic hazard analysis, based on empirical earthquake forecast models and attenuation relationships. (2) Ground-motion prediction using an anelastic wave model (AWM) and a site-response model (SRM). (3) Earthquake forecasting using a fault-system model (FSM) and a rupture-dynamics model (RDM). (4) Inversion of ground-motion data for parameters in the unified structural representation (USR), which includes the 3D information on faults, stresses, and seismic wave speeds needed by the other pathways.

3. *Earthquake System Science*

The SCEC research program concerns the two fundamental physics problems of earthquake science: the *dynamics of fault rupture*—what happens on a time scale of seconds to minutes when a single fault breaks during a given earthquake—and the *dynamics of fault systems*—what happens within a network of many faults on a time scale of hours to centuries to generate a sequence of earthquakes. These system-level problems are highly nonlinear and coupled to one another through the complex processes of brittle and ductile deformation of the lithosphere. SCEC has adopted a system-specific approach based on the principle that constructing models of the Southern California fault system and its earthquake behavior will lead to better understanding of earthquakes in general. Most of these system-specific models are numerical, and the most advanced models simulate earthquake dynamics in three spatial dimensions.

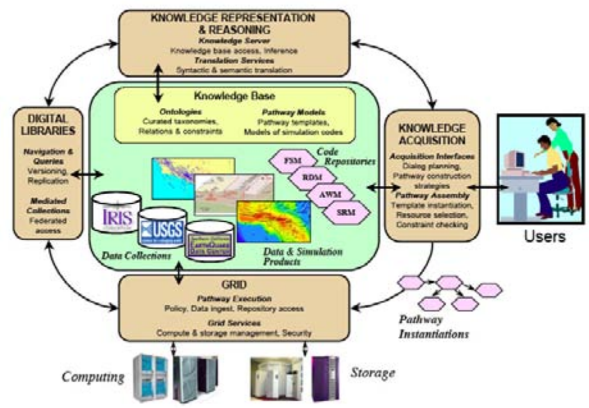


Fig. 1.6. The SCEC Collaboratory, which applies advanced information technologies in knowledge acquisition, grid computing, digital libraries, and knowledge representation and reasoning (outside boxes) to the development and operation of the Community Modeling Environment (SCEC/CME).

Fully three-dimensional (3D) simulations of fault-rupture and fault-system dynamics are challenging computational problems, but they are now becoming possible through the increasing availability of terascale computing resources. Using these capabilities, SCEC has integrated physics-based models into a new scientific framework for seismic hazard analysis (SHA). We have formulated this framework in terms of four "computational pathways," schematized in Fig. 1.5. Pathway 1 is an SHA computational framework that supports a variety of earthquake forecast models and ground motion intensity measure relationships, primarily through the new OpenSHA software platform (Field et al., 2003). Pathway 2 utilizes the predictive power of wavefield simulation in the construction of intensity-measure relationships. Pathway 3 incorporates fault-system and rupture-dynamics models into earthquake forecasting and assessments of predictability. Pathway 4 assimilates various types of data into a "unified structural representation" of Southern California needed by the other pathways.

Under a five-year grant from the National Science Foundation's Information Technology Re-

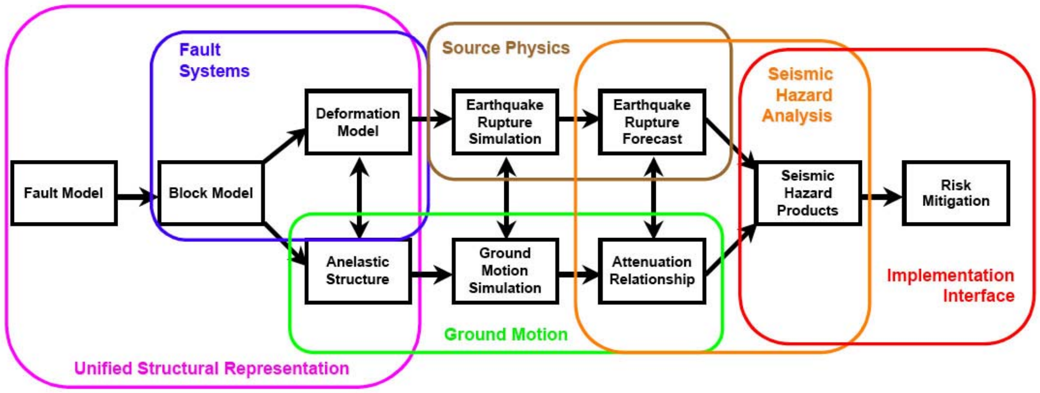


Fig. 1.7. The main components in SCEC's current system-level "master model" for seismic hazard analysis and risk mitigation (black boxes), showing the overlapping areas of interest of its interdisciplinary focus groups and implementation interface (colored boxes).

search (ITR) Program,[2] SCEC is leading a large collaboration to develop a Community Modeling Environment (CME) The CME is an integrated but distributed framework that automates the process of selecting, configuring, and executing simulations and other research activities. During the Project's first three years, we have developed substantial system capabilities, software tools, and data collections (see §V.C.3). The net product has been a new collaboratory for earthquake system science based on advanced information technologies (Fig. 1.6). In SCEC3, the community will utilize this collaboratory as a core facility for developing, testing, and maintaining the system-level models discussed in this proposal. It will also form the basis for important collaborations with Geosciences Network (GEON) and other geoinformatics projects.

C. Intellectual Merit of the Proposed Research

Earthquakes are one of the great unsolved puzzles of science. Large earthquakes cannot be predicted in terms of their location, time, and magnitude. Even in regions where we know a big one will eventually happen, its effects are difficult to anticipate. The hazard posed by the southernmost San Andreas fault is recognized to be high, for example; more than 300 years have passed since its last major earthquake. If the fault ruptures from the southeast to the northwest, toward Los Angeles, we can calculate that the damage to that city will be much worse than if it ruptures in the other direction (Fig. 2.17). Yet we have essentially no information about which way it will go.

The fundamental science outlined in this proposal addresses the unusual physics of how matter and energy interact during the extreme conditions of rock failure. No theory adequately describes the basic features of dynamic rupture, nor is one available that fully explains the dynamical interactions among faults. The search for a comprehensive theory is motivated by the need to understand active fault systems on time scales of days to centuries to improve earthquake forecasting, and fault ruptures on time scales of seconds to minutes for predicting strong ground motions.

SCEC is the NSF/USGS center for earthquake science in the United States, and it is uniquely qualified to coordinate a broad program aimed at these basic research goals. The program focuses on Southern California because this natural laboratory arguably has the best data and offers the best opportunity for deciphering the interrelationships among stress, displacement, and rheology needed to understand earthquake dynamics in general. Moreover, through its interdisciplinary focus groups and implementation interface, the Center is organized to translate this understanding into seismic hazard products that can be used to reduce earthquake risk (Fig. 1.7).

SCEC will extend its work on earthquake physics beyond Southern California through its network of national and international research collaborations. In its expanding partnerships with earthquake engineers, it will also generalize the natural system under consideration to include components of the built environment, thereby extending its analysis from seismic hazard to earthquake risk.

[2] The CME project is jointly funded by the Geosciences and Computer and Information Science & Engineering Directorates under grant EAR-0122464. SCEC's partners include the USGS, the San Diego Supercomputer Center (SDSC), the USC Information Sciences Institute (ISI), and the Incorporated Research Institutions for Seismology (IRIS).

D. Broader Impacts of the Proposed Research

Earthquakes pose the greatest natural threat to the built environment of California and other seismically active regions of the United States. Because more than 23 million people live in Southern California, the high seismic hazard of the region translates to high seismic risk. The Federal Emergency Management Agency estimates that almost half of the national earthquake risk is concentrated in Southern California (FEMA, 2000). The proposed research program will have a broad impact on risk assessment and loss reduction here and elsewhere.

Fig. 1.8. The earthquake "risk equation," written in terms of four factors. Proposed research will contribute to all aspects of seismic hazard analysis and, through end-to-end studies with engineering partners, to understanding the interaction of hazard, exposure, and fragility in determining earthquake risk.

The earthquake "risk equation" (Fig. 1.8) depends on three factors that amplify probable loss—(1) the *hazard* (the ground faulting and shaking, as well as secondary effects such as landslides, liquefaction, and tsunamis), (2) the *exposure* (density and extent of the built environment), (3) the *fragility* of the built environment (structural and non-structural vulnerability). It also depends on (4) the *resiliency* of the community, which attenuates risk through effective response to earthquake disasters and the ability to spread losses over a wider economic base through insurance.

Characterization of the hazard is the key to risk assessment and loss reduction. The hazard is set by nature, so its primary effects cannot be reduced, only anticipated. The practical outputs of the SCEC research program are better techniques for earthquake forecasting and better attenuation relationships, the two main components of probabilistic seismic hazard analysis (PSHA). Central to the SCEC approach has been the development of alternative representations of the building blocks used to construct the PSHA for Southern California. These alternative models not only quantify the epistemic uncertainty in PSHA, but also highlight research directions that will lead to reduced uncertainty. SCEC proposes to partner with the USGS and the CGS in a new Working Group on California Earthquake Probabilities (WGCEP) to provide the State of California with its first uniform earthquake rupture forecast based on a time-dependent methodology (§III.C.3). It is also participating in a PEER-Lifelines/SCEC/USGS partnership to use physics-based methods in creating the next generation of attenuation (NGA) relationships (§III.C.4). The WGCEP and NGA project plans extend well into SCEC3.

Once the hazard has been characterized, the exposure must be predicted by mapping land use and building inventories, and the fragility predicted by performance-based engineering assessments. Fragility assessments are usually made on the basis of simplified relationships between the shaking intensity and the predicted damage; though easy to use, these approximations can be misleading in terms of actual damage. A major initiative described in this proposal (§III.C.5) is to predict aspects of building damage for large scenario earthquakes based on "end-to-end" simulations. This approach, which will be pioneered in a partnership with engineering organizations, will subject a geographic distribution of buildings to realistic shaking histories and, in a single simulation, directly compute measures of predicted damage, taking the loss-estimation problem from "ruptures to rafters". In terms of Fig. 1.8, this research will attempt to improve loss prediction through a state-of-the-art analysis that couples together the loss factors (1), (2), and (3).

The experience gained by SCEC in coordinating system-level science will help to guide other integrated studies of complex geosystems, and it will prototype integrative frameworks for NSF's EarthScope program. Through national and international partnerships (§III.C.7&8), the innovative developments in SCEC's Community Modeling Environment will be extended to the study of geosystems in other regions. Indeed, SCEC's establishment of a functional collaboratory for earthquake science provides an exemplar for system-level science in general.

II. Accomplishments

The Center's main research goals involve the big science of system-level modeling and prediction, so the bulk of this review assesses the progress in this arena. Section II.A summarizes the principal achievements of SCEC1 in general terms; Section II.B treats the science accomplishments of SCEC2 in more detail. However, an analysis of the demographics and funding patterns shows that most of the Center's resources are actually spent to support students and early-career investigators, who are

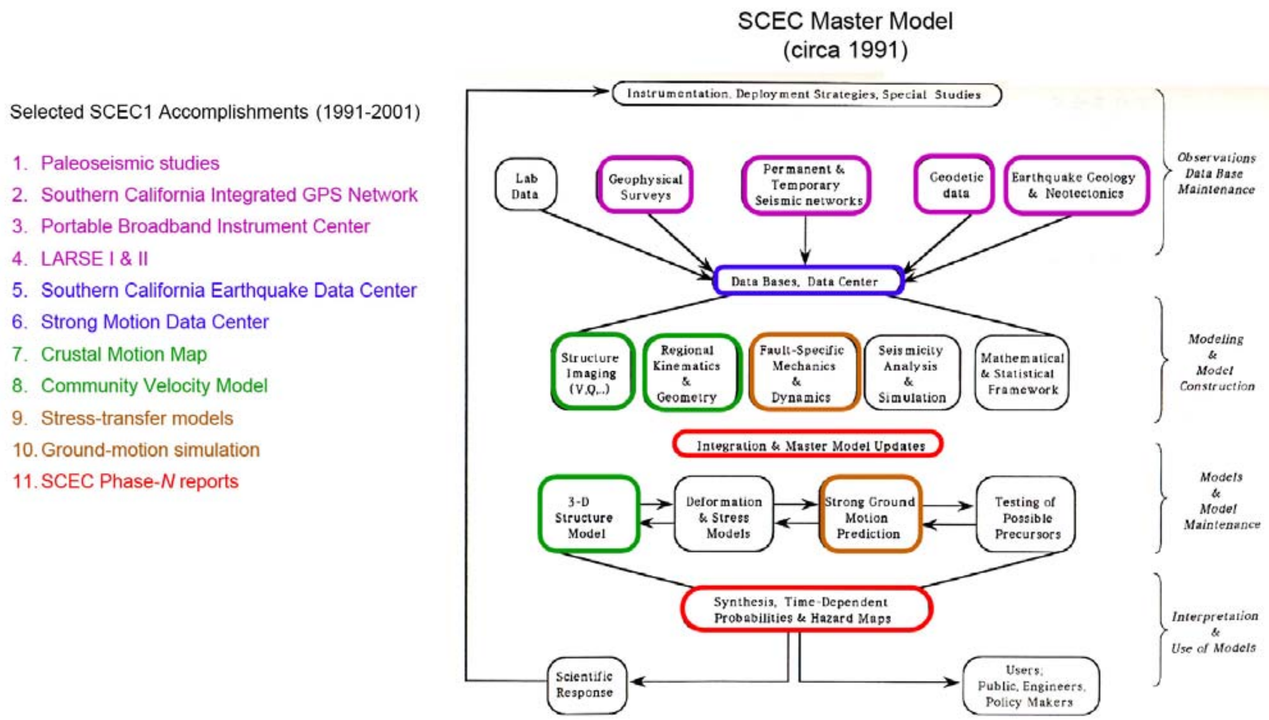


Fig. 2.1. A diagram of the science activities and information flow associated with building SCEC master model, circa 1991. A selection of SCEC1 achievements with a few associated publications is listed on the left and color-coded to the diagram. The comparison indicates how the master-model concept help to guide the SCEC1 program. See Henyey et al. (2002) and Aki (2003) for further discussion of the SCEC1 accomplishments.

primarily engaged in small science.[3] We have therefore tried to capture the diversity of investigator-driven projects in a collection of one-page "science nuggets," available on the web at (http://www.scec.org/nuggets).

A. Principal Achievements of SCEC1

SCEC2 has prospered in the rich legacy of SCEC1 (Henyey et al., 2002; Aki, 2002). The founders of the original STC, led by its first director, Professor Keiiti Aki, articulated a powerful vision for the Center: disciplinary groups would coordinate their investigations through SCEC and, working together, weave their results into a "master model" for seismic hazards for Southern California. The master-model concept quickly ramified into the principal blueprint for the collaboration. The 1991 version of this blueprint is color-keyed to a partial listing of major SCEC1 accomplishments in Fig. 2.1. The comparison illustrates how the master model successfully guided the Center's activities.

As illustrated in Fig. 2.1, the Center initiated a new multidisciplinary and integrative approach to earthquake science in Southern California. Scientists engaged in data collection were brought together with other data gatherers and modelers in a collaborative process that greatly accelerated our understanding of the region's seismic hazard—a principal goal of the Center.

SCEC1 initiated the first systematic earthquake study of the greater Los Angeles Basin that included extensive paleoseismic investigations (Dolan et al., 1995), broadband recordings of ground motion (Tumarkin & Archuleta, 1995; Saikia & Somerville, 2000; Olsen, 2000; Lee et al., 2000; Brune, 2002), many in concert with the geotechnical engineering community, and exploration of the structure beneath the Basin and Transverse Ranges through seismic imaging (LARSE—Los Angeles Region Seismic Experiments; Fuis et al., 2000, 2003; Lutter et al., 2004; Kohler & Davis, 1997; Fuis et al., 2001; Fuis et al., 2002), body wave inversion using local earthquakes (Zhao et al., 1996; Hauksson & Scott, 1994), and analysis of well data. The establishment of the SCEC broadband instrument center at UCSB, and SCEC-funded upgrade of the Southern California Earthquake Data Center at Caltech, greatly aided these efforts.

[3] We have demographic information on 563 scientists sponsored by SCEC since 2002. Of these, 347 were students, postdocs, and early-career faculty or research scientists.

Moreover, with a primary objective to determine which structures might be accommodating the most crustal strain, the Center, in conjunction with NASA's Jet Propulsion Lab and the USGS, established the 250-station Southern California Integrated GPS Network (SCIGN; Prescott et al., 1996, Hudnut et al., 2002)—the predecessor to, and prototype for, the EarthScope Plate Boundary Observatory.

While instrumentation and data gathering consumed a significant portion of Center resources during the first few years of SCEC1, including the important coordinated responses to the 1992 Landers and 1994 Northridge earthquakes, data integration later became top Center priority. This integration including the development of the community velocity model (Magistrale et al., 1996; Hauksson & Hasse, 1996), the crustal motion map (Feigl et al., 1993; also see http://epicenter.usc.edu/cmm3), and stress transfer models (King et al., 1994; Harris, 1998), and a variety ground motion simulations (Haase et al., 1996) that were tested against data recorded from the Northridge earthquake (e.g., Olsen et al., 1995; Wald & Graves, 1998; Day, 1998; Olsen, 2000). Existing data and the newly generated data were organized and assessed in workshops and by research teams organized by the Center. Models were updated and refined through a set of feedback processes that repeatedly tested them against observation.

Distillation of disciplinary data and models into a synthesis of seismic hazard in Southern California occurred though a series of interdisciplinary "Phase-*N*" studies. Phase I and its report related specifically to the Landers earthquake and its probable impact on future earthquake occurrence in the region. Phase II integrated the wide variety of new and existing data and models into an updated consensus earthquake forecast model and report for Southern California (Ward, 1994; Jackson et al., 1995; WGCEP, 1995). Phase III consisted of 14 papers in the *Bulletin of the Seismological Society of America* that investigated site effects in probabilistic seismic hazard analysis (Field et al., 2000), and Phase IV began an update of the fault, geodetic and seismicity databases, and an evaluation of a range of seismic source models, with a goal toward the development of online deterministic seismic hazard analysis tools. This activity continues under SCEC2 auspices as the Regional Earthquake Likelihood Models (RELM) project.

B. SCEC2 Science Accomplishments

SCEC remains committed to its original vision: it continues to advance seismic hazard analysis through an interdisciplinary, multi-institutional research program based on community models and an expanding array of information technology. SCEC2 has taken this program to a new level by building a fully articulated collaboratory for earthquake science with an integrated set of data-processing and model-building activities designed to facilitate a system-level understanding of earthquake behavior in Southern California.

In this section, we highlight the scientific accomplishments in six problem areas central to the Center's collaborative approach to earthquake science. The summaries are assessment-oriented: general goals and specific objectives are stated, and SCEC2 activities and their results are discussed. Owing to space limitations, the summaries are far from comprehensive; many notable accomplishments of the 14 science working groups are not even listed. A fuller accounting of the Center's recent accomplishments can be found in the SCEC2 annual reports for 2002-2004, which are organized by working group and available on the web (http://www.scec.org/aboutscec/documents/).

1. Fault Mechanics

Understanding fault ruptures is largely a mechanical problem: the nucleation, propagation, and arrest of fault ruptures depend on the stress response of rocks approaching and participating in failure. In these regimes, the rock behaviors can be highly nonlinear, strongly dependent on temperature, and sensitive to minor constituents such as water. The SCEC1 program did not explicitly involve rock mechanics. The SCEC2 proposal recognized that "the move toward the physics-based modeling of earthquake phenomena requires that greater attention be paid to field and laboratory data on small-scale fault-zone processes." A disciplinary committee in Fault and Rock Mechanics (FARM) was thus established in 2002 (T. Tullis, leader; J. Chester, co-leader).

Goal and Objectives. The principal FARM goal is to construct and verify a model of fault-zone mechanics applicable to the nucleation, propagation, and arrest of dynamic rupture. The SCEC2 program in fault mechanics has three main objectives: (1) promote new types of laboratory experiments on the frictional resistance during high-speed coseismic slip, (2) understand the implications of exhumed-fault data for earthquake dynamics, and (3) incorporate the lab and field data into better models of dynamic rupture. These objectives overlap with those of Earthquake Source Physics, Fault Systems, and Ground Motions, and they are central to the goal of Seismic Hazard Analysis.

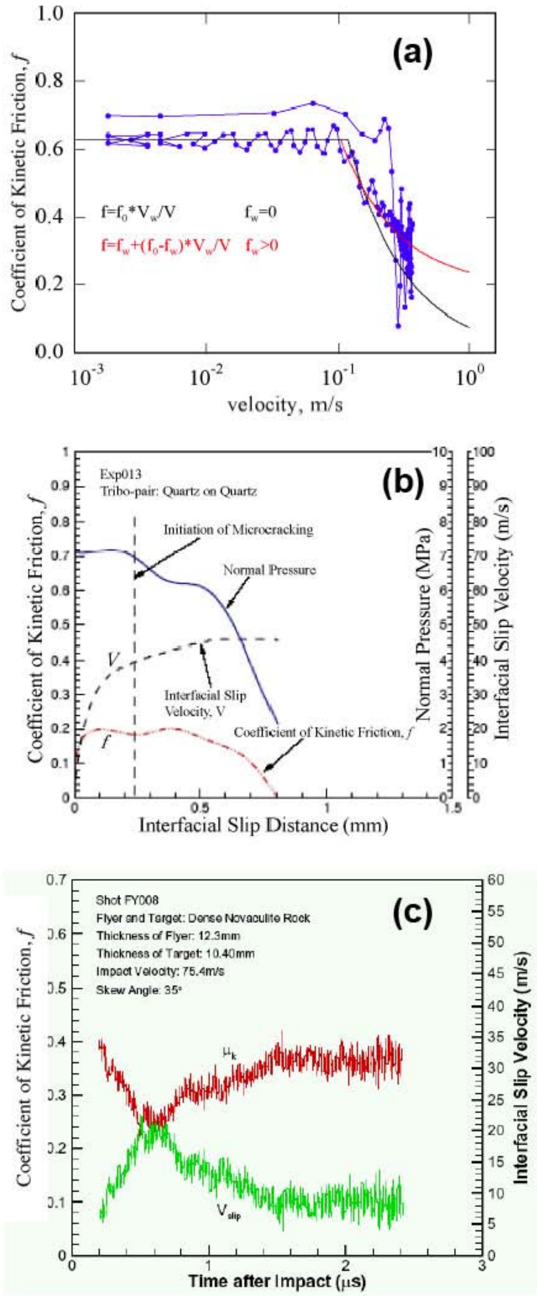


Fig. 2.2. High-velocity weakening of a dense Arkansas novaculite using new techniques developed by the FARM group. **(a)** Friction coefficient *f* for slip velocities up to 0.4 m/s (Tullis and Goldsby, 2003), fit with the flash melting equations of Rice (1999a) (black) and Beeler & Tullis (2004) (red). **(b)** Experiment with slip rates up to 4 m/s using a pre-twisted torsional Kolsky bar (Prakash, 2004), resulting in *f* slightly less than 0.2. **(c)** Results from the plate impact apparatus; the low friction at high slip rates is compatible with flash melting and the subsequent increase is compatible with enlargement of a viscous melt layer.

Results. The FARM initiative brought into SCEC a new community of scientists concerned with laboratory rock mechanics experiments, field studies of exhumed fault zones, and theoretical modeling of friction processes and fault mechanics. The FARM workers began their activities with a highly successful workshop (75 attendees) in September 2002. They have held two subsequent workshops to establish collaborations, prioritize experimental research, and discuss results. The synergy from the FARM workshops has resulted in rapid advances, illustrated by three cooperative efforts.

A collaboration comprising J. Rice, T. Shimamoto, D. Goldsby, N. Beeler, T. Tullis, V. Prakash, and N. Lapusta has made substantial progress in understanding the dynamic frictional weakening that can result from "flash" melting—the local melting at small asperity contacts caused by frictional heat generation. Beeler & Tullis (2004) modified Rice's (1999b) theory to include the effect of finite strength of melted asperities and a distribution of asperity sizes, obtaining a better fit than Rice to Tsutsumi & Shimamoto's (1997) laboratory data. Encouraged by these results, Goldsby & Tullis (2003) conducted a new series of experiments to search for flash melting; they found that the expected weakening fit the theoretical predictions nicely (Fig. 2.2a). Experiments testing the applicability of new high-speed friction techniques by Prakash (2004), described below, have produced interesting preliminary data also indicating low friction at high slip speeds (Fig. 2.2b,c). Based on this experimental validation, Lapusta & Rice (2004a,b) used rheologies incorporating flash melting and thermal fluid pressurization in models of dynamic rupture (Fig. 2.3). They found rupturing at low values of tectonic stress, sliding with little frictional heat generation, and nearly complete stress drops consistent with observed values.

A second example of FARM collaboration merges field observations, experimental data, and theoretical models of small-scale processes of earthquake slip. Previous reports on the exposed slip zones of the Punchbowl and San Gabriel faults had documented the existence of a narrow high-slip fault core and little evidence for fault-parallel shear within the bounding damage zone (Chester & Chester, 1998; Chester et al., 1993, 2003; Chester & Logan, 1986, 1987; Schulz & Evans, 1998, 2000; Wilson et al., 2003). New SCEC-organized studies of fault structure demonstrate an even greater degree of slip localization within the fault core (Chester et al., 2003; Fig. 2.4). These data, combined with field and laboratory data on permeability of fault rocks (Wibberley, 2002), have reinvigorated modeling of dynamic fault weakening by thermally-induced increase of pore fluid pressure (Rice, 2003, 2004; Lapusta & Rice, 2004a, 2004b).

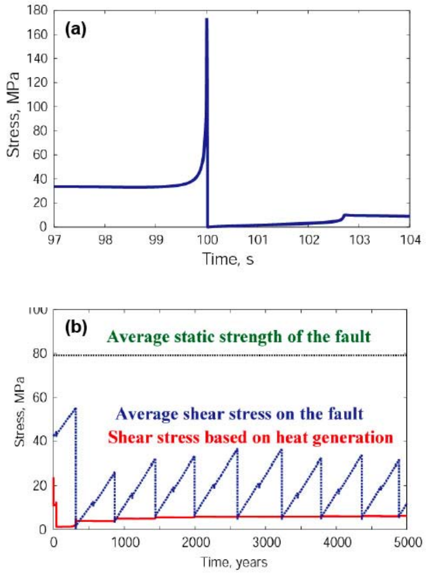


Fig. 2.3. (a) Stress variation in a 2D dynamic rupture with rate and state friction and strong dynamic weakening (Lapusta & Rice, 2004a,b). The diagram shows the stresses around the tip of a rupture propagating to the left and located at the 100s mark. **(b)** In a series of dynamic ruptures similar to that shown in (a) the average shear stress on the fault oscillates, but never reaches the static strength. Because most of the slip all occurs at a low stress level, heat generation is low and satisfies the observed heat flow constraint (Lachenbruch & Sass, 1980).

At the FARM 2002 workshop, J. Brune reinvigorated the debate about off-fault damage by reemphasizing the lack of fault-parallel shear within bounding damage zones of large faults and speculated that the observed near-fault damage could have resulted from dynamic reductions in fault-normal stress. Subsequent studies along the active trace of the San Andreas fault (Wilson et al., 2004, 2005) encouraged a merger of field data, lab experiments and theory to reexamine the problem from an integrated perspective (Ben-Zion & Sammis 2004; Dor et al., 2004). One spin-off study concerns whether asymmetry in damage across the fault might result from asymmetrical rupture propagation governed by contrasts in elastic properties across the fault (Dor et al., 2004). Another involves the significance of off-fault damage to earthquake energetics and implications for dynamic rupture (Rice et al., 2005; Andrews, 2004). Substantial progress in understanding dynamic weakening mechanisms, the origin of off-fault damage, and earthquake energetics is expected in the remaining two years of SCEC2.

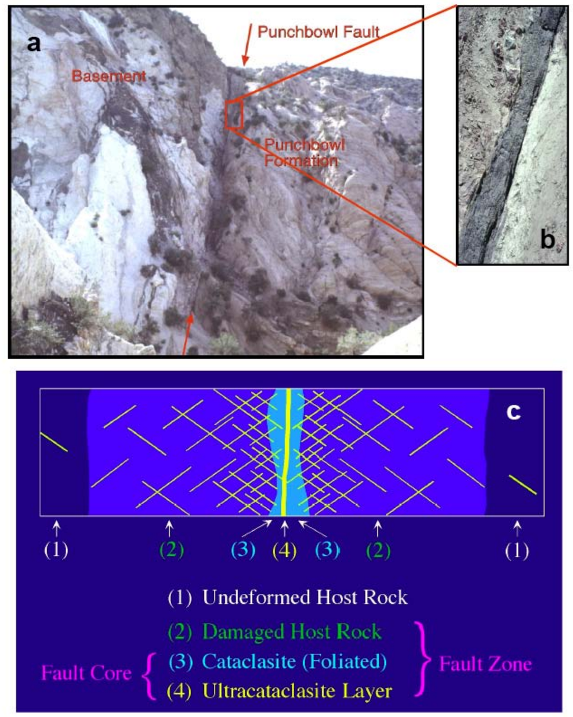


Fig. 2.4. (a) In the Devil's Punchbowl area, the Punchbowl fault is a 100-m-thick zone of fractured and folded rock bounding a meters-thick, narrow zone of high shear strain containing a single, continuous layer of ultracataclasite. **(b)** The dominantly brittle ultracataclasite is distinct and forms sharp contacts with the bounding cataclasites. **(c)** Conceptual model of a typical large displacement fault (after Chester et al. 1993).

A third area of FARM achievement—new laboratory techniques for measuring high-velocity friction—illustrates how the SCEC program, with limited but highly leveraged resources, can stimulate and support experimental advances in rock mechanics through careful prioritizing of laboratory activities. The first FARM workshop identified as its highest priority for experimental improvement *the measurement of frictional resistance at high slip speed and normal stress*. A project team lead by V. Prakash (Case Western) has tested several techniques new to geophysics for measuring friction at high slip velocity (see Fig. 3.1). These novel experiments have produced the first data on geological materials (Fig. 2.2b,c), which are consistent with flash melting that reduces the friction, followed by more extensive melting that increases the contact area (and thus the friction). Tullis and his colleagues, with the help of an undergraduate intern from Puerto Rico, have investigated a newly discovered high-speed, gel-lubrication weakening mechanism (Goldsby and Tullis, 2002) to determine variations in gel-weakening as a function of silica content (Roig Silva et al., 2004a,b). The results suggest this mechanism may be another viable candidate for reducing coseismic slip resistance (Di Toro et al., 2004).

2. Earthquake Rupture Dynamics

Earthquakes are generated by the dynamic processes of fault rupture. The coseismic behavior reflects the stress field and rheology inherited from previous earthquakes and thus depends on interactions across a wide range of space and time, from the microscopic inner scale (frictional contact asperities breaking over microseconds) to the fault-system outer scale (regional tectonic loading and relaxation over thousands of years). The coseismic slip process also radiates the seismic waves that lead to ground motion. This problem thus connects the research of the Earthquake Source Physics (ESP) focus group, led by R. Harris and D. Oglesby, with the working groups in FARM, Fault Systems, and Ground Motion.

Goal and Objectives. SCEC's goal is to create physics-based models of fault rupture that can predict dynamic slip distributions and the ground motions they generate. The primary SCEC2 objectives, addressed first in the simple slip-weakening context, have been to (1) validate 3D numerical simulations by cross-comparing the results of different codes on standard test problems, (2) verify the 3D simulations by comparisons with laboratory experiments and real earthquakes, and (3) couple the dynamic rupture models with anelastic wave propagation models to investigate the ground motions expected for large earthquakes in Southern California. The latter bridges ESP developments with activities of the Ground Motion and Seismic Hazard Analysis focus groups.

Results. ESP is currently conducting an exercise to validate 14 computer codes employed to simulate 3D rupture dynamics (Harris & Archuleta, 2004; Harris et al., 2004). Scientists from the U.S. and France, Germany, Italy, Japan, Slovakia, and Switzerland are involved. The collaboration has shown that "fat-fault" methods produce different synthetics from split-node methods; excellent matches have been obtained between boundary-integral and finite-difference algorithms, as well as reasonably good matches with some finite-element algorithms (Fig. 2.5), giving us confidence in the validity of the models. In the next year, the collaboration will explore the subshear/supershear rupture speed transition, the effect of an asperity and a weak patch away from the hypocenter, and other complex initial conditions relevant to real earthquake dynamics. The objective is to validate codes for realistic fault geometries that can be used for seismogram synthesis in the NGA project (§III.C.4) as well as other SCEC modeling activities, such as the TeraShake simulations (§II.B.6).

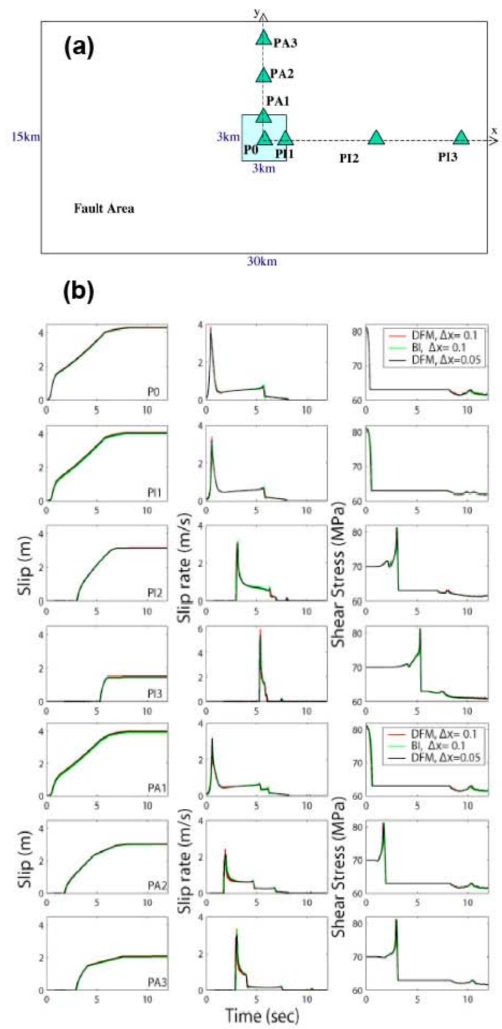


Fig. 2.5. Results of the Dynamic Rupture Simulation Verification Project. **(a)** Model for testing dynamic rupture simulations. Square is the nucleation area; triangles are receivers. **(b)** Time-history of the slip, slip rate and shear stress at the selected points for split-node finite difference method (DFM) with grid interval 0.05km (black line) and 0.1km (red line), and boundary integral method with grid interval 0.1km (green line) (Harris et al., 2004; Day et al., 2005).

Three groups have been comparing laboratory results with numerical simulations of dynamic rupture. These studies, joint between the ESP and FARM groups, show promise in elucidating fault behaviors that are hard to observe under natural conditions. Recent lab experiments by Xia et al. (2005) for ruptures on faults with material contrasts agree with the numerical simulations of Harris & Day (1997); both find bilateral rupture propagation and a transition to supershear rupture speeds for a specific range of material contrasts. Laboratory studies also show an impressive correlation with branching patterns predicted by theory (Rousseau & Rosakis, 2003; Kame et al 2003). Numerical simulations by S. Day & coworkers (Day & Ely, 2002; Day et al., 2004) have shown similar results to the laboratory foam-rubber experiments of J. Brune and R. Anooshehpoor.

The next step is to compare computer results with the real earthquakes, as has been done for the 1992 Landers earthquake (Fliss et al., 2005). Toward this end, SCEC is establishing a database of Reference Earthquakes. One aspect well underway through a collaboration with M. Mai at ETH Zurich is a web-accessible database on fault slip distributions from kinematic inversions of well-recorded earthquakes (http://www.seismo.ethz.ch/srcmod). More extensive compilations of event-specific data and models are underway for two important Reference Earthquakes, 1992 Landers and 2004 Parkfield. The latter has produced maybe the best-ever data set for rupture dynamics studies (Langbein et al., 2005; Bakun et al., 2005), and it will be the focus of an intense modeling effort.

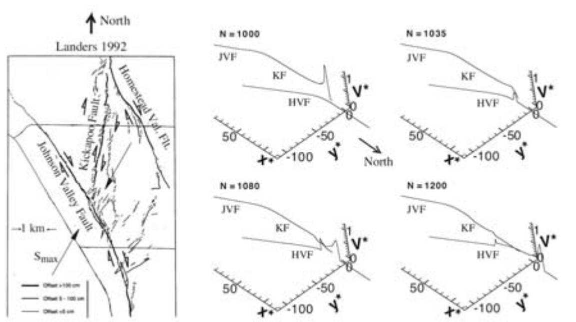


Fig. 2.6. Map at ***left*** shows how the branching of 1992 Landers rupture from the Kickapoo Fault (KF) onto the Homestead Valley Fault (HVF) left behind a "backward branch" structure (Kame et al., 2003). The panels at ***right*** show a simulation of the processes forming the backward branch (Fliss et al., 2005). Results support the hypothesis that rupture transferred to the HVF by stopping suddenly at the KF termination, radiating stress to the HVF, and nucleating rupture on it, which then propagates bilaterally, forming that backward branch along the curved SE section of the HVF.

Numerical simulations show promise in replicating some observed features, such as the effects of fault geometry on the rupture behavior of kinked thrust faults (Oglesby & Archuleta, 2003) and stepped, bent, or branched strike-slip faults (Harris et al., 2002; Kame et al., 2003; Oglesby et al., 2003). A dynamic explanation by Fliss et al. (2005) for the unusual "backward branch" structure formed on the Homestead Valley fault during the 1992 Landers rupture is illustrated in Fig. 2.6.

The 2002 Denali earthquake has provided evidence on how fault geometry and strength heterogeneity affect rupture propagation (Oglesby et al., 2004; Bhat et al., 2004) and may have propagated at supershear rupture speeds (Dunham & Archuleta, 2004). The transition to supershear rupture can have a significant effect on the ground motions from large strike-slip events and is the subject of much current research, including comparisons between laboratory experiments and numerical simulations.

The Earthquake Source Physics work on multi-cycle earthquake behavior serves as a bridge connecting this group's work with that of the Fault Systems group. The modelers are including true coseismic earthquake dynamics in their simulations and coupling them to interseismic fault behavior that governs rupture nucleation. This process is crucial for producing realistic pre-stress patterns for dynamic rupture models, and also for producing realistic initial strain fields for fault system modeling. So far, this multi-cycle work is largely carried out in 2D due to the computational expense of full 3D simulations. These studies (Lapusta et al., 2000; Lapusta & Rice, 2003; Duan & Oglesby, 2004; B. Shaw 2004a,b) employ a range of interseismic rheologies and are a healthy start to work that will continue into SCEC3.

3. *Unified Structural Representation*

Southern California is laced with a three-dimensional, fractal network of active faults. The shear localization on major faults defines tectonic blocks that are themselves deforming and have heterogeneous, anisotropic structures inherited from a turbulent geologic history. Physics-based models of the fault system rely on knowledge of this mechanical architecture, which itself depends on understanding the present-day plate-boundary kinematics as well as the geological evolution of the major blocks. The main features needed for the ground-motion modeling and seismic hazard analysis are the geometry of the fault network and the material properties—seismic velocities, attenuation parameters, and density distribution—within the tectonic blocks. These structures are interrelated, because material property contrasts are often governed by fault displacements.

Goal and Objectives. SCEC's goal is to construct a Unified Structural Representation (USR) for Southern California that describes the structure of the fault system needed for physics-based earthquake forecasting and ground-motion predictions. The SCEC2 objectives are to (1) improve versions of the Community Velocity Model (CVM) for use in earthquake simulations, (2) develop a Community Fault Model (CFM) capable of expressing uncertainties through alternative representations, (3) extend the CFM to a Community Block Model (CBM) for fault-system modeling, and (4) prototype the USR by merging the CVM into the CFM/CBM structural framework.

Results. In the SCEC2 proposal, we put forward the notion of a USR that would assimilate the information about fault structure and geologic heterogeneity into a common model. The construction of the USR has become one of the most interactive projects in the SCEC collaboration. The activity is centered in the Structural Representation focus group (J. Shaw, leader; J. Tromp, co-leader), but it also involves the Geology disciplinary group, the Borderland special project group, and the Ground Motion and the Seismic Hazard Analysis focus groups. A key intermediate step in USR development has turned out to be the extension of the CFM to a Community Block Model (CBM).

Community Velocity Model (CVM). Current versions of the CVM are based on data primarily sensitive to the compressional velocities (V_P); shear velocities (V_S) and densities are derived from V_P through empirical scaling relations. The latest release of the original SCEC model, CVM-S3.0 (S = SCEC), was built on a crustal tomographic model by Hauksson (2000), supplemented with rule-based definitions of the velocity structure in the sedimentary basins by Magistrale et al. (2000) and a compatible mantle tomographic structure (Kohler et al., 2003). The CVM-S3.0 has been widely used for numerical modeling of ground motions, including the TeraShake simulations (Minster et al., 2004), earthquake catalog relocations (Hauksson, 2004), and recent improvements in the recovery of earthquake source parameters (Chen et al., 2005). In 2004, the Structural Representation focus group released an alternative velocity parameterization, CVM-H1.0 (H = Harvard), based on the analysis of wellbore and seismic reflection data by Suess & Shaw (2003). The inclusion of this new model is a move toward the USR objective of delivering alternative structural representations that reflect epistemic uncertainties.

Techniques have been developed to measure precisely the amplitude and phase differences between observed and synthetic waveforms in localized time and frequency bands. About 10,000 such measurements have been made on direct phases in the band 0.2-1.2 Hz from 25 small earthquakes with paths crossing the Los Angeles region, and they have been used to assess the waveform fidelity provided by the two CVMs (Chen et al, 2005b). Both the SCEC and Harvard versions provide substantial (~60%) and similar variance reduction relative to standard 1D models. Moreover, the V_P-V_S scaling relations used in the CVMs yield good fits to the *S*-wave data, and the 3-component data constrain the anisotropy of the upper crust to be small (< 1%). These types of waveform data are now being directly inverted for CVM improvements, as described in §III.A.4.

Another objective for CVM development has been the inclusion of an attenuation structure. Olsen et al. (2003) determined shear-wave attenuation by comparing the Northridge observations with their low-frequency (< 0.5 s) simulations, obtaining the scaling relations $Q_S = 0.02\ V_S$ for $1000 \leq V_S \leq 2000$ m/s and $Q_S = 0.1\ V_S$ for $V_S > 2000$ m/s—results generally consistent with the recent tomographic inversions for Q_S by Shearer & Hauksson (2004), who found low Q_S in the sedimentary basins. In contrast, the basins appear to have high coda-*Q* because they trap energy (Davis & Wu, 2005). The SCEC borehole array (Steidl, 2004) is providing critical information on the lowest *Q* leg of the path, while methods to stack seismograms are being used to identify scattering sources, such as basin edges (Clayton, 2004).

Community Fault Model (CFM). The Community Fault Model is a new SCEC2 product: a version-controlled, object-oriented, 3D representation of more than 140 active faults in Southern California, defined by surface geology, earthquake hypocenters and focal mechanisms, wellbore, and seismic reflection data (Fig. 2.7). The CFM effort exemplifies the SCEC approach to building a community resource from the cumulative efforts of many individual SCEC scientists. The latest CFM-V2.0 includes more than 35 new fault representations (Plesch et al., 2005), guided by contributions from more than 20 SCEC investigators. The model, including its alternative fault representations, was evaluated and approved by the SCEC community in a series of workshops, in which scientists used the LA3D software tool, developed by the SCEC Intern Program, to visualize and analyze the faults. Based on feedback from these evaluations, the inventory of CFM versions was defined, and the groundwork laid for developing a set of viable alternative fault models for use by the SCEC/USGS working group on Regional Earthquake Likelihood Models (RELM; see §II.B.5).

Development of the CFM has supported geologic and seismologic investigations that substantially revised our understanding of the nature, and in many cases the inventory, of active faults throughout Southern California. For example, it is now recognized that shortening in the northern Los Angeles basin is not manifest in a single structure, but rather occurs on a vertically stacked set of at least six blind thrust faults (J. Shaw et al., 2002; Dolan et al., 2003; Griffith & Cooke, 2004; Plesch et al., 2005; see Fig. 2.8). This newly defined fault architecture substantially impacts next-generation seismic hazard models via RELM, and will constrain velocity discontinuities within future versions of the CVM. Complex fault architectures, including alternative representations, are now compiled for each of the densely populated coastal basins of Southern California and the adjacent continental borderland (e.g. Kamerling et al., 2003; Carena, 2003; Rivero, 2004; Sorlien et al., 2004). The CFM effort has also compiled fault representations and alternatives for the interior regions, including the San Andreas fault itself and the Eastern California shear zone, in order to build a comprehensive model of the Southern California fault network.

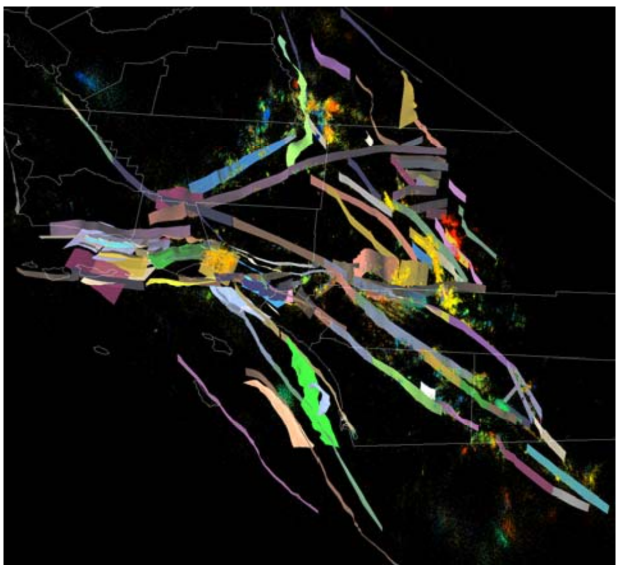


Fig. 2.7. Perspective view of the SCEC Community Fault Model (CFM-V2; Plesch et al., 2005). Seismicity is from Hauksson (2000) and color-coded by year of occurrence.

In conjunction with the CFM, we have developed a Fault Activity Database (FAD), in which we have compiled numeric activity data from observational studies, including slip rate studies on over 100 faults in Southern California; the FAD currently comprises information on all faults compiled for the USGS National Quaternary Fault and Fold Database (NQFFD) and about 80% of the faults in CFM. The FAD has proceeded in close collaboration with the USGS and CGS fault database efforts and is complementary to them. Data in the FAD are used by SCEC researchers who need the full range of published data, rather than the best estimates and the preferred (consensus) values available in the NQFFD and as input parameters to the National Seismic Hazard Maps (NSHM).[4]

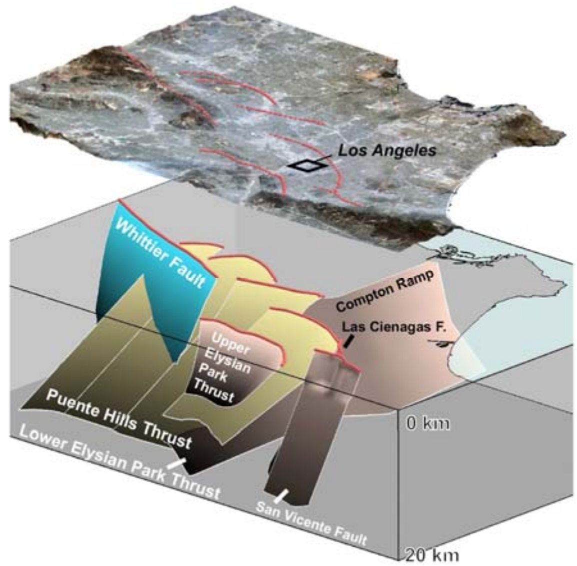


Fig. 2.8. Perspective view of the CFM in the northern Los Angeles basin, showing an imbricated stack of six blind-thrust faults lying beneath the downtown region (Plesch et al., 2004). Previous hazard compilations (e.g., Dolan et al., 1995) considered only a single blind-thrust earthquake source in the region.

Community Block Model (CBM) & Unified Structural Representation (USR). The next generation of SCEC velocity models will provide alternative parameterizations in a framework that builds on the foundation of fault representations provided by the CFM. To accomplish this, the Structural Representation group, working with the Fault Systems group, has developed the first version of a Community Block Model. The CBM consists of major fault surfaces from the CFM extrapolated and connected with topographic, base-of-seismicity, and Moho surfaces to define closed blocks (Fig. 2.9). It is currently being used to generate volumetric meshes that will be used by the Fault System group to model crustal motions through 3D quasi-static, finite-element codes (see §II.B.4). In addition, the CBM and additional geological surfaces will be used to define fault-bounded blocks in which one or more alternative velocity parameterizations may apply, allowing users to develop new property models that are, by

[4] The FAD separates out numeric data and keys each datum to the fault, the publication, and the site where the study was conducted. Users may obtain FAD data programmatically or through a browser interface (http://www.scec.org/FIS). Scientists may also contribute new data using a browser-based GUI, which are then reviewed by the database manager and inserted into the database. The next step in our collaboration with USGS and CGS database efforts will be to adapt the FAD data contribution form for long-term maintenance of the NQFFD.

definition, compatible with the CFM fault representations. This framework, including fault surfaces and geologic horizons in the CFM and CBM, and compatible property models (CVM), will constitute the Unified Structural Representation. An initial version of the USR is expected by the end of SCEC2. The USR will mature as a core resource and testbed under SCEC3.

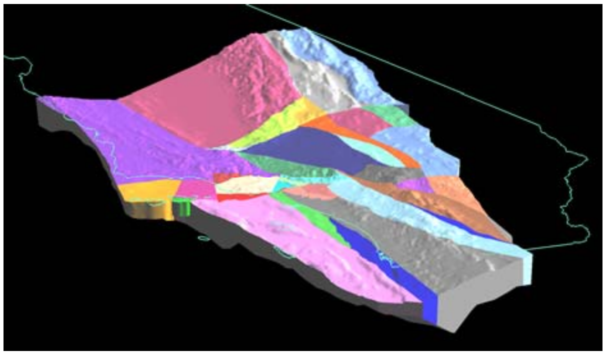


Fig. 2.9. Perspective view of the SCEC Community Block Model (CBM-V1.0), which consists of more than 75 tectonic blocks bounded by major faults, derived from the CFM, and regional topography, base-of-seismicity, and Moho surfaces (J. Shaw et al., 2004).

4. *Fault System Behavior*

SCEC2 research on fault system behavior addresses the key question: on interseismic time scales from hours to millennia, how does the seismogenic zone of Southern California accommodate the stress and deformation driven by the plate-tectonic boundary conditions? To answer this question SCEC2 has developed a physics-based context for interdisciplinary research through a fault-oriented, model-based approach in which structural information is combined with geodetic measurements of deformation and geologic observations of fault slip to produce dynamically balanced tectonic block models. These activities are based in the Fault System focus group (B. Hager, leader; S. McGill & J. Dieterich, co-leaders), but they involve collaborations with the Geodesy disciplinary committee (D. Agnew, leader; M. Simons, co-leader), the SCIGN coordinating committee (T. Herring, chair), FARM, Structural Representation, and Earthquake Geology (T. Rockwell, leader; M. Oskin, co-leader). Geodesy and SCIGN collaborate to revise the Crustal Motion Map (CMM), which represents surface deformations across the fault system, an important intermediate product.

Goal and Objectives. SCEC's goal is to develop models that describe how strain is released and stress evolves within the Southern California fault system. The SCEC2 objectives include (1) the collection and analysis of deformation signals from InSAR and GPS, including GPS data from both SCIGN and campaigns, and the incorporation of the GPS data into the Crustal Motion Map, (2) the collection of geologic records of past fault system behavior, (3) the development of tectonic block models and other types of fault-system models for physics-based earthquake forecasting, and (4) the advancement of finite-element methods for assimilating the CMM and geologic data into a fault-system deformation model based on the CBM.

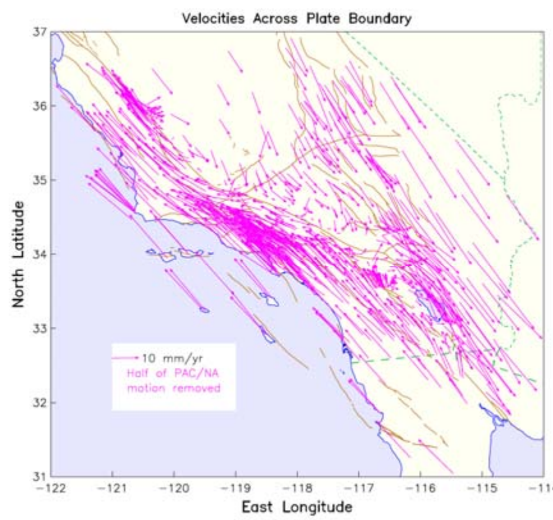


Fig. 2.10. The SCEC Crustal Motion Map, Version 3.0, which includes estimates of 833 horizontal velocities at 762 points in Southern California and northern Baja California, together with coseismic offsets for the Landers earthquake (at 353 locations), the Northridge earthquake (97 locations), and the Hector Mine earthquake (250 locations). The secular velocities were derived from EDM data between 1973 and 1991 and GPS data from 1986 through 2001; much care was taken to avoid contaminating them with post-earthquake transients.

Results. *Geodetic Measurements of Fault-System Deformation*. The most tangible accomplishment of SCEC's geodesy collaborations is the on-going Crustal Motion Map project (Fig. 2.10). Its third version, CMM-V3.0, was released in August 2003 (http://epicenter.usc.edu/cmm3)—the first to incorporate data from the 250-station Southern California Integrated GPS Network (SCIGN). This PBO prototype network was begun in 1995 and completed in 2001. Owing to SCIGN, the CMM-V3.0 sampling is much denser in Los Angeles, the Mojave Desert area, and San Diego County. The production of this model also required organizing, quality-checking, and processing thousands of survey-mode GPS data files from several dozen sources. When corrections for groundwater pumping and withdrawal (Bawden et al., 2001) are applied to the SCIGN data, the pattern of deformation from faults is concentrated about 20 km south of the San Gabriel mountains, consistent with strain loading on the Puente Hills and other blind thrust systems in the LA basin (Schneider et al., 1996; Shaw & Shearer, 1999; Oskin et al, 2000; J. Shaw et al. 2002; Dolan et al. 2003), an inference of considerable importance to seismic hazard analysis.

Deformations observed after the 1992 Landers and 1999 Hector Mine earthquakes have been intensively studied by a number of SCEC scientists, using both GPS and InSAR data. The latter have been made much more available through the SCEC-managed WInSAR archive. Postseismic motions are the outward and measurable sign of an internal redistribution of stress, which needs to be understood in order to improve our ability to forecast earthquakes through models of earthquake triggering. While the pattern of deformation is becoming clear, whether it is due to slow slip on the original rupture, fluid equilibration and poroelasticity, and/or linear and nonlinear rheologies in the crust and mantle is still unclear (e.g., Shen et al., 1994; Peltzer et al., 1998; Pollitz et al., 2001; Fialko, 2004; Freed & Bürgmann, 2004). Resolving the relative contributions of these mechanisms is an important SCEC objective.

Deformation data collected and analyzed by SCEC scientists have also revealed new and unexpected phenomena on earthquakes. The InSAR measurements of coseismic displacements from the Hector Mine earthquake showed a puzzling feature (Fig. 2.11): many faults in the area had small offsets, in some cases in a direction opposite to their long-term geologic motion (Fialko et al., 2002, 2004). Further analysis has shown a similar result for the Landers earthquake. The best explanation is that local deformation is enhanced because the shear modulus along the fault zone (out to widths of a kilometer) is as little as half that of the surrounding material, an inference similar to that from fault-zone trapped waves (Li et al., 2002). That this occurs on faults with relatively little total slip is surprising and potentially important for modeling fault slip and radiation.

The postseismic studies have shown the importance of good measurements of vertical motions—a difficult task for GPS, but now feasible through the SCIGN network. The next release of the CMM (V4), anticipated for 2006, will include vertical-motion estimates. Thanks to SCEC collaborations with groups in Northern California (M. Murray & colleagues) and Mexico (J. Gonzales & colleagues), CMM-V4 will also include estimated velocities for the entire state, providing a seamless map for all of Baja and Alta California. This product will be central to the model-building activities of the new SCEC-sponsored Working Group for California Earthquake Probabilities, described in §III.C.3.

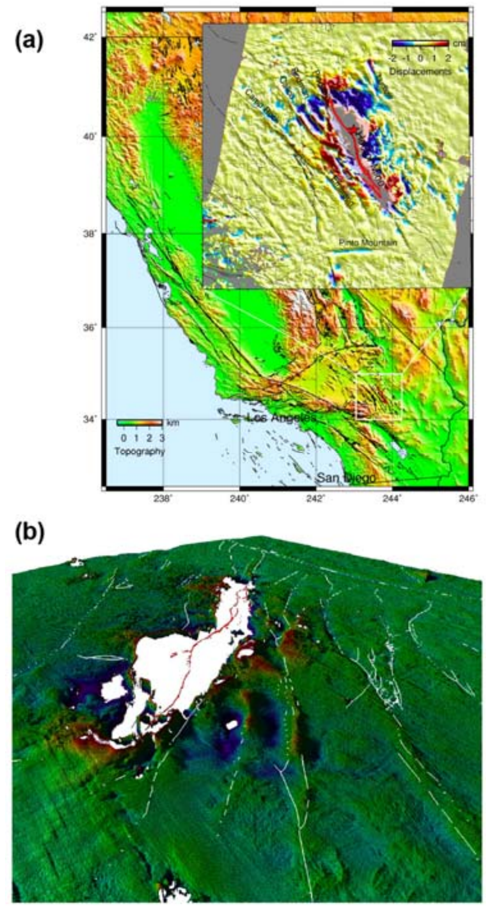


Fig. 2.11. Vertical-view **(a)** and oblique-view **(b)** maps of centimeter-scale displacements induced by the Hector Mine earthquake on nearby faults. Modeling of the anomalous fault zone displacements revealed by InSAR suggests significant (up to a factor of two) reduction in the effective rigidity of the fault zone material compared to the ambient "intact" crustal rocks, most likely result from extensive cracking and damage due to prior earthquakes (Fialko et al., 2002, 2004).

Geologic Records of Fault System Behavior. Investigations of long paleoseismic records are providing Center scientists with a real sense of variability of moment release. Analysis of the paleo-displacements along the San Andreas suggest that two distinctly different characteristic earthquakes overlap at Wrightwood (Weldon et al., 2004). Preliminary compilations of other data imply that pairs of faults or pairing of fault systems may alternate clustered earthquake activity in space and time. T. Rockwell, G. Seitz & T. Dawson have discovered potential prehistoric interactions between the San Andreas and San Jacinto faults. Paleoseismic trenching of the San Jacinto fault at Hog Lake, near Anza, has revealed no apparent surface ruptures for several centuries (400-900 C.E.) during a period of high earthquake activity on the San Andreas fault. Since 1000 C.E., the activity level at Hog Lake has increased, while that on the San Andreas fault at Wrightwood has decreased.

Subsidiary fault systems on both sides of the San Andreas also show evidence for anticorrelated strain release. T. Rockwell and his colleagues (Rockwell et al. 2000) have documented paleoseismic evidence for clustering in the Eastern California Shear Zone (ECSZ). Dolan et al. (submitted 2005) have generated probability distribution functions for paleoearthquakes in the Los Angeles area that indicate four major bursts of seismic activity over the past 12,000 years, separated by periods of relative seismic quiescence. Interestingly, the two subsystems have a similar periodicity, but they appear to be out of phase, motivating Sammis et al. (2003) to devise simple dynamic models to explain how this phase-locking might occur. Targeted fault slip rate investigations have shown convincing discrepancies between geodetic signals, paleoseismic moment release, and long-term fault slip rate, inviting the possibility that both fault loading and moment release can vary with time (Oskin & Iriondo, 2004).

The Earthquake Geology group has also been active in the construction of community databases, such as the CFM component of the USR, the FAD, and the new Geologic Vertical Motion Map. An important aspect of these SCEC2 efforts is the inclusion of alternative representations and reference frames, rather than simply building an expert consensus that masks geologic uncertainty. These community databases are just now beginning to see fruition for their intended use, which is to bring rich geologic data sets to the fault-system and earthquake modelers.

Tectonic Block Modeling. B. Hager & his collaborators (Meade & Hager, 2004, 2005a,b) have developed a tectonic block model (TBM) that inverts geodetic and geologic data to infer fault slip rates and locking depths (Fig. 2.12). Geodetic velocities are represented as a combination of block rotation and elastic strain accumulation on bounding fault segments, parameterized by their geometry and locking depths, with deep slip at rates determined by the relative motion between blocks. The increased detail of the models shows promise in identifying regions of high seismic deficit and, therefore, earthquake potential, as well as increasing understanding of the details of fault behavior. In the ECSZ, for instance, strain is now accumulating faster than it has been released on geologic time scales—perhaps the best documented among a series discrepancies that are being uncovered between geologic and geodetic estimates of slip rates.

InSAR observation indicate a large (3-7 mm/yr) localized displacement gradient across Blackwater fault in Mojave (Peltzer et al., 2001; Fialko et al., 2004), consistent with the GPS-based TBM but significantly larger than new geologic measurements of 0.5 mm/yr (Oskin & Iriondo, 2004). The locking depth inferred using classic elastic half-space model is surprisingly shallow, suggesting that a low-modulus fault zone (damage zone), like that hypothesized by Fialko for Hector Mine, results in steep displacement gradients.

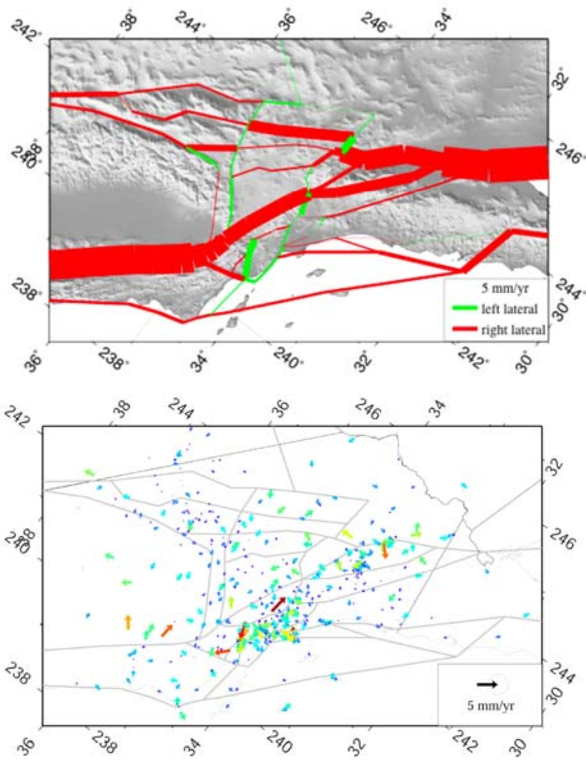


Fig. 2.12. Top: Estimated strike-slip rates from the Meade-Hager tectonic block model. Red and green lines indicate right- and left-lateral motion, respectively, with width proportional to slip rate. **Bottom:** Residual velocities (observed–model); largest residual velocities (hot colors) are usually atypical compared to nearby sites. Gray lines show block boundaries. 72% of the residuals are smaller than 1σ uncertainty estimates (error ellipse on scale arrow is typical).

The balance between elastic strain accumulation and release defines the extent to which a fault system exhibits a surplus or deficit of large earthquakes. The TBM results imply that the scalar moment accumulation rate is approximately 50% larger than the average moment release rate over the last 200 years. The differences indicate moment deficits localized in three regions: the Southern San Andreas and San Jacinto faults, offshore faults and the Los Angeles and Ventura basins, and the Eastern California shear zone. To balance the moment budget would require a distribution of earthquakes with a composite magnitude greater than 8.0 (Fig. 2.13).

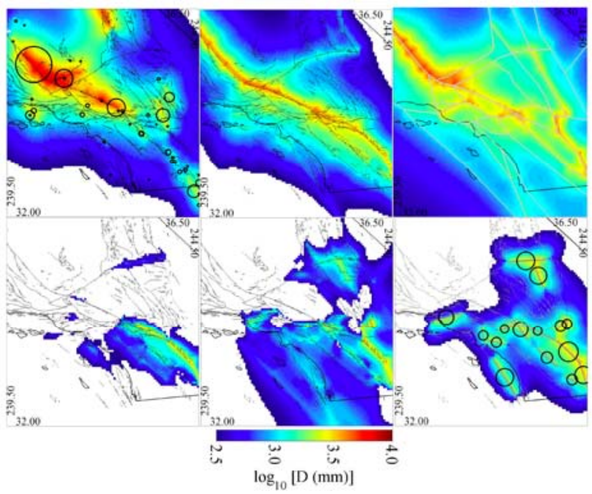


Fig. 2.13. Magnitudes of accumulated (calculated via backslip; i.e. relative to the block motions at depth) and released (via coseismic slip) elastic displacements in Southern California, based on the Meade-Hager TBM over the period of historic seismicity. (a) Earthquake displacements with historical earthquake epicenters and magnitudes. (b) Accumulated interseismic geologic displacements calculated using geologic estimates of fault slip rates. (c) Accumulated interseismic displacements using geodetic (block model) estimates of fault slip rates. (d) Differential geology-earthquake displacements. (e) Differential block model-earthquake displacements. (f) Model of deficit source displacements and locations of potential sources that would relieve the slip deficit. The radii of the circles are proportional to estimated moment magnitude, which ranges from 7.0 to 7.8.

Community Finite Element Models. Over the past three years, B. Hager, C. Gable & M. Simons have coordinated a SCEC crustal deformation modeling group to develop and validate 3D quasi-static, finite-element codes for modeling crustal deformation; develop deformation models of Southern California consistent with observed topography, fault geometries, rheological properties, geologic slip rates, geodetic motions, and earthquake histories; and use these models to infer fault slip, rheologic structure, and fault interactions through stress transfer. In order to leverage funding and take advantage of ongoing work, this effort has been carried out in coordination with several other modeling efforts—SERVO, GeoFEM, ACES—and it is now built into the new NSF-funded Computational Infrastructure for Geodynamics (http://www.geodynamics.org).

An essential part of our strategy for community building, as well as building software, is a series of workshops, three to date, which connect SCEC investigators with other groups. Two were hosted at Los Alamos National Laboratory and leveraged SCEC, NASA, and LANL support. Workshops have focused on assessing the accuracy, speed, and ability to modify software in use by members of the community, meshing of complex domains, solution methods well adapted to MPI environments, the definition of rigorous benchmarks, and discussion of Computational Frameworks including significant interchange of ideas and software with members of the NASA-sponsored SERVO QuakeSim group.

C. Williams has made substantial progress in morphing the old workhorse TECTON into a flexible modern software package—LithoMop. The interface for importing GOCAD TSURF format files into LaGriT mesh generation software has been improved and enhanced, which has allowed the group to build 3D tetrahedral FEMs of the Southern California fault system from the CBM, including geologic models of the northwestern Los Angeles basin and the larger Mojave block representation from the new CBM (see Fig. 3.2). This FEM capability will be the basis for the deformation modeling proposed for SCEC3.

5. *Earthquake Forecasting*

Improving earthquake forecasting methods and related studies of earthquake predictability are central to SCEC's mission. The key problem is to move from Poissonian (time-independent) probabilities into time-dependent formulations that can account for the state and history of the fault system. Progress has been made by the Working Group on California Earthquake Probabilities in Southern California (Jackson et al., 1995—the SCEC Phase II report) and in the San Francisco Bay Region (WGCEP, 2003). The main activity in SCEC2 has been the RELM project, directed by the Seismic Hazard Analysis focus group (N. Field, leader; D. Jackson, co-leader), although the themes of forecasting and prediction have also motivated collaborations spanning Geology, Seismology, Fault Systems, and ESP. As usual, the Center is striving towards a physics-based approach.

<ins>Goal and Objectives</ins>. The SCEC goal is to forecast earthquakes using physics-based models of fault interaction and earthquake triggering. The SCEC2 objectives are to (1) excavate the paleoseismic record in Southern California to constrain earthquake recurrence intervals, earthquake clustering, and earthquake mediated interactions among faults;

(2) use the seismicity data to map seismogenic structures and test models of earthquake triggering; (3) formulate regional earthquake likelihood models for use in seismic hazard analysis and earthquake predictability experiments; and (4) test the earthquake likelihood models using a rigorous methodology to evaluate prediction skill.

Results. *Paleoseismology*. The study of prehistoric earthquakes has become a major discipline of earthquake science over the last 15 years, developing its own special tools and methodologies. The SCEC program has contributed heavily to this accomplishment, and the payoff in terms of new information on earthquake behavior has been enormous.

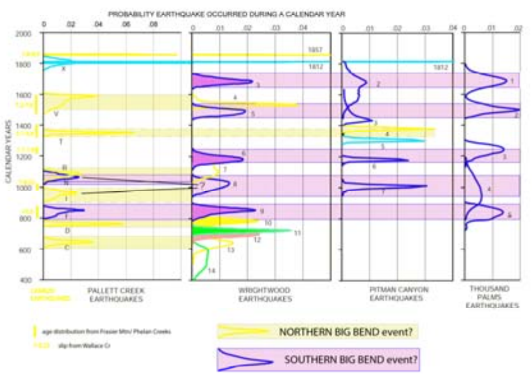


Fig. 2.14. Summary of paleoseismic results from Pallett Creek, Wrightwood, Pitman Canyon and Thousand Palms. For each site, probability density functions for the ages of earthquakes at that site are shown. The age constraints suggest possible correlation of some earthquake events between adjacent paleoseismic sites, but they are not definitive. Biasi et al. (2004) refined the correlation using a Bayesian method to incorporate earthquake scaling relations and observed slip distributions. The results suggest that most of the paleoseismic record can be explained by earthquakes that rupture either the northern or southern part of the Big Bend in the San Andreas fault.

The southern San Andreas—from Parkfield to Bombay Beach—is the master fault of the Southern California system and a special focus of the SCEC program. Efforts to date prehistoric earthquakes on the southern San Andreas fault began during SCEC1, with work at Cholame, Frazier Mountain, Plunge Creek and Burro Flats, supplemented by work at Wrightwood, Pitman Canyon and Thousand Palms funded through other programs. Many of the results were documented in a special issue of the *Bulletin of the Seismological Society of America* (Grant and Lettis, 2002).

A major effort in SCEC2 has been to derive models of the prehistoric ruptures by cross-correlating the paleoseismic results from several sites. The uncertainties in dating paleoevents are at least a few decades, and sometimes a century or more, so the along-fault extent of individual ruptures cannot be resolved by event ages alone; consequently, the current models are highly non-unique. G. Biasi, R. Weldon and T. Fumal have quantified the likelihood of rupture-sequence interpretations by carefully applying Bayesian inference methods to intersite correlations (Biasi et al. 2004; Biasi & Weldon, 2005). In particular, they have shown how site-specific displacement estimates (e.g., from 3D trenching) can be combined with the statistics of observed surface slip (e.g., Hemphill-Haley & Weldon, 1999) and slip-vs.-length scaling relations (e.g., Wells & Coppersmith, 1994) to constrain rupture-sequence models.

Such analyses indicate that the Wrightwood (near the southeastern end of the Mojave segment) and Pitman Canyon sites (near the northwestern end of the San Bernardino segment) have most often ruptured at the same time as the Thousand Palms site (on the Coachella Valley segment to the southeast), despite the complex fault geometry in the intervening San Gorgonio Pass (Fig. 2.14). On the other hand, the Wrightwood and Pitman Canyon sites have also occasionally ruptured at the same time as Pallett Creek (on the Mojave segment to the northwest). Only one event, around 800-900 C.E., is interpreted as rupturing all four sites (on the Mojave, San Bernardino and Coachella Valley segments) simultaneously.

Seismicity Studies. SCEC scientists are working to improve the 73-year SCSN catalog. Hauksson, Shearer & co-workers have assembled the *P* and *S* waveforms from 380,000 events digitally recorded since 1984 into an online database. For each station they have cross-correlated the waveform of an event with its 100 nearest neighbors, producing ~1 billion cross-correlagrams. A selected data set of 55 million differential times have been used to generate two new catalogs of Southern California seismicity, one based on the double-difference relocation method (Hauksson & Shearer, 2005) and the other on a cluster analysis that uses source-specific station terms (Shearer et al., 2005). SCEC has also supported F. Waldhauser to work with Shearer & Hauksson on intercomparisons that quantitatively evaluate the different relocation techniques.

The relocated catalogs create a more focused picture of the previously identified, spatially complex distributions of seismicity (Fig. 2.15). The depth distribution of the seismicity shows sudden changes across some of the major strike-slip faults, while regions of dip-slip faulting are often bound by dipping surfaces that are clearly defined by the deepest hypocenters. The major aftershock sequences such as 1992 Landers, 1994 Northridge, and 1999 Hector Mine form clusters, with distinct internal structures, illuminating secondary faults and a heterogeneous main fault rupture surface. Some of these alignments suggest that high angle cross-faults were activated by the mainshock. In general, there are a surprising number of conjugate faults at small scales that strike nearly perpendicular to the main seismicity trends.

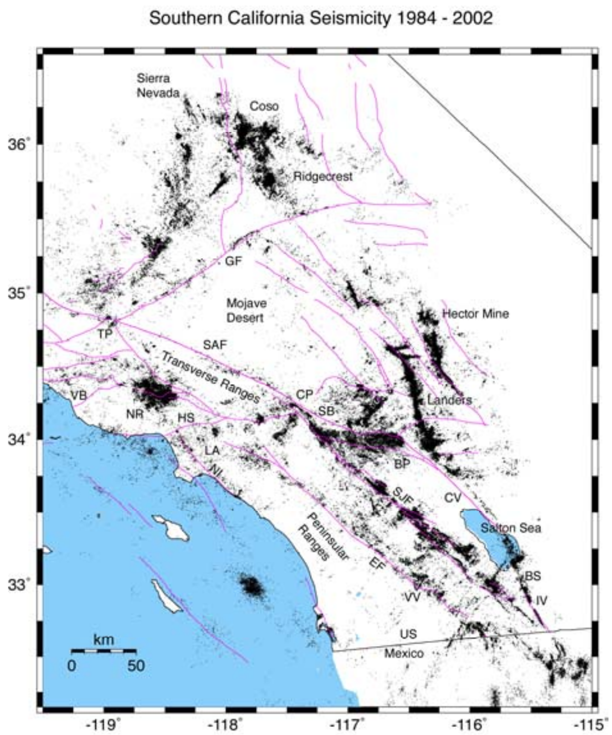


Fig. 2.15. Seismicity patterns from Hauksson & Shearer (2005) relocated catalog. BP – Banning Pass; BS – Brawley seismic zone; CP – Cajon Pass; CV – Coachella Valley; EF – Elsinore fault; GF – Garlock fault; HS – Hollywood-Santa Monica fault; IV – Imperial Valley; LA – Los Angeles; NI – Newport-Inglewood fault; NR – Northridge; SAF- San Andreas fault; SB – San Bernardino Mountains; SJF, San Jacinto fault; TP – Tejon Pass; VB – Ventura Basin; VV- Vallecitos Valley.

The relocated catalogs, which were released in 2004 and can be downloaded from SCEDC, have sharpened our picture of seismogenic structures throughout Southern California and the spatiotemporal relationships of earthquake clustering. Needless to say, they have been a special boon to the Structural Representation focus group in their efforts to improve the CFM and create the USR. The next objective in the SCSN data-mining project is to integrate cross-correlation methods into standard network processing and to derive new types of information from the waveform dataset, including t^* measurements and source spectra.

Much recent research has been done on point-processes models, such epidemic-type aftershock sequence (ETAS) models, which characterize earthquake triggering in term of Gutenberg-Richter (frequency-magnitude) and Omori (aftershock-decay) statistics, making no distinction among foreshocks, mainshock and aftershocks (Kagan and Knopoff, 1987, Ogata, 1988; Helmstetter & Sornette, 2002). Point-process models appear to describe the seismicity of Southern California and other active regions rather well (Helmstetter et al, 2003a,b,c; Felzer et al., 2003; Schorlemmer et al., 2005; Helmstetter et al., 2005a,b). Several earthquake prediction schemes based on point-process models are being tested under the RELM project, described below. Given these developments, there is considerable interest in understanding the relationship of subevents in the coseismic process to aftershocks. Kagan (2004) has recognized that extended coda cause many aftershocks to be missed in catalogs. His analysis suggests that Omori's law extends into the mainshock, which can be considered as a tightly clustered group of subevents with a fractal distribution. J. Vidale, G. Beroza and Shearer are processing the CISN coda records from intermediate-size events to test this hypothesis.

Table 2.1. Earthquake forecast and prediction models currently under development and testing by the RELM working group.

Field et al.	Review of previous Working Groups on California Earthquake Probabilites (WGCEPs)
Petersen et al.	The 2002 National Seismic Hazard Mapping Project (NSHMP) Model for California
Stirling et al.	The 2002 NSHMP Model with Time-Dependent Probabilities
Ward	Different Models Based on Geologic, Seismic, and Geodetic Constraints.
Jackson & Kagan	An Earthquake Rupture Forecast Based on Smoothed Seismicity
Shen & Jackson	An Earthquake Rupture Forecast Based on the Geodetic Strain-rate Field
Liu & Bird	A Time-Independent Forecast Based on NeoKinema
Wiemer, et al.	Asperity Based Likelihood Models (ALMs).
Bowman et al.	A Model that Incorporates Accelerating Moment Release and Coulomb Stress Change
Tiampo et al.	A Earthquake Forecast Based on Pattern Informatics
Gerstenberger et al.	Short-Term Earthquake Probability (STEP) model
Helmstetter et al.	Epidemic Type Aftershock Sequence (ETAS) model
Helmstetter & Dieterich	A Forecast Based on Observed Seismicity Rate Changes and Rate & State Friction
Sornette	The Multifractal Stress Activation Model (MSA)
Console, Murru & Catalli	Real Time Forecasts Through an Earthquake Clustering Model Constrained by the Rate-and-State Constitutive Law.
Ward	Standard Physical Earthquake Model for Southern California (simulation based model).
Rundle et al.	The Virtual California Earthquake Simulation Model

Regional Earthquake Likelihood Models. A joint SCEC/USGS working group on Regional Earthquake Likelihood Models—the RELM project—was established under the leadership of N. Field near the end of SCEC1 to develop a variety of viable earthquake rupture forecasts (ERFs). A total of 19 models are currently being implemented, including seismicity-based short-term forecasts, geodetically drive models, pattern recognition algorithms, stress interaction and rate-and-state models and purely numerical models, and papers on a number of these will be submitted for publication in a special volume of *Seismological Research Letters* during 2005 (Table 2.1).

Examples of the kinds of models that are being developed are illustrated in Fig. 3.6. The Short Term Earthquake Probabilities (STEP) model (Gerstenberger et al., 2004; Fig. 3.6a) predicts the probability of strong ground shaking for the next 24 hours based on simple statistical models of clustered seismicity. These forecasts, updated hourly, will become publically available on the USGS website starting in March, 2005. In many locations, the time-dependent contribution to earthquake hazard exceeds the stationary background 10-1000 fold. Surprisingly, these effects are long lasting; hazard "echoes" of large events can remain significant contributors years, sometimes decades, after the respective mainshock. Purely statistical models such as STEP and the closely related ETAS models (Helmstetter et al., 2005b; Fig. 3.5 & 3.6b) offer the requisite null hypothesis against which more sophisticated, physics-based forecast models can be tested.

An essential aspect of the RELM project is its testing program (RELM-T), which has set up rigorous procedures for *prospective* (rather than retrospective) evaluations of the RELM models. Two contests have been initiated, one for strongly time-dependent models, such as STEP and ETAS, which uses a 24-hr prediction window, evaluated daily, and a second for slowly evolving (quasi-stationary) models, which uses a five-year window, evaluated yearly. The performance of each model is measured with respect to the observed seismicity, as well as relative to all other models in the same contest, using a likelihood-ratio test (Schorlemmer et al., 2005). The statistical significance of the tests is established by computing a number of realizations of each model. To ensure truly prospective testing, modelers must implement a closed version of their code on a central testing computer and are allowed no further access to it. The code can access only authorized data sources, such as the CISN network catalog, and the evaluation procedures are time-lagged to allow testing against quality controlled data. Non-authorized data must be supplied before the forecast period. RELM-T is thus prototyping the kind of testing center that we propose to establish under SCEC3; this *Collaboratory for the Study of Earthquake Predictability* is discussed in §III.C.6.

6. Ground Motion Prediction

Reliable prediction of the expected ground motions is the main goal of seismic hazard analysis. Standard PSHA methodology relies on empirical attenuation relationships to account for event magnitude, fault geometry, path effects, and site response. SCEC research is directed at using physics to predict ground motions across the entire spectrum of interest to seismologists and engineers. The physics needs to account for rupture propagation along the fault, wave propagation through the crust, response of the surface rocks and soils, and response of the buildings embedded in those soils. SCEC2 researchers have made a start at coupling numerical models of these physical processes in "end-to-end" earthquake simulations.

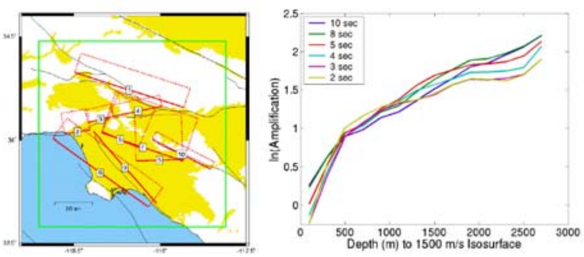


Fig. 2.16. Left panel is a map of Los Angeles showing 10 faults for which earthquake scenarios were computed by the 3D Basin Modeling Project. This on-line database comprises 96,000 three-component time histories (http://webwork.sdsc.edu:10081/sceclib/portal). Right panel shows 3D amplification factors as a function of basin depth (v_S = 1.5 km/s) derived from simulations for periods 2-10 s. Depth of 500 m is used as a rock site reference (Day et al., 2004).

Goal and Objectives. The SCEC goal is to predict the ground motions using physics-based methods that account for source complexity and 3D geologic structure. SCEC2 is striving towards five objectives: (1) Simulate low-frequency ground motions (< 1 Hz) using the CVM, realistic source models, and validated numerical codes; (2) Formulate stochastic methods for predicting high-frequency ground motions, and combine them with the low-frequency deterministic methods to attain a broadband (0-10 Hz) simulation capability. (3) Collect observations to test broadband ground motion predictions, including precarious-rock data and other geologic indicators of maximum shaking intensity. (4) Use observed ground motions to improve the CVM by refining its 3D wavespeed structure and by incorporating new parameters that account for the attenuation and scattering of broadband seismic energy. (5) Apply SCEC's ground-motion simulation capabilities to improving SHA intensity-measure relationships and creating realistic scenarios for potentially damaging earthquakes in Southern California. To achieve these objectives, the Ground Motion focus group (P. Davis, leader; R. Graves, co-leader) has been collaborating with the working groups in ESP, USR, and Seismology, as well as with SCEC's Implementation Interface, which engages earthquake engineers.

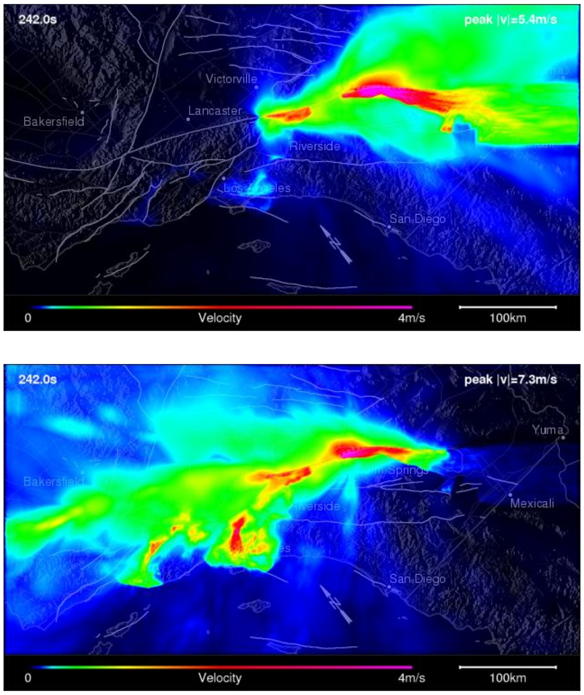


Fig. 2.17. Peak-velocity maps from the first TeraShake simulations (Minster et al., 2004) for two M 7.7 earthquake on the southern San Andreas fault, which differ only in their rupture propagation direction. In the top panel, the fault ruptures unilaterally from NW to SE; in the bottom panel, it propagates unilaterally from SE to NW. The kinematic source function was scaled from Chen Ji's model of the 2002 Denali earthquake. The directivity effects are striking, with substantial implications for seismic hazards in Southern California and northern Mexico.

Results. Because the wave physics of ground motions is largely linear—soil response to strong shaking is a notable exception—the simulation of dynamic ground motions is considerably more advanced than the simulation of fault ruptures, which involve some very nonlinear physics. In a collaborative study sponsored by SCEC and the PEER-Lifelines program, five groups of researchers participated in extensive testing of procedures for simulating ground motions in basins using 3D finite difference and 3D finite element methods (Day et al., 2002). Having eliminated virtually all discrepancies among the five simulation procedures, they then computed ground motion time histories at 1600 sites from six different earthquake rupture scenarios on ten faults in the Los Angeles region (Day et al., 2004). From this database, they developed relationships between ground motion amplification and the depth of the basin (Fig. 2.16). These amplification factors have been used in developing new attenuation relations in the NGA-E project (see §II.C.1).

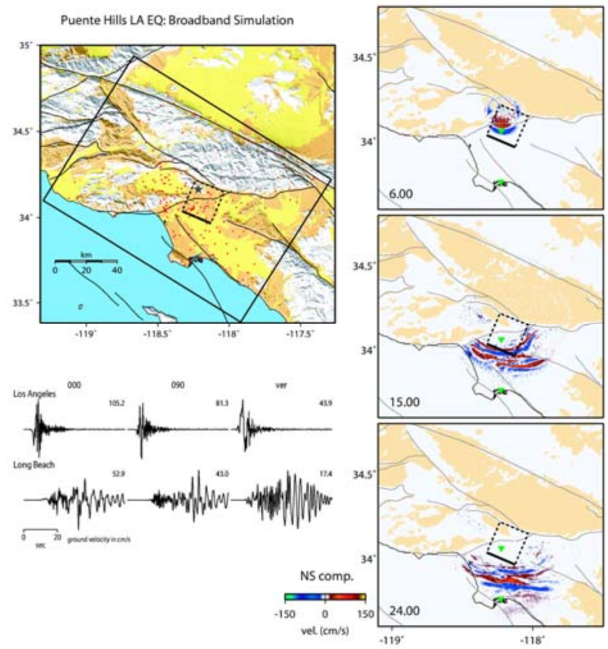


Fig. 2.18. Broadband (0-10 Hz) simulation for the Puente Hills fault. Three component ground motion time histories are obtained at over 66,000 locations covering most of the greater Los Angeles metropolitan region, parameterized in a 3D model with 400 million nodes. The panels at right show snapshots of the NS component of broadband ground velocity. Time (in seconds) after earthquake initiation is indicated at the lower left. The black rectangle indicates the surface projection of the fault plane. Green triangles denote locations for downtown Los Angeles and Long Beach for the broadband waveforms shown at left. Strong rupture directivity channels large amplitude pulses of motion directly into the Los Angeles basin, which then propagate southward as surface waves.

The southern San Andreas fault is one of the most hazardous in Southern California, last rupturing about 320 years ago (see Fig. 3.4). To evaluate the impact of such an event, simulations of a M 7.7 earthquake have been run at the San Diego Supercomputer Center as part of the CME Project (Minster et al., 2004). These simulations are unprecedented in scale (Fig. 2.17). Each computed 220 s of motion (22,000 time steps) in a 1.8-billion-node version of CVM-S3.0. To test file-handling and storage capabilities, the complete 4D output of the NW-SE rupture simulation—a 44-TB data volume comprising approximately 150,000 files—was archived in the SCEC Digital Library supported by the SDSC Storage Resource Broker. This large-scale simulation capability, which we have dubbed

"TeraShake," provides a platform for the future integration of dynamic rupture simulations in the computation of ground motion from anticipated earthquakes.

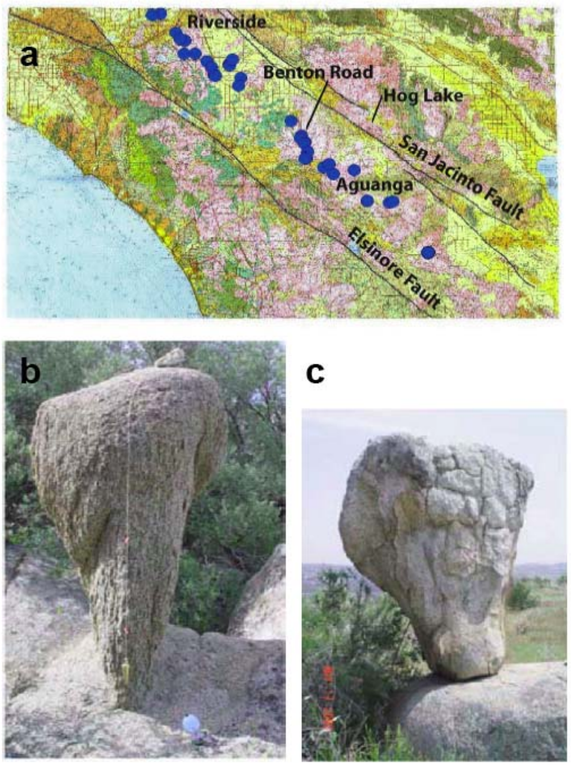


Fig. 2.19. (a) Geologic map showing locations of precariously balanced rocks between the San Jacinto and Elsinore faults. **(b)** & **(c)** Examples of precarious rocks found approximately halfway between Elsinore and San Jacinto faults.

The success of the deterministic low-frequency simulations provides the foundation for extending ground motion simulations to higher frequencies. The Puente Hills blind thrust has been the subject of particular scrutiny. This significant hazard to Los Angeles has been characterized only recently (Shaw & Shearer, 1999; J. Shaw et al., 2002; Dolan et al., 2003) and is one of the faulting scenarios in the basin simulations described earlier. R. Graves has recently simulated a Northridge-type rupture occurring on the Los Angeles segment of the Puente Hills system as a pilot study for computing broadband (0-10 Hz) ground motion (Fig. 2.18). These simulated ground motions are currently being used to analyze building response in a project on end-to-end simulation, sponsored in part by the SCEC Implementation Interface grant, which was jointly funded in 2004 by the CMS and EAR divisions of NSF.

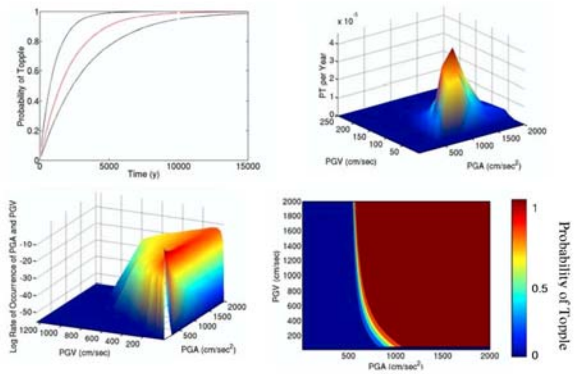


Fig. 2.20. Probability of toppling as a function of time (top left) from integration of the probability of toppling as a joint function of peak acceleration (PGA) and peak velocity (PGV) (top right); this function is obtained by convolution of the vector-valued hazard surface representing the joint frequency of exceedance of PGA and PGV (lower left), and the vector-valued fragility surface representing the probability of toppling of the rock as a function of PGA and PGV (Purvance et al., 2004).

One of the hallmarks of SCEC has been its support of innovative approaches to scientific research. A prime example of this is J. Brune's ongoing investigations of precariously balanced rocks (Brune, 2002; Stirling et al., 2002; Brune et al., 2004; Anooshehpoor et al., 2004). These studies have documented precarious rock sites along several major faults in Southern California, including the San Andreas, White Wolf, Elsinore, and San Jacinto. The Ground Motion focus group has been analyzing these data to help provide constraints on estimates of peak near-fault ground motions that have occurred during paleoearthquakes. Brune has recently found a number of such rocks (Fig. 2.19) along a 70-km line almost midway between the Elsinore and San Jacinto faults. T. Rockwell's paleoseismic studies indicate that these rocks have experienced about six M7 earthquakes every thousand years. Recent work by Purvance et al. (2004) has shown that rock toppling requires both an acceleration above some threshold (to start a rocking motion), and subsequent longer period motion (e.g., large peak velocity) near its rocking period. Such a joint occurrence of multiple ground motion intensity measures falls within the framework of vector-valued probabilistic seismic hazard analysis (VPSHA) (Bazzuro & Cornell, 2002). Thus, study of the precarious rocks has direct relevance to understanding the response of engineered structures such as tall buildings, which may have a significant contribution not only at its fundamental mode, but also its first higher mode. Purvance et al. (2004) have applied VPSHA to show that the presence of precariously balanced rocks between the

San Jacinto and Elsinore faults appears to be inconsistent with current empirical ground motion models (Fig. 2.20).

C. SCEC2 Accomplishments in Communication, Education & Outreach

The SCEC2 Communication, Education, and Outreach (CEO) program has been built on SCEC's 11-year experience as an NSF Science and Technology Center. A series of community planning workshops prior to SCEC2 developed four long-term CEO goals:

- Coordinate productive interactions among a diverse community of SCEC scientists and with partners in science, engineering, risk management, government, business, and education.
- Increase earthquake knowledge and science literacy at all educational levels, including students and the general public.
- Improve earthquake hazard and risk assessments.
- Promote earthquake preparedness, mitigation, and planning for response and recovery.

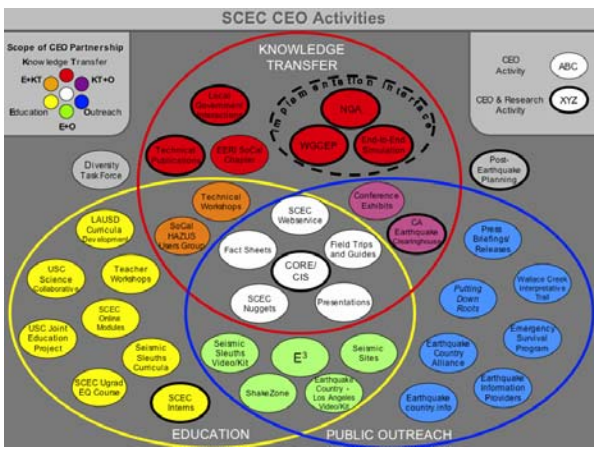


Fig. 2.21. SCEC CEO activities arrayed within the primary areas of knowledge transfer (red), education (yellow), and public outreach (blue). Many activities span two focus areas (orange, purple, and green) and some involve all three (white). Activities restricted to SCEC community development focus area ("inreach") are shown outside the three circles (gray), although all of the white activities and a number of the others also contribute substantially to development of the SCEC scientific community.

SCEC is moving towards these goals through a growing web of active partnerships with many other organizations (see Fig. 1.3 and the Supporting Letters) and an expanding array of activities in four CEO focus areas: *knowledge transfer*, *education*, *public outreach*, and *SCEC community development* (Fig. 2.21).

The list of activities is long and SCEC's organizational relationships are often complex, but we emphasize that the Center's resources, including its staff time, are carefully allocated through a prioritization process that maintains good alignment between the CEO and science objectives. For example, the yearly revisions to the CEO plan are articulated within the revised SCEC Science Plan, published each October, which solicits annual proposals from the SCEC Community; the proposals that respond to the CEO solicitation are evaluated along side the science proposals in the collaboration-building process managed by the Planning Committee. This mechanism involves scientists in setting and achieving the CEO objectives.

Here we briefly survey a selection of accomplishments in the four CEO focus area. A more comprehensive discussion can be found in the SCEC2 annual reports for 2002-2004, available on our website.

1. Implementation Interface

A goal of SCEC2 was to establish a closer working relationship with the earthquake engineering community that would be more effective in implementing physics-based hazard and risk analysis. We therefore established a new working group, the *SCEC Implementation Interface* (P. Somerville, leader; R. Wesson, co-leader), as a funded component of the Center's program to promote these partnerships. It coordinates activities with all other SCEC working groups, particularly the Seismic Hazard Analysis focus group (N. Field, leader; D. Jackson, co-leader), which is responsible for developing earthquake forecasting models (with the ESP and Fault Systems groups) and intensity-measure relationships (with the Ground Motions group).

Objectives. The objectives of the Implementation Interface are to (1) integrate physics-based seismic hazard analysis (SHA) developed by SCEC into earthquake engineering research and practice through two-way knowledge transfer and collaborative research, (2) provide a flexible computational framework for system-level hazard and risk analysis through the OpenSHA platform and the Community Modeling Environment, and (3) interface SCEC research with major initiatives in earthquake engineering, such as the Next Generation Attenuation project and the NSF-sponsored George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES).

Results. The first initiative was to set up a research partnership with the Pacific Earthquake Engineering Research (PEER) Center and its companion PEER-Lifelines Program. Several efforts were jointly funded by SCEC and PEER, including a large collaboration to study basin effects through wavefield modeling, led by S. Day (see Fig. 2.16), and a collaboration between A. Cornell and P. Somerville to develop vector-valued probabilistic seismic hazard analysis (VPSHA; Bazzuro & Cornell, 2002). The latter led to a novel application of VPSHA to the use of precariously balanced rocks in PSHA by Purvance et al. (2004) (see Fig. 2.20).

The partnership with PEER continues to develop through the Next Generation Attenuation (NGA) Project, a major collaboration involving SCEC, the PEER-Lifelines Program, and USGS, which has been sponsored by the California Department of Transportation, the California Energy Commission, and PG&E. In its current phase, NGA-E (for *empirical*), SCEC scientists have used validated broadband ground motion simulation techniques to investigate features of attenuation models poorly constrained by currently available strong motion data, including rupture directivity effects, footwall vs. hanging wall effects for dipping faults, depth of faulting effects (buried vs. surface rupture), static stress drop effects, and depth to basement and basin effects. SCEC work has involved the use of results from dynamic rupture models and foam experiments to shed light on the physics of rupture directivity and shallow/deep faulting effects on strong ground motion; the development of pseudodynamic models to facilitate the representation of the physics of these phenomena in earthquake source models; and kinematic ground-motion simulations of these effects using pseudodynamic source models to guide the development of functional forms of ground-motion models representing these effects. The new set of attenuation models produced by the NGA-E project will be finalized in Spring, 2005. These models will significant change hazard estimates at short distances from seismic sources and how such estimates depend on magnitude.

The activities of the Implementation Interface were broadened through a workshop held in October 2003, which identified end-to-end simulation from the earthquake source through to structural response ("rupture-to-rafters") as a key area for SCEC collaborations with the engineering community. This idea is the focus of a major SCEC3 initiative that will involve partnerships with PEER and CUREE (§III.C.5).

A collaboration between SCEC and the USGS has developed OpenSHA (Field et al., 2003), an open-source, object-oriented, web-enabled software integrated into the SCEC Community Modeling Environment that provides a very flexible platform for seismic hazard analysis. OpenSHA allows investigators to easily perform strong motion simulations and seismic hazard analyses, accounting for multiple earthquake potential models and multiple approaches to ground motion prediction, including physics-based simulation approaches as well as conventional attenuation relation approaches. The OpenSHA group has participated in the formal PSHA-validation exercises sponsored by the PEER-Lifelines Program, and the software is gaining wide acceptance as the platform-of-choice for PSHA calculations.

2. Knowledge Transfer

In addition to the research partnerships organized through the SCEC Implementation Interface, SCEC also engages practicing engineers, emergency managers, public officials, and other users of earthquake science, in wide range of knowledge transfer activities.

Objectives. SCEC2 Knowledge Transfer objectives are to (1) develop useful products and activities for practicing professionals, (2) support improved hazard and risk assessment by local government and private industry, and (3) promote effective mitigation techniques and seismic policies.

Results. *Landslide Report and Workshops*. In 1998, a committee of geotechnical engineers and engineering geologists was assembled by SCEC to develop specific slope stability analysis implementation procedures that could aid local Southern California city and county agencies in complying with the State's Seismic Hazard Mapping Act. The result was a detailed set of procedures for analyzing and mitigating landslide hazards in California that SCEC published in 2002. In June 2002 and again in February 2003, geotechnical engineers, government regulators and others attended SCEC workshops that explained the Landslide document and discussed its implementation. The course materials (still being ordered and used throughout California) include all PowerPoint presentations and two CDs with software tools and all presentations and printed materials. The CD also includes materials from the 1999 SCEC Liquefaction Hazards workshop.

HAZUS Activities. SCEC is coordinating the Southern California HAZUS Users Group (SoCalHUG) with the Federal Emergency Management Agency (FEMA) and the California Office of Emergency Services (OES). SoCalHUG brings together professionals from industry, government, universities, and other organizations to (a) train GIS professionals in using HAZUS, FEMA's earthquake loss-estimation software, (b) improve earthquake databases and inventories, and (c) develop and exercise emergency management protocols.

EERI Southern California Chapter. Since 2003, SCEC has hosted the bi-monthly meetings of the Southern California chapter of the Earthquake Engineering Research Institute (EERI). These meetings include a speaker on a particular topic of interest to the attendees, typically civil, structural, and geotechnical practicing engineers. In January 2005, for instance, 20 EERI members attended a briefing at SCEC on the recent Sumatran earthquake and Indian Ocean Tsunami.

3. Education

SCEC and its expanding network of education partners are committed to increasing earthquake knowledge and science literacy at all educational levels, especially K-12 and college-level education in Earth science. In addition to activities highlighted below, the CEO Program also is developing an undergraduate earthquake course with new visuals and online interactive modules, revising and developing standards-based earthquake curricula, supporting activities at the SCEC-developed *ShakeZone* museum exhibit, and working with the Los Angeles Unified School District on a sixth grade earth sciences unit which will include SCEC images and videos.

Objectives. SCEC2 Education objectives are to (1) interest, involve and retain students in earthquake science, (2) develop innovative earth-science educational resources, (3) offer effective professional development for K-12 educators.

Results. Each summer since 1994, the *Summer Undergraduate Research Experience* (SURE) has supported students to work one-on-one as student interns with scientists at SCEC institutions. This program has been effective in providing hands-on experiences for undergraduates, expanding student participation in the earth sciences and related disciplines, and encouraging students to consider careers in research and education, including women, members of underrepresented minorities, persons with disabilities, and students outside the earth sciences. SCEC/SURE has supported students to work on numerous issues including the history of earthquakes on faults, seismic velocity modeling, science education, and earthquake engineering.

Fig. 2.22. Left panel shows SCEC SURE and UseIT interns at the EarthScope San Andreas Fault Observatory at Depth (SAFOD) drill site in July, 2004. Right panel is a screen-shot from the LA3D visualization system developed by the UseIT interns, showing a distribution of focal mechanisms and CFM faults beneath a DEM surface.

The *Undergraduate Studies in Earthquake Information Technology* (USEIT) program, unites undergraduates from across the country in an NSF REU Site at USC. More than 40 students have participated since Summer 2002. The USEIT interns interact in a team-oriented research environment with some of the nation's most distinguished geoscience and computer science researchers. The program allows undergraduates to use advanced tools of information technology to solve important problems in earthquake research and engages them in the practical problems of reducing earthquake risk. It has been effective in cross-training undergraduates in computer science and geoscience. The USEIT interns have developed the "LA3D" visualization platform, an object-oriented, open source, and Internet-enabled system, which has become the platform-of-choice for researchers interested in visualizing the complex subsurface structure of Southern California.

The SCEC2 Intern programs have grown each year, and they are drawing a very diverse set of students into geoscience. Of the 75 SCEC2 interns (SURE and USEIT combined): 29 were female; 15 were Asian, 7 were Hispanic, 1 was African American, 1 was Middle Eastern, and 1 was Pacific Islander. Only 30 were white male. Of the 34 interns in 2004, 7 were first-generation college students and 6 were from schools without research opportunities (this is the first year this information was tracked). One student changed from an astrophysics major to a geology major, and two computer science undergraduates are now pursuing graduate degrees in geophysics. Through extensive recruitment activities in 2005 and beyond, we hope to improve our success in engaging well-qualified and diverse students from around the country.

Electronic Encyclopedia of Earthquakes (E3). SCEC has partnered with CUREE and IRIS to develop this digital library of educational resources and earthquake information as part of the NSF National Science Digital Library (NSDL) initiative (www.scec.org/e3). When complete, over 500 earth science and engineering topics will be included, with links to curricular materials useful for teaching and learning about each topic. E3 also is a platform for cross-training scientists and engineers and is a basis for sustained communication and resource building between major education and outreach activities. A sophisticated information system for building and displaying the E3 collection and web pages has been developed, now called the SCEC Community Organized Resource Environment (SCEC/CORE, see §V.C).

Teacher Workshops. SCEC has offered nine full-day workshops since 2002, involving over 180 K-12 teachers. The workshops include content and pedagogical instruction, ties to national and state science education standards, and materials teachers can take back to their classrooms. Activities include the Dynamic Plate Puzzle, Seismic Waves with Slinkys, Brick and Sandpaper Earthquake Machine, and a Shake Table Contest. At the end of the day teachers receive an assortment of free materials provided by IRIS, including posters, maps, books, slinkys, and the binders with all the lessons from the workshop included. Since 2003 SCEC has partnered with the SIO Visualization Center to offer teacher workshops that feature 3D animations.

USC Science Education Collaborative. Since 2003, SCEC has greatly increased its activities in the inner-city schools around USC via several partnerships, in order to improve science education and increase earthquake awareness. These partnerships include USC's *Joint Education Project (JEP)*, a program that sends USC students into schools to teach eight lessons related to what they are learning in their USC courses (SCEC has provide educational resources and training to over 300 JEP students in several earth-science courses) and the *Education Consortium of Central Los Angeles (ECCLA),* which supports mini-courses during year-round school intersession periods (SCEC revised an earthquake curriculum and arranged guest speakers and field trips for 4 courses, totaling 60 students).

4. *Public Outreach*

The Public Outreach focus area involves activities and products for the general public, civic and preparedness groups, and the news media, and has been a high priority during SCEC2. Much of 2003 was focused on planning activities and developing products for the 10-year anniversary of the Northridge earthquake in January 2004. These activities have continued into 2005 with product revisions and continued interactions with SCEC partners.

Objectives. SCEC2 Public Outreach objectives are to (1) provide useful general earthquake information, (2) develop information for the Spanish-speaking community, (3) facilitate effective media relations, and (4) promote SCEC activities.

Results. SCEC has established a new partnership, the *Earthquake Country Alliance* (ECA), that includes earthquake scientists and engineers, preparedness experts, news media, community leaders, and education specialists to present common messages and develop new public-outreach activities and products. The ECA first met in June 2003 to plan for the 10th anniversary of the 1994 Northridge earthquake, and it organized a series of activities during the anniversary month of January, 2004. SCEC created www.earthquakecountry.info to provide answers to frequently asked questions and descriptions of the resources and services provided by ECA members.

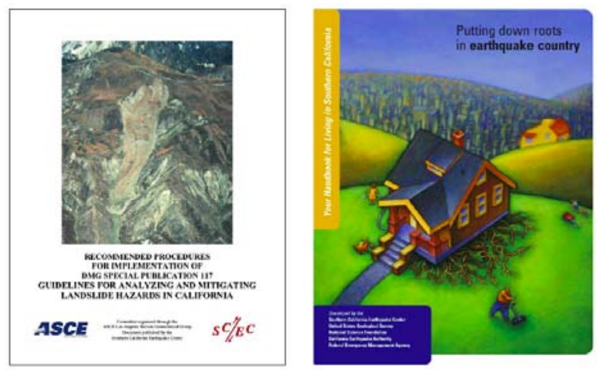


Fig. 2.23. Two popular SCEC publications. On left is Recommended procedures for Implementation of DMG Special Publication 117: Guidelines for Analyzing and Mitigating Landslide Hazards in California. On right is Putting Down Roots in Earthquake Country, a popular 32-page public information document produced by SCEC that will be published in Spanish as well as English and is being extended to other regions through a partnership with the USGS.

Putting Down Roots in Earthquake Country. For the 10-year anniversary of the Northridge earthquake, a new version of this colorful, 32-page handbook was produced by SCEC. The updated handbook features current understanding of when and where earthquakes will occur in Southern California, how the ground will shake as a result, and descriptions of what information will be available online. The preparedness section has been completely reorganized into the “Seven Steps on the Road to Earthquake Safety.” In January 2004, 200,000 copies of “Roots” were printed, with funding from the California Earthquake Authority (CEA) and FEMA, and another 150,000 copies were printed in September 2004, with funding from CEA, USGS, Edison, Amgen, Quakehold, and others. Copies of the document have been distributed at home improvement centers, by the American Red Cross, and by many others. In October 2004 over 15,000 copies were included in Earth Science Week packets distributed to science teachers nationwide. The handbook is online at www.earthquakecountry.info/roots.

Earthquake Country – Los Angeles. This video was produced by P. Abbott of SDSU as the second in his "Written in Stone" series. It tells the story of how the topography of the Los Angeles area formed, including the important role of earthquakes. The video features aerial photography, stunning computer animations (including LA3D fault visualizations created by the UseIT interns), and interviews with well-known experts. SCEC assisted in the development of the video, organized several focus groups with teachers and preparedness experts to provide evaluations, and developed curricular kits based on the video for school and community groups.

III. Science Plan

Accomplishments make the case that SCEC is advancing earthquake research through an interlocking web of collaborations ranging from small projects to community-wide programs. SCEC3 will build on these accomplishments. We will emphasize integrated system-level research because this approach offers the best route toward "a comprehensive, physics-based understanding of earthquake phenomena," which remains our mission and our scientific dream (Box 1.1). We will also focus on research that can deliver better physics-based techniques for forecasting earthquakes and predicting ground motions—thus improving our ability to predict seismic hazards in Southern California and elsewhere.

A. Basic Research Problems

SCEC is, first and foremost, a *basic research center*. We therefore articulate our work plan in terms of four basic science problems: (1) earthquake source physics, (2) fault system dynamics, (3) earthquake forecasting and predictability, and (4) ground motion prediction. These topics organize the most pressing issues of basic research and, taken together, provide an effective structure for stating the SCEC3 goals and objectives. In each area, we outline the problem, the principle five-year goal, and some specific objectives. We then assess the research activities and the new capabilities needed to attain our objectives. The Science Plan motivates some significant changes in the organization of the working groups, which will be discussed under each topic and summarized in the next section (§III.B). The research requirements also lead us to propose eight research initiatives, which are described in §III.C.

1. Earthquake Source Physics

Problem Statement. Earthquakes obey the laws of physics, but we don't yet know how. In particular, we understand only poorly the highly nonlinear physics of earthquake nucleation, propagation, and arrest, because we lack knowledge about how energy and matter interact in the extreme conditions of fault failure. A complete description would require the evolution of stress, displacement, and material properties throughout the failure process across all relevant scales, from microns and milliseconds to hundreds of kilometers and many years. A more focused aspect of this problem is the physical basis for connecting the behavior of large ruptures at spatial resolutions of hundreds of meters and fracture energies of megajoules per square meter with laboratory observations of friction at centimeter scales and fracture energies of kilojoules per square meter. Two further aspects are the problem of stress heterogeneity—the factors that create and maintain it over many earthquake cycles—and the related problem of defining the concept of strength in the context of stress and rheological heterogeneity.

Goal and Objectives. The goal for SCEC3 will be *to discover the physics of fault failure and dynamic rupture that will improve predictions of strong ground motions and the understanding of earthquake predictability*. This goal is directly aligned with our mission to develop physics-based seismic hazard analysis. Specific objectives include:

(1) Conduct laboratory experiments on frictional resistance relevant to high-speed coseismic slip on geometrically complex faults, including the effects of fluids and changes in normal stress, and incorporate the data into theoretical formulations of fault-zone rheology.
(2) Develop a full 3D model of fault-zone structure that includes the depth dependence of shear localization and damage zones, hydrologic and poroelastic properties, and the geometric complexities at fault branches, step-overs, and other along-strike and down-dip variations.
(3) Combine the laboratory, field-based, and theoretical results into effective friction laws for the numerical simulation of earthquake rupture, test them against seismological data, and extend the simulation methods to include fault complexities such as bends, step-overs, fault branches, and small-scale roughness.
(4) Develop statistical descriptions of stress and strength that account for slip heterogeneity during rupture, and investigate dynamic mod-

els that can maintain heterogeneity throughout many earthquake cycles.

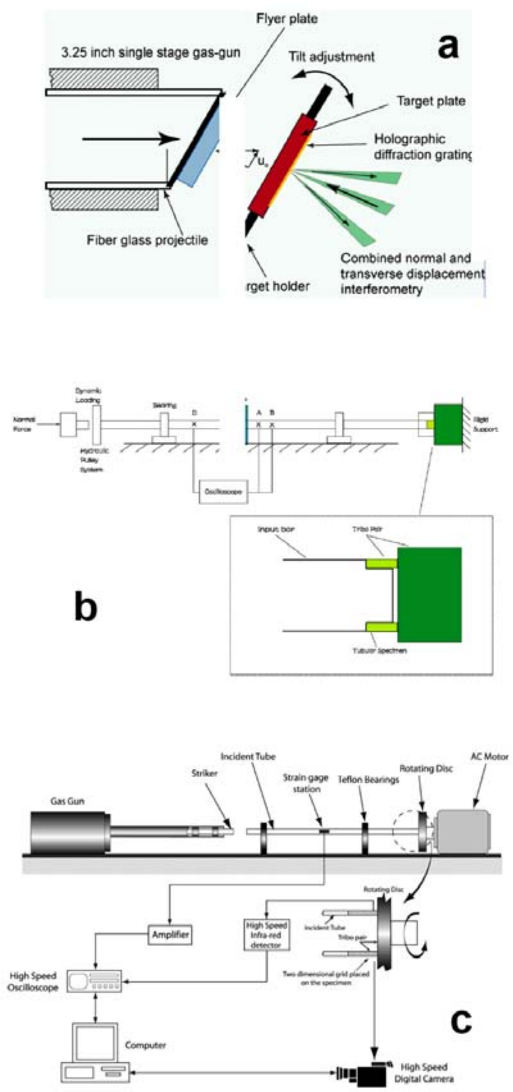


Fig. 3.1. Three experimental configurations being developed in SCEC2 that will be used in SCEC3 to study high-speed friction. **(a)** Plate impact pressure shear friction experiment. Normal stresses can range from 100 to 2000 MPa, slip speeds from 1 to 50 m/s, and slip up to 0.5 mm. **(b)** Torsional Kolsky bar friction experiment. Normal stresses can range from 1 to 100 MPa, slip speeds from 1 to 10 m/s, and slip up to 10 mm. **(c)** Modified split Hopkinson pressure bar experiment, currently under development to study high-speed friction. Stress, speed, and displacement capabilities are similar to the torsional Kolsky bar method, but control of speed is better, and abrupt changes in normal stress can be introduced.

Research Activities & Required Resources. SCEC2 is currently investigating these problems through two working groups, the Fault and Rock Mechanics (FARM) disciplinary committee and the Earthquake Source Physics (ESP) focus group. We propose to merge the FARM work on fault mechanics with the ESP research on rupture dynamics into a reconstituted focus group on Earthquake Source Physics. We also propose to merge the dynamic rupture simulation activities of the current ESP and the Ground Motion focus groups into a new focus group on Ground Motion Prediction, which we will describe in §III.A.4.

In SCEC2, we have made substantial investments in new experimental techniques for measuring coseismic frictional resistance (Fig. 3.1; see also §II.B.1), and the preliminary results look very promising (Fig. 2.2b,c). In SCEC3, we will apply these techniques to obtaining new data on several potential weakening mechanisms, including thermal pressurization of pore fluids, gel-lubrication, flash melting, and wholesale shear melting. A special effort will be made to understand wholesale shear melting through a combination of experimental measurements, theoretical work, and field observations. Available experimental evidence (Tsutsumi & Shimamoto, 1997) suggest that wholesale melting produces less weakening than flash melting, but the transition from flash melting to complete shear melting is poorly understood. The only unequivocal evidence that this process takes place during earthquakes on natural faults is the presence of pseudotachylytes, but the overall importance of wholesale melting in determining the shear resistance is debatable. In this regard, fieldwork needs to focus on faults exhumed from greater depths and on localities that show pseudotachylytes. In addition to the investigation of pseudotachylyte localities in Southern California (e.g. Santa Rosa mylonite zone), we plan to work with our international partners on deeply exhumed fault zones in other regions.

Laboratory experiments will continue to be funded primarily by other programs such as USGS/EHRP program and the NSF/Geophysics. However, the limited funding provided by SCEC has turned out to be critical as venture capital for developing new techniques, as an incentive to bring the participants into the SCEC collaboration, and as a mechanism for coordinating research. As an example of how SCEC will leverage its modest resources, we propose a project to compare the numerical results with observed dynamic rupture propagation in laboratory samples large enough to measure rupture propagation. This project, just now in its planning stage, is made possible by the reactivation of the unique large-sample apparatus at USGS-Menlo Park (Junger et al., 2004). Some data on rupture propagation has already been collected, but additional instrumentation of the rock sample will be needed in order to adequately characterize the rupture, and the numerical rupture codes will have to be modified to include rate- and state-dependent friction to adequately match the behavior of the rock sample.

SCEC scientists are only beginning to incorporate rate and state friction and substantial high-velocity weakening into dynamic rupture models (e.g., Lapusta and Rice, 2004a,b). So far this has been possible only for 2D modeling, but 3D modeling is clearly required, and this will depend on new algorithms on parallel computers currently under development. Documented computer codes with this capability will be delivered for use in the Community Modeling Environment during the first year of SCEC3, so that they can be used, understood, and improved by others.

The validation of 3D spontaneous rupture codes on simple problems has already given us confidence that at least in simple systems, our methods produce similar results (§II.B.2). However, because faults in nature are so complex, it is imperative that we continue to compare more complex faulting scenarios, especially more complex friction scenarios so that we may have confidence in our methods. It may be possible that certain methods lose their accuracy when symmetry or homogeneity are no longer present in the models, or when different constitutive laws are used. Continuing our code validation work will therefore be necessary.

Modeling in SCEC2 continues to elucidate the effects of fault geometry on rupture dynamics. We have already had success in modeling the effects of fault segmentation (see Fig. 2.6), and we are approaching an understanding of the generic effects of fault geometry (e.g., segment offset and orientation) on earthquakes (Kame et al., 2003; Fliss et al., 2005). However, our models are still quite idealized, and do not take into account the geometry of Southern California faults at the kilometer scale, which may be crucial for predicting the ability of rupture to transfer between fault segments. Furthermore, we have thus far neglected small-scale structure such as "fault topography" and roughness. It will also be important to understand the interaction between fault geometry and frictional complexity in producing the observed complexity of slip and rupture history in real earthquakes (Dieterich, 2004). SCEC3 will present us with opportunities to address these issues.

Earthquake simulations derived from field, laboratory and theoretical results require validation and testing against seismological and other data for actual earthquakes. Until recently, few strong-motion recordings have been available to study the near-source region where most models make their clearest predictions, and the observations available for individual earthquakes have been too sparse to provide much in the way of independent data against which to compare model predictions. The 1999 M 7.6 Chi Chi, Taiwan and 2004 M 6.0 Parkfield, California, earthquakes dramatically changed this picture, as each was captured by an extensive strong motion array that provides dense spatial sampling of the wavefield in the near-source region.

For example, the 2004 Parkfield earthquake was recorded at 8 sites within 1 km of the rupture and at 40 sites between 1 and 10 km from the rupture, nearly doubling the global data set of strong-motion records within those distances (Shakal et al, 2004). These records capture the wavefield in unprecedented detail and reveal large and rapid spatial variations in shaking amplitude. Explaining these large amplitude variations over distances of just a few kilometers exemplifies the challenges these new data sets pose for our understanding of earthquake rupture dynamics. The extensive instrumentation of Southern California faults achieved through TriNet, ANSS, and California Strong Motion Instrumentation Program will hopefully return similarly rich data sets for future strong earthquakes in the region.

In SCEC3, we also propose to model rupture dynamics over multiple earthquake cycles, including full inertial dynamics, the interseismic period, and rupture nucleation. This research effort is in its infancy; our 2D models are producing tantalizingly interesting results but we are just now reaching the computational power and still lack the model sophistication to go beyond general conclusions about the effect of long-term fault evolution on earthquake physics. The ESP and CDM focus groups will join forces to produce accurate models of the full earthquake cycle. With more accurate models of the interseismic period (including tectonic loading, relaxation, fluid effects, frictional heating, creep at depth, among other processes), we will produce much more accurate pre-stress fields for our dynamic models. Our dynamic rupture models will likewise produce much more accurate initial conditions for models of the interseismic period, including the effects of geometrically- and dynamically-induced stress complexity.

In terms of field studies, a main focus of SCEC3 will be to extend the widely used damage-zone/fault-core model (Fig. 2.4) to develop a truly 3D model of fault-zone structure. Such a model will need to include geometric complexity at fault branches and step-overs, as well as define damage-zone characteristics for rupture propagation models. Contrasting observations of broad zones of distributed pulverization (Tejon Pass surface exposure of the SAF) with localized slip in a zoned core-damage structure (Punchbowl exposure) will be need to be reconciled. Research will be needed to determine the depth dependence of damage zones and whether the deformation is caused by dynamic or quasi-static effects, or both. A 3D model also must incorporate changes in fault zone structure with depth, particularly the structure at the base of seismogenic zone, about which we now know very little. To this end, studies of exhumed faults need to focus on greater exhumation depths and on localities that show pseudotachylytes. Generally speaking, the structural investigations will be guided by the question of whether variations in structure and properties along strike (localized slip versus distributed crush zones, branches and steps, permeability) correlate with earthquake rupture characteristics (e.g., moment release, rupture propagation velocity, creep), and they will be directed toward providing the information needed for up-scaling laboratory results. We especially need more field-based data on the hydrologic and poroelastic properties of each domain within a fault zone.

In this regard, and indeed on all aspects of fault-zone structure, we will work closely with the SAFOD element of EarthScope. The proposed SCEC program will highly leverage SAFOD results to build physics-based models of fault-zone mechanics and rupture dynamics. Hence, this component of the SCEC program—and most others as well—will directly support EarthScope science.

2. Fault System Dynamics

Problem Statement. In principle, the Southern California fault system can be modeled as a dynamic system[5] with a state vector **S** and an evolution law d**S**/d*t* = **F**(**S**). The state vector represents the stress, displacement, and rheology/property fields of the seismogenic layer as well as its boundary conditions. Its evolution equation describes the *forward problem* of fault dynamics. Many of the most difficult (and interesting) research issues concern two inference or *inverse problems*: (1) model building—from our knowledge of fault physics, what are the best representations of **S** and **F**?—and (2) data assimilation—how are the parameters of these representations constrained by the data *D* on the system's present state $\mathbf{S}_0$ as well as its history?

The SCEC approach is *not* to proceed by trying to write down general forms of **S** and its rate-of-change **F**. Rather, we use judicious approximations to separate the system evolution into a series of numerical simulations representing the interseismic, preseismic, coseismic, and postseismic behaviors. In particular, the natural time-scale separation between inertial and non-inertial dynamics usually allows us to decouple the long-term evolution of the state vector from its short-term, coseismic behavior. Therefore, in describing many interseismic and postseismic processes, we can treat the fault system quasi-statically, with discontinuous jumps in **S** at the times of earthquakes. On the other hand, the dynamics of earthquake rupture is clearly important to the basic physics of fault system evolution. In the modeling of stress heterogeneity, for example, the coupling of inertial and non-inertial dynamics must be addressed by integrating across this scale gap.

Goal and Objectives. The principal SCEC3 goal for fault system dynamics is *to develop representations of the postseismic and interseismic evolution of stress, strain, and rheology that can predict fault system behaviors within the Southern California Natural Laboratory*. The SCEC3 objectives are sixfold:

(1) Use the community modeling tools and components developed in SCEC2 to build a 3D dynamic model that is faithful to the existing data on the Southern California fault system, and test the model by collecting new data and by predicting its future behavior.
(2) Develop and apply models of coseismic fault slip and seismicity in fault systems to simulate the evolution of stress, deformation, fault slip, and earthquake interactions in Southern California.
(3) Gather and synthesize geologic data on the temporal and spatial character and evolution of the Southern California fault system in terms of both seismogenic fault structure and behavior at geologic time scales.
(4) Constrain the evolving architecture of the seismogenic zone and its boundary conditions by understanding the architecture and dynamics of the lithosphere involved in the plate-boundary deformation.
(5) Broaden the understanding of fault systems in general by comparing SCEC results with integrative studies of other fault systems around the world.
(6) Apply the fault system models to the problems of earthquake forecasting and predictability.

Research Activities & Required Resources. Many of the tools and components needed to set up the

[5] *Dynamic* in the sense of being fully specified by **S** and **F** (e.g., Arnold & Avez, 1984), but not necessarily involving inertial forces. A dynamic model of a fault system must involve the force (stress) field and material-property (rheology) field, compared with *kinematic* models, which only involve the displacement field.

forward and inverse problems of fault system dynamics have been assembled in SCEC2 (see §II.B). The Community Finite Element Model (CFEM) provides a flexible platform for representing the state vector and solving the forward problem for a range of geometries and rheologies; the Community Block Model (CBM) represents the subsurface geometry of the system; the Crustal Motion Map (CMM) summarizes the geodetic constraints, and Fault Activity Database (FAD) contains many of the geologic constraints on the Holocene part of the fault system history. The job for SCEC3 is to put these components together in a fault system model, and then to iterate the model through several cycles of model prediction, data gathering and analysis, hypothesis testing, and model improvement.

How to make this inference process actually work was considered in the Crustal Deformation Modeling (CDM) workshops in 2003 and 2004. The participants recommended an interdisciplinary program focused on five main applications of the new CDM toolkit (http://geoweb.mit.edu/fe): (1) understand the response of the fault system to single earthquakes, and make geodetic comparisons, infer rheology, and constrain structures; (2) simulate fault system interactions, regional strain and stress field evolution, and produce results that assist in the estimation or modeling of fault slip and constraining earthquake physics; (3) understand transient stress interactions among faults; and (4) make predictions of geologic features for observational testing (e.g., topography, fault slip). We therefore propose to replace the current Fault Systems group with a new Crustal Deformation Modeling (CDM) focus group, which will sponsor SCEC3 activities on these five research tasks in partnership with CIG and other modeling efforts such as SERVO and GeoFEM. Finite element models derived from the CBM will be an important component of this modeling effort (Fig. 3.2).

The CDM and ESP focus groups will work together to refine representations of fault system rheology, both within active fault zones and the tectonic blocks defined by the major faults. A number of important questions regarding the appropriate macroscopic rheology can be addressed by combining geodetic and geologic observations with fault system modeling: How do the damage zones inferred from InSAR and seismic studies affect geologic estimates of slip rates? How does the localization of deformation depend on the amount of slip on fault zones? Is the discrepancy between geologic and geodetic inferences of fault slip rate (e.g., in the Mojave region of the ECSZ) the result of breakdown of classic paleoseismic techniques (e.g., geologic displacement occurs across damage zones and is not localized on easily recognized fault traces) or is it the result of the breakdown of the classic (elastic halfspace) method of inferring fault slip rates from geodesy? The CDM group will work with the Tectonic Geodesy and Earthquake Geology groups to answer these questions.

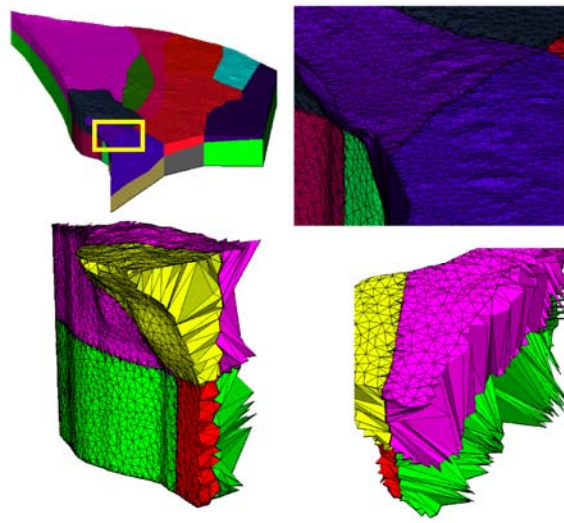


Fig. 3.2. Tetrahedral mesh generated for the Mojave region of the Community Block Model The Mojave region is shown in the upper left; the upper right panel shows an enlarged view of the region in the yellow box. The bottom two panels show detail in regions of geometric complexity in interior regions. The extension of this mesh to the entire CBM will be used for finite-element modeling of Southern California deformation.

Earthquakes are a manifestation of fault system dynamics that lies at the focus of the SCEC3 research. Earthquake occurrence in the context of fault system dynamics involves processes not fully addressed by, but touching upon, the research described under Earthquake Source Physics. These include rupture propagation on geometrically complex faults, and the stress conditions controlling the final size propagating ruptures. Because coseismic slip largely determines stress evolution, models of fault system dynamics and physics-based earthquake simulators must examine and model the earthquake interactions over a wide range of magnitudes through many major earthquake cycles—a task that is not feasible using detailed simulations that represent the full inertial dynamics of earthquake rupture processes. Quasi-static approximations of earthquake rupture will be necessary. Hence, this research will be closely coordinated with the ESP research, to insure intelligent quasi-static approximations are used that incorporate results from the more complete source models. SCEC is good at this type of coordinated cross-disciplinary research.

Another aspect of earthquake occurrence and stress evolution in fault systems arises in the context of "off-fault" seismicity—earthquakes that occur in areas where faults are not recognized. Because faults systems have fractal-like geometry, no finite-scale model can represent all the faults that participate in the fault system deformation. Slip on non-planar and geometrically complex faults leads to stress buildup in regions adjacent to faults that must be accommodated by bulk yielding or faulting below the scale of model resolution. Several approaches to address the off-fault processes in models will be explored. These include the direct expedient of using visco-elastic or elasto-plastic rheologies to limit off-fault stresses. More detailed and explicit approaches are be based on the use of damage mechanics to represent the breakdown and failure in regions of stress buildup, and the use of constitutive formulations for the dependence of seismicity on stressing history (Dieterich, 1994) to represent off fault earthquakes and release of built-up strain.

Interdisciplinary research will continue on the refinement of the fault and block geometry in the USR, which will form the structural basis for much of the CDM and ESP research. Further improvements in fault geometry can be expected from detailed studies of the seismicity relocated using double-difference techniques and 3D velocity models (Hauksson et al., 2004; Shearer et al., 2004; see Fig. 2.15), as well as from studies of the source characteristics of small earthquakes. For example, Chen et al. (2004) have recently shown that finite-source inversions of the low-frequency ($\leq$ 0.5 Hz) data can be used to automatically resolve the fault-plane ambiguity for events as small as M 3.3, and they have produced dislocation source models for more than 30 small events in the Los Angeles region. This new catalog of fault-plane data shows interesting features, such as a NE-trending distribution of left-lateral earthquakes from the Puente Hills to Fontana, perhaps indicative of nascent faulting associated with escape tectonics south of the San Gabriel mountains.

Any attempt to build a 3D model that captures the behavior of the Southern California fault system requires reliable constraints on constitutive properties, such as fault geometry and lithologic characteristics, and dynamic behavior as represented at geologic time scales by fault slip rates, timing and extent of past ruptures, permanent off-fault strain, and both vertical and horizontal displacement. Several major gaps exist in our current knowledge. For example, despite its seismogenic potential, the slip history of the southern San Andreas Fault is poorly known at present and will be one focus of our paleoseismic and neotectonic efforts. These issues, which will be a focus of the Earthquake Geology group, are further discussed in §III.A.3 and in the presentation of the Southern San Andreas Fault initiative in §III.C.2. Another will be the actual surface complexity of Southern California fault zones, particularly at step-overs, bends, and fault junctions, which is only documented in detail at a limited number of sites (e.g., Sowers et al., 1994). As a supplement to the large-scale structures represented in the USR, we propose to expand this database with a focus on the 10^1-10^4 m scales at major fault intersections and steps.

At the other end of the scale range, the present-day geometry and lithologic characteristics of major faults and large fault-bounded blocks are clearly important controls on how stress is transformed into ruptures. Previous SCEC-driven projects, such as the Los Angeles Regional Seismic Experiment (LARSE), have revealed lithospheric anomalies, including deep structures under the Peninsular Ranges, seismic "bright spots" apparently associated with fluids, and Moho thickening that is offset from the mountainous topography, all of which feed into our fault block model (Fuis et al., 2001, 2003). This geometry and character, as well as the evolution of the stress field, result from the geologic evolution of Southern California. Our goal is to investigate aspects of this history that provide the controls on fault geometry, lithologic character, and stress history.

These geologic and geophysical studies cannot be confined to the seismogenic layer alone. In SCEC3, we will broaden our investigations to include the entire lithosphere involved in plate-boundary deformation. Fault system dynamics may be tightly coupled to lithospheric dynamics. A classic example is the "lithospheric drip" beneath the Transverse Ranges that may drive the compressional deformation in the vicinity of the Big Bend (Houseman et al., 2000; Billen & Houseman, 2004). Under this interpretation, the convergence driven by mantle flow is responsible the geometry of the San Andreas, rather than the other way around. Knowing how such forces act on the seismogenic layer is a key problem of fault system dynamics. Moreover, the history of the lithosphere has determined the present-day architecture of the fault system, including its compositional state. The distribution within and below the seismogenic zone of hydrated subduction-derived rocks may play an important role in the geometry of the tectonic blocks and their boundary conditions, such as decollément structures imaged by the LARSE experiments (Fuis et al., 2001), as well as in governing salient aspects of earthquake behavior (Hauksson et al., 2004). Inferences regarding crustal composition from plate-tectonic reconstructions are an

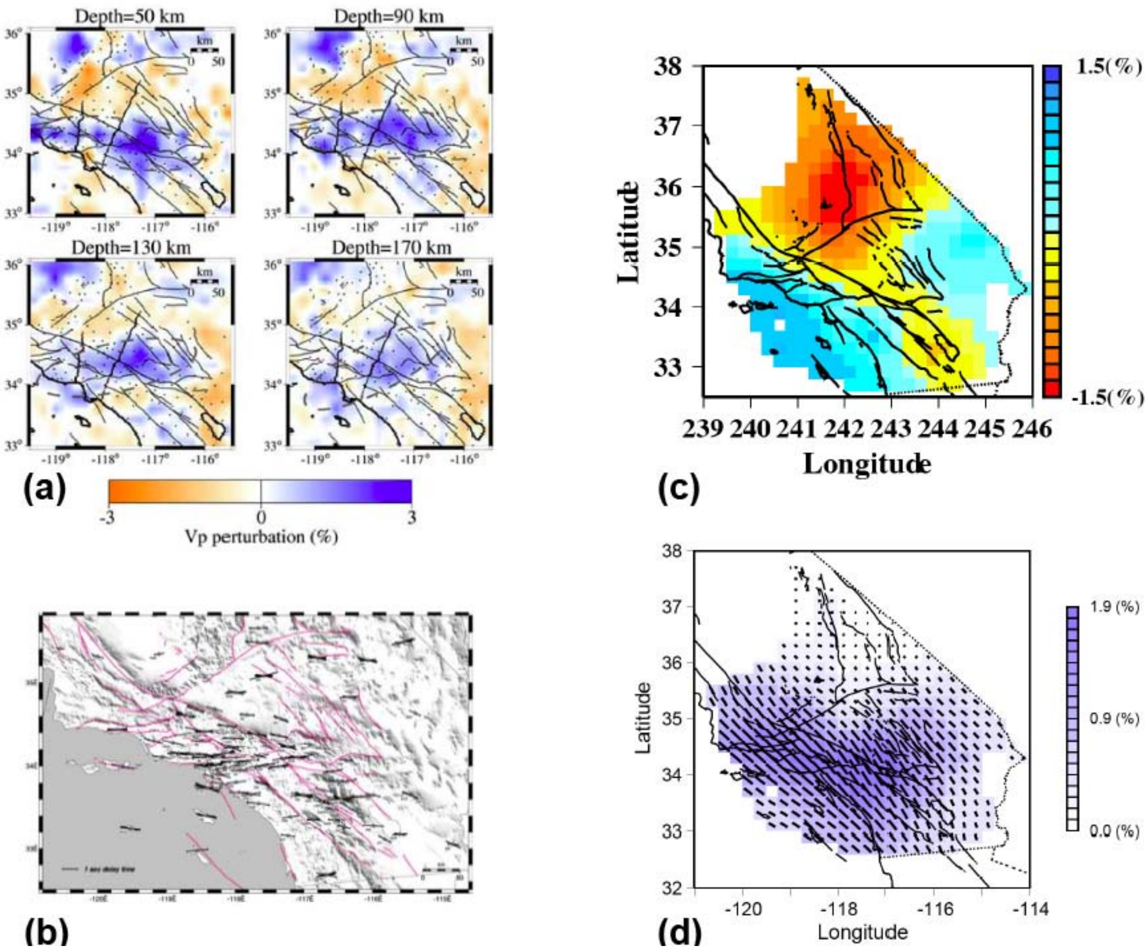


Fig. 3.3. Some recent results on the structure of the lithosphere in Southern California that illustrate issues to be considered by the LAD focus group in SCEC3. **(a)** Anomalies in compressional velocities from teleseismic tomography (Kohler et al., 2003). **(b)** Splitting directions from *SKS* waves (Polet and Kanamori, 2002). **(c)** Phase-velocity map for 30-mHz Rayleigh waves (Tanimoto, 2004), and **(d)** azimuthal anisotropy map for 40-mHz Rayleigh waves (Prindle and Tanimoto 2005). In (a), the high-velocity "mantle drip" structure beneath the Transverse Ranges rotates clockwise with depth ; is this due to a change in Big Bend structure with time or a change in mantle flow with depth? How can the geometry of the drip be reconciled with the sharp change in upper mantle shear velocity across the San Andreas, as indicated by (c)? What explains the discrepancy in the direction of mantle azimuthal anisotropy seen with body waves (c) and surface waves (d)?

important supplement to the information on crustal structure from seismic imaging.

For these reasons, lithospheric-scale studies were explicitly built into the SCEC2 Science Plan, and significant new results have been obtained from SCEC-sponsored projects (Fig. 3.3). However, we now perceive new opportunities for an expansion of these efforts, primarily through the EarthScope program. To promote the study of the crustal structure, lithospheric dynamics, and lithosphere-asthenosphere interactions that may be important for fault system dynamics, we will form a new focus group on Lithospheric Architecture and Dynamics (LAD) within SCEC3. The LAD goal will be to understand how the Southern California lithosphere accommodates the stress and deformation driven by Pacific-North America plate motions and underlying asthenospheric flow on time scales of 10^4 years and greater.

3. *Earthquake Forecasting and Predictability*

Problem Statement. The problems considered by SCEC3 in this important area of research will primarily concern the physical basis for earthquake predictability. Forecasting earthquakes in the long term at low probability rates and densities—the most difficult scientific problem in seismic hazard analysis—is closely related to the more controversial problem of high-likelihood predictions on short (hours to weeks) and intermediate (months to years) time scales. Both require a probabilistic characterization in terms of space, time, and magnitude; both depend on the state of the fault system (conditional on its history) at the time of the forecast/prediction; and, to put them on a proper science footing, both need to be based in earthquake physics.

Goal and Objectives. The SCEC3 goal is *to improve earthquake forecasts by understanding the physical basis for earthquake predictability*. Specific objectives are to:

(1) Conduct paleoseismic research on the southern San Andreas and other major faults with emphasis on reconstructing the slip distributions of prehistoric earthquakes, and explore the implications of these data for behavior of the earthquake cycle and time-dependent earthquake forecasting.
(2) Investigate stress-mediated fault interactions and earthquake triggering and incorporate the findings into time-dependent forecasts for Southern California.
(3) Establish a controlled environment for the rigorous registration and evaluation of earthquake predictability experiments that includes intercomparisons to evaluate prediction skill.
(4) Conduct prediction experiments to gain a physical understanding of earthquake predictability on time scales relevant to seismic hazards.

Research Activities & Required Resources. Earthquake rupture forecasting has moved beyond a Poissonian future into increasingly sophisticated forecasts that try to account for the state of the system as defined by its history. A partnership is being constituted among SCEC, USGS, and CGS to develop a uniform California earthquake rupture forecast (UCERF) based on a time-dependent methodology that incorporates statewide geodetic data and geologic constraints. As described in §III.C.3, the new WGCEP initiative will sponsor research that contributes directly to objectives (1) and (2).

Paleoseismology will provide key data for developing a better time-dependent earthquake forecast for California, and the basic research needed to improve these data will be one aspect of the SCEC3 effort. Most past paleoseismic studies have focused on reconstruction of the timing of past events, but have often failed to define the slip per event. Consequently, a paucity of well-constrained slip rates limits development of a reliable framework for defining the temporal evolution of strain. Fig. 3.4 shows three rupture-sequence interpretations by R. Weldon, G. Biasi and colleagues consistent with the paleoseismic data. The seismic hazard implications for each model are quite different. To reduce the epistemic uncertainties, we need better data and interpretation tools.

We propose to address this gap through both geomorphic studies of long-term slip rates (10^3-10^5 yr), as well as trenching that investigates paleoseismic events during the past 2000 years. A major component of this effort will be the southern San Andreas fault initiative, described in §III.C.2. We plan to push the methodological analysis of paleoseismic data to new standards that will underpin more robust interpretations of geologic data. In particular, through collaborations "in the trenches" and in subsequent data analysis, we propose to develop shared approaches and resources for slip and event interpretations, for placing improved limits on timing of events and correlations within and among sites, and for defining strain across fault zones. Recent paleoseismic data suggest that clustering of earthquakes and spatially alternating displacement rates have characterized Holocene faulting in the Mojave and Los Angeles areas (see §II.B.4). Similar analysis needs to be extended to nearby fault zones in other parts of the Southern California fault system. Do the subparallel San Jacinto and southern San Andreas faults also show trade-offs in events, slip partitioning, and rates? Do blind thrust faults associated with the Big Bend show clustering behavior?

These observational questions are closely connected to the problem of stress-mediated fault interaction, which has been a major research issue for the SCEC community since the 1992 Landers earthquake sequence (Harris & Simpson, 1992; King et al., 1994; Harris, 1998). Progress continues to be made in developing fault interaction models based on quasi-static and dynamic stress changes following large earthquakes (e.g., Harris & Day, 1993; Gomberg et al., 2003; Kilb, 2003; Freed, 2005). However, the degree to which earthquake-induced stress changes control seismicity is still being debated (Felzer & Brodsky, 2005; Toda et al., 2005), and research remains to be done on the implementation of stress-interaction models in time-dependent forecasting (Parsons, 2002; WGCEP, 2003; Hardebeck, 2004). The new WGCEP will provide both a driver and a forum for this work in SCEC3. The problem of how earthquake-induced stress changes affect the long-term stress evolution will also be addressed by the CDM focus group using the fault-system models described in the previous section.

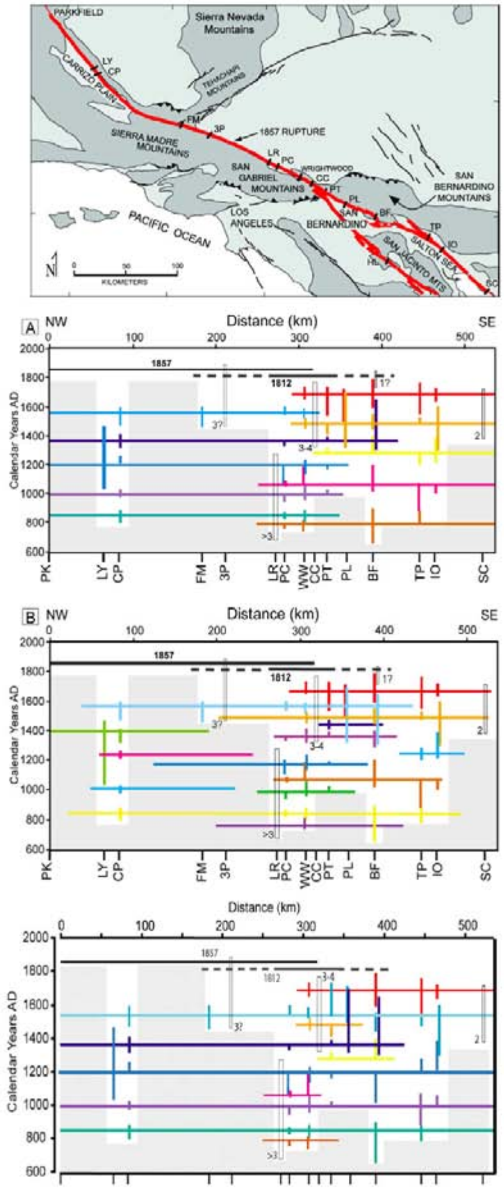


Fig. 3.4. (A) Paleoseismic sites on the San Andreas and San Jacinto faults in Southern California. **(B-D)** Three possible rupture sequences on the southern San Andreas fault consistent with the paleoseismic data. Vertical colored bars are age ranges for events and horizontal bars are rupture lengths. Open boxes represent multiple event age ranges. Gray shading indicates no data. Panel B shows a sequence alternating between the northern and southern portions, with variable overlap along the San Bernardino and southeastern Mojave segments; the overall pattern of this model is violated by the 1812 earthquake, however (Weldon et al., 2004). The data can be also be fit by an alternative model with more irregular recurrence intervals and rupture lengths (panel C), or one featuring "wall-to-wall" (M8+) ruptures extending from Parkfield to the Salton Sea (panel D) (Weldon et al., in preparation).

A key issue in earthquake forecasting is how stress on a fault recovers after a large earthquake. King & Bowman (2003) have argued that the stress recovery on a fault segment during its (characteristic) earthquake cycle can be monitored by the patterns and rates of seismicity, and they use their model to investigate the acceleration and spatial correlation of seismicity prior to fault failure. This research provides a connection between physics-based models of stress evolution and some of the seismicity patterns that have been proposed as intermediate-term earthquake precursors (e.g., Mogi, 1981; Sykes & Jaumé, 1990; Bufe & Varnes, 1993; Bowman et al., 1998; Keilis-Borok, 2002).

Some aspects of intermediate-term precursors, such as accelerating seismicity and high-magnitude enrichment, are also replicated by point-process triggering models, such as the ETAS model described in §II.B.5 (see Helmstetter et al., 2003a). The RELM testing program (RELM-T) is demonstrating that the ETAS and related point-process models (e.g., the STEP model of Gerstenberger et al., 2004) provide significant short-term probability gain over time-independent models (Fig. 3.5).

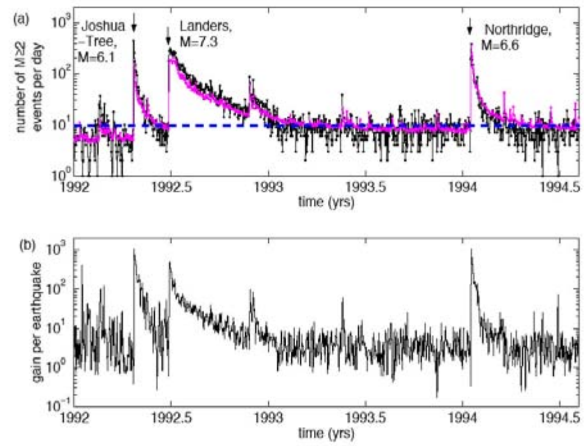


Fig. 3.5. (a) Comparison of the observed number of earthquakes in Southern California (black line) with the daily (retrospective) predictions of the ETAS model of Helmstetter et al. (2005b) (purple line). The dashed blue line is the average seismicity rate. **(b)** Probability gain per earthquake. This model, which is being tested in a prospective mode as part of the RELM-T program, demonstrates the short-term predictability of earthquake rates. The spatial probability of earthquake occurrence predicted by this model for a particular day is shown in Fig. 3.6b.

We therefore see new opportunities for the systematic investigations of earthquake predictability across all time scales—long-, intermediate-, and short-term. Our objective is to understand this predictability in terms of the stress evolution and rheology of the fault system. In some cases, it is clear how a physics-based, system-specific approach might be able to improve upon current models of predictability. For example, we know that large earthquakes preferentially occur on large, well-developed faults, but this fact is not built into current point-process models, which usually assume event probabilities are given by a Gutenberg-Richter distribution with no upper magnitude cutoff. Adding a spatially variable cutoff consistent with the long-term forecasting models and scaling relations derived from the observed seismicity would presumably improve ETAS predictability. Further enhancement may come from the consideration of spatially anisotropic ETAS kernels that conform to observed moment-tensor distributions and the stress orientations derived from fault-system deformation models.

In SCEC3, research on these topics will be coordinated by a new focus group for Earthquake Forecasting and Predictability, which will expand the investigations of earthquake predictability begun under the RELM program. Examples of short-term and intermediate-term earthquake prediction models currently being developed and evaluated under RELM are given in Table 2.1 and Fig. 3.6. In particular, this group will extend the testing procedures of RELM-T by establishing a Collaboratory for the Study of Earthquake Predictability (CSEP). CSEP will provide a carefully controlled environment for the registration of prediction experiments and the rigorous evaluation of their results. In particular, it will allow the predictive skill of proposed algorithms to be compared with reference methods, such as the long-term, time-independent forecasts of the National Seismic Hazard Maps and the short-term, time-dependent predictions of ETAS models. The details of the CSEP initiative are discussed in §III.C.6.

Earthquake prediction is a controversial, "hot-button" topic. In formulating our plans for a research program in this area, we recognize that considerable care must be taken in how the science of earthquake prediction is presented to the media and general public, who often confuse research experiments with operational predictions that deserve some sort of public safety or policy response. The SCEC leadership, as represented by its Board of Directors, has had considerable experience in dealing with these matters. We therefore propose to coordinate all activities in our studies of earthquake predictability with the two bodies that have statutory responsibilities for assessing earthquake predictions—the California Earthquake Prediction Evaluation Council (CEPEC), which is managed by the California Office of Emergency Services, and the National Earthquake Prediction Evaluation Council (NEPEC), which is currently being reconstituted by the USGS. We will advise CEPEC and NEPEC of research results and respond to the requests either group may have for information or special studies.

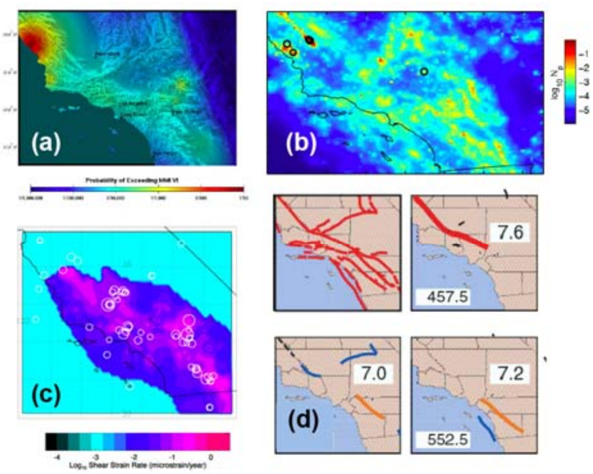


Fig. 3.6. Examples of regional earthquake likelihood models from the RELM project. **(a)** STEP map for 2003 Dec 26 21:28:32PST, four days after the M6.5 San Simeon earthquake (Gerstenberger et al., 2004). **(b)** ETAS-based prediction of seismicity for 2004 Oct 24 (Helmstetter et al., 2005b). **(c)** GPS strain model with levels of geodetic shear strain rate (colors on log scale) and earthquakes with $M \geq 5$ (Jackson et al., 2005). **(d)** Fault-based earthquake simulation, showing fault set (red lines, upper left panel) and simulated earthquakes (other panels) (Ward, 2004).

4. Ground Motion Prediction

<u>Problem Statement</u>. Given the gross parameters of an earthquake source, such as its magnitude, location, mechanism, rupture direction, and finite extent along a fault, we seek to predict the ground motions at all regional sites and for all frequencies of interest. The use of 3D velocity models in low-frequency (< 0.5 Hz) ground motion prediction was pioneered in SCEC1 (§II.A), and this type of simulation, based on direct numerical solution of the wave equation, has been taken to new levels in SCEC2 (§II.B.6). The unsolved basic research problems fall into four classes: (a) the ground motion inverse problem at frequencies up to 1 Hz; (b) the stochastic extension of ground motion simulation to high frequencies (1-10 Hz); (c) simulation of ground motions using dynamically consistent sources; and (d) nonlinear wave effects, including nonlinear site response. In addition, there remain scientific and computational challenges in the practical prediction of ground motions near the source and within complex structures such as sedimentary basins, as well as in the characterization of the prediction uncertainties.

<u>Goal and Objectives</u>. The principal SCEC3 goal is *to predict the ground motions using realistic*

earthquake simulations at frequencies up to 10 Hz for all sites in Southern California. The SCEC3 objectives are:

(1) Combine high-frequency stochastic methods and low-frequency deterministic methods with realistic rupture models to attain a broadband (0-10 Hz) simulation capability, and verify this capability by testing it against ground motions recorded at a variety of sites for a variety of earthquake types.
(2) Use observed ground motions to enhance the Unified Structural Representation (USR) by refining its 3D wavespeed structure and the parameters that account for the attenuation and scattering of broadband seismic energy.
(3) Apply the ground-motion simulations to improve SHA attenuation models, to create realistic scenarios for potentially damaging earthquakes in Southern California, and to explain the geologic indicators of maximum shaking intensity and orientation.
(4) Investigate the geotechnical aspects of how built structures respond to strong ground motions, including nonlinear coupling effects, and achieve an end-to-end simulation capability for seismic risk analysis.

Research Activities & Required Resources. The first three objectives overlap considerably with the SCEC2 research program described in §II.B.6. By the end of SCEC2, the Earthquake Source Physics and Ground Motion focus groups expect to have conducted verification tests of the dynamic-rupture and wave-propagation computer codes for objective (1), but these codes will have to merged. More data and further testing will be necessary, especially to verify the adequacy of the source models. Therefore, we propose to combine the dynamic-rupture simulations currently coordinated by ESP with the ground-motion simulations currently coordinated by GM into a research program managed by a new working group on Ground Motion Prediction.

Most current procedures for characterizing earthquake rupture models for the simulation of strong motion are based mainly on kinematic descriptions (Somerville et al., 1999; Mai & Beroza, 2002; Miyake et al., 2003), but such descriptions can be inconsistent with earthquake rupture physics. Moreover, kinematic models do not provide a physical explanation for some important but puzzling observations, such as the surprising difference in ground motions between shallow and buried ruptures (Fig. 3.7). Simulation of ground motions from large earthquakes will require source models that incorporate insights from rupture dynamics studies (e.g., Irikura et al., 2003; Guatteri et al., 2003). Reliable simulation procedures can then be used to generate ground motions to fill the gaps in the data set of recorded ground motions for large magnitudes and close distances and to quantify the effects of various individual earthquake source and fault geometry characteristics on the level of ground shaking. This is the main objective of the NGA-H initiative described in §III.C.4.

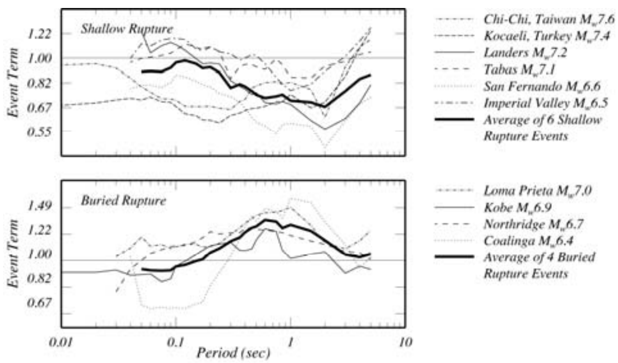


Fig. 3.7. Comparison of response spectral amplitude of individual earthquakes having surface rupture (top) and buried rupture (bottom), averaged over recording sites, with the amplitude of the average earthquake as represented by the model of Abrahamson & Silva (1997), represented by the zero line, which accounts for magnitude, closest distance and recording site category. The event terms (residuals) are shown as the ratio of the event to the model. We seek to understand these differences through studies that combine dynamic-rupture models into ground-motion simulations.

The generation of high-frequency energy by the source and its scattering by small-scale geologic structures is too complex to be calculated deterministically and must therefore be treated stochastically (Zeng et al., 1994; Hartzell et al., 1999; Graves & Pitarka, 2004). An important goal is to represent this stochastic nature in a manner compatible with the deterministic, physics-based treatment of the low-frequency components. We will explore the elements responsible for the inter-event and site-to-site components of high-frequency ground motion variability. To carry out such explorations, we need to push the frequency limits of physics-based ground motion simulations (e.g., those based on dynamic ruptures) up to several hertz to overlap the band of principal engineering interest, using advanced computational capabilities such as the TeraShake platform (§II.B.6).

Topography can also have a major effect on amplitudes. Both the finite element and spectral element methods currently in use by SCEC researchers are suitable for investigating topographic effects (Yoshimura et al., 2003; Komatitsch et al., 2004), and deterministic 3D simulations will be applied to gain understanding of these effects. Topographic effects are likely to become increasing significant as our simulation bandwidth increases.

The inclusion of site-specific information in the broadband simulations is typically done using empirical factors (Graves and Pitarka, 2004) or geotechnical engineering models (e.g., Ni et al., 2001). Improvement of these approaches will require more sophisticated site response calculations (Archuleta et al, 2003) that include methods such as frequency-dependent equivalent-linear (Kausel & Assimaki, 2002; Assimaki & Kausel, 2002) and fully nonlinear models (e.g., Bonilla, 2000, Yoshida, 2002). Inclusion of nonlinear response require advances on three fronts: (1) improved analysis of data recorded in boreholes in order to differentiate between surficial attenuation and nonlinearity; (2) detailed mapping and cataloging of soil properties in regions of interest to SCEC (e.g., the Los Angeles basin) in order to know which areas will require full nonlinear time domain analysis and those where frequency domain methods will suffice; and (3) categorizing available constitutive models with respect to the extent that they capture the nonlinear effect as a function of the soil condition.

The current empirical site effects based on soil type and shear-wave velocities to 30 m are simple multiplicative factors for response spectra and provide only a rough average; these factors cannot account for the variation in the temporal response of the soil. The standard premise is that nonlinearity will attenuate peak acceleration; e.g., the Port Island borehole records of the 1995 Hyogo-ken Nanbu (Kobe) earthquake (Iwasaki & Tai, 1996). Lacking direct borehole records the general approach is to compare site response from weak motion with that obtained using strong motion. A weakness in this approach is that it requires a reference site. This has led to some controversy whether the difference in weak and strong motion site response is due to nonlinear effects (Field et al., 1997) or inadequacies in the model of the velocity/attenuation structure (O'Connell, 1999). Nonetheless when strong ground motion is computed in cohesionless soils, nonlinear response has to be taken into account.

One of the challenges is that the computation of ground motion is done for thousands of sites; accounting for full nonlinear response, as done by Archuleta et al. (2003), may not be feasible. Thus one has to explore the possibility of using frequency-dependent equivalent linear methods (Kausel & Assimaki, 2002) at some sites while using complete hysteretic models at softer sites (Hartzell et al., 2004). It has also been recognized that site effects can be highly azimuth and frequency dependent. One explanation is that structural focusing or defocusing from variable geology at depth can have a greater effect on amplitudes than rock type. For example, basin-edge focusing effects have been hypothesized to account for damage for damage from the Northridge earthquake (Gao et al., 1996; Graves et al., 1998; Alex & Olsen, 1998; Davis et al., 2000), which may be explicable in terms of diffraction catastrophes (Husker & Davis, 2005). To understand this phenomenon we need better geological descriptions of faults and fold and thrust belts at depth. Seismic inversion schemes that invert amplitudes and travel times will eventually address this problem, but here is a need for data recording at higher resolution than the current network.

We will also build upon the ground motion simulation techniques to construct an end-to-end simulation capability that can serve as a new methodology for system-level prediction of earthquake risk (§III.C.5). By end-to-end, we mean simulations of the structural response of buildings, using as input the ground motions from physics-based simulations. A pilot study of this end-to-end simulation capability is being conducted by S. Krishnan and his Caltech colleagues. They have simulated the ground motions for an 1857-type earthquake (M 7.9) on the San Andreas fault using the spectral element method (Komatitsch et al., 2004). The ground motion time histories from this simulation have been fed into a non-linear time-domain analysis of a 20-story moment frame building designed to the 1997 UBC standards. The middle panel of Fig. 3.8 portrays the expected level of building deformation, and the corresponding FEMA-356 damage performance levels, for this model building. The bottom map shows the performance of a redesigned building. By covering the entire region affected by the earthquake scenario, the end-to-end simulation provides a comprehensive view of the improvement in building performance that is achieved by the redesign.

End-to-end simulations such as this one are designed to characterize earthquake effects directly in terms of effects on structures. They therefore also provide a natural framework for the development of new intensity measures better correlated with damage metrics (compared with existing intensity measures). New intensity measures may be formulated as vector-valued intensity measures (Bazzuro & Cornell, 2002), or perhaps take more general form. Formulation of improved intensity measures will be an important application of the end-to-end simulation capability.

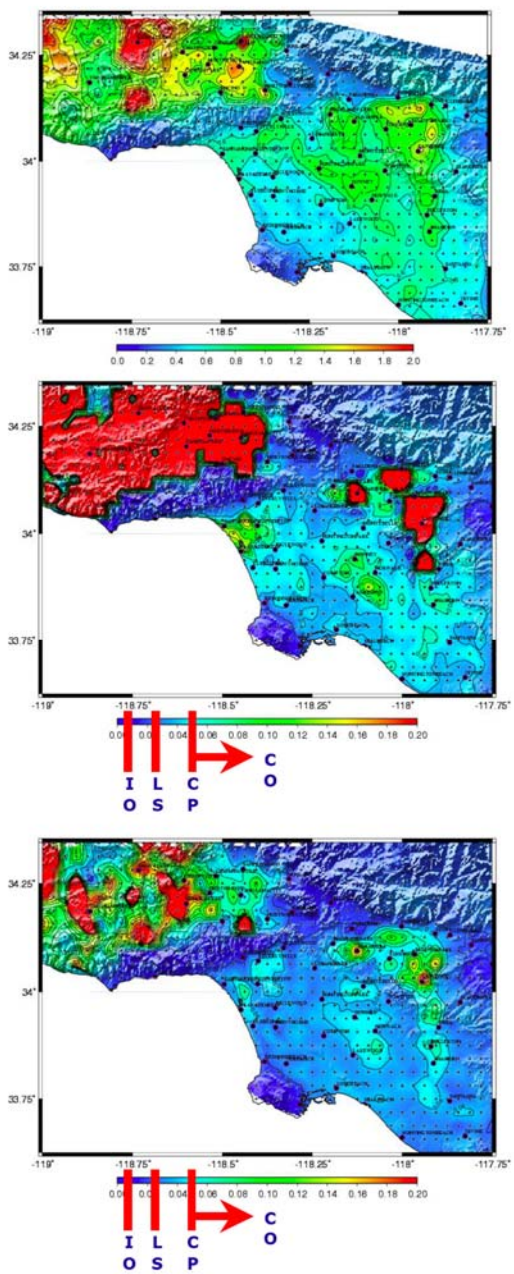


Fig. 3.8. An end-to-end simulation experiment by Krishnan et al. (2004). Top: Peak ground velocity (in the E-W direction, in m/sec, bandlimited to periods longer than 2 sec) in the Los Angeles region for a M 7.9 earthquake on the San Andreas fault. Middle: Map of the drift index for an existing 20-story steel moment frame building, calculated from the ground motion time histories whose peak velocities are shown at top. Bottom: A map of the drift index for a redesigned building, calculated from the ground motion time histories whose peak velocities are shown at top. The FEMA-356 damage performance levels shown with the drift ratio at the bottom are: IO: Immediate Occupancy; LS: Life Safety; CP: Collapse Prevention and CO: Collapsed.

Earthquake simulations produce large volumes of synthetic ground motion data. SCEC, under the CME project, has developed and populated a prototype digital library of synthetic ground motions for scenario earthquakes, as a resource for the engineering and seismological research communities (e.g., Fig. 2.16). This resource will be greatly expanded using results from the very large earthquake simulations made possible by the TeraShake platform, further enhanced by the new broadband simulation capability.

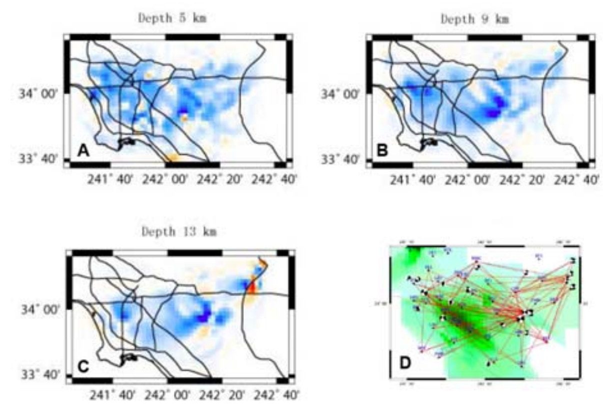


Fig. 3.9. Full 3D inversions of waveform data for the Los Angeles region using CVM-S3.0 as a starting model (Chen et al., 2004). Maps of the V_P perturbations to CVM-S3.0 are shown at depths of **(A)** 5 km, **(B)** 9 km, and **(C)** 13 km. Blue colors are positive perturbations and red are negative; the maximum is +2.1%. The maps are mainly blue because CVM-S3.0 has lower average velocities in the upper crust than in the actual Earth. **(D)** Map showing the earthquakes, stations, and paths used in this preliminary inversion. The inverted data are frequency-dependent phase delays of *P* and *S* waves and some internally reflected phases, measured at frequencies from 0.2 to 1.0 Hz.

In SCEC3, we will use the discrepancies between the observed and synthetic seismograms to improve the geologic structure model parameterized through the Community Velocity Models of the Unified Structural Representation through the techniques of full-3D tomography that are being developed in SCEC2. A new collaboration has been formed to pursue this structural inverse problem, currently comprising groups from Caltech (T. Tromp), CMU (J. Bielak), and USC (T. Jordan). One challenge is the computation of Fréchet kernels that quantify the sensitivity of a particular measurement to the 3D distribution of seismic wave speeds. Two algorithms for generating these 3D functions have been tested, a scattering formulation by the USC group (Zhao et al., 2005) and an adjoint-operator formulation by the Caltech group (Tromp et al., 2005); computational techniques for solving the waveform inverse problem by the adjoint method have also been developed by Bielak and his colleagues (Akcelik et al., 2003).

Using kernels calculated for the CVM-S3.0 reference model, the USC group has inverted the waveform data from Chen et al. (2004) for the V_P perturbation needed to improve the fit of the CVM to the waveform data (Fig. 3.9). This is the first time that frequency-dependent waveform data have been inverted for a 3D refinement to a 3D starting model using accurate 3D kernels—the proper definition of "full-3D" tomography. The collaboration is accumulating waveform measurements, and it plans kernel-based and adjoint-based inversions to improve both CVM-S3.0 and CVM-H1.0 during the remaining two years of SCEC2. Full-3D tomography will be applied to improving the new USR early in SCEC3, and it should see wide applicability in the EarthScope Project.

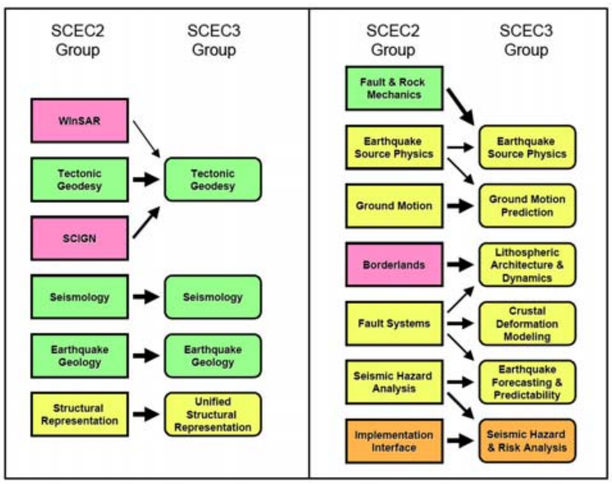


Fig. 3.10. A diagram showing the transition in working group structure from SCEC2 (square boxes) to SCEC3 rounded boxes). The boxes are color-coded by the same categories used in the SCEC organization chart (Fig. 1.4): disciplinary committees (green), interdisciplinary focus groups (yellow), and CEO working groups (orange). The arrow thickness scale in rough proportion with the degree that the current SCEC2 activities will be transferred to the new SCEC3 working groups.

B. Working Group Structure

As described in §III.A, the SCEC3 research program will be coordinated by a set of working groups restructured to coordinate the new activities of the SCEC3 Science Plan. The major organizational changes are diagrammed in Fig. 3.10 and can be summarized as follows:

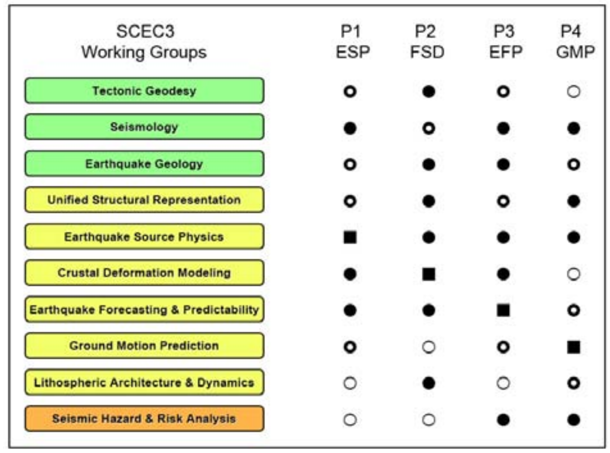


Fig. 3.11. Diagram depicting how the reconfigured working groups will participate in the main research problem areas of the SCEC3 Science Plan. P1 is Earthquake Source Physics, P2 is Fault System Dynamics, P3 is Earthquake Forecasting & Predictability, and P4 is Ground Motion Prediction. The squares (■) identify the lead focus groups, and the circle strengths give a rough indication of participation by the other groups: major (●), moderate (⭘), and minor (○).The boxes are color-coded by the same categories used in Fig. 3.10.

- Over the next two years, half of the SCIGN network will be incorporated into the UNAVCO-operated Plate Boundary Observatory (PBO) as part of EarthScope; the other half will be operated by the USGS and UCSD. Most WInSAR activities will also be transferred to UNAVCO. The WInSAR and SCIGN working groups will therefore be disbanded, and all geodetic research activities will be transferred to the Geodesy Disciplinary Committee. This group will continue to have the responsibility for developing the SCEC Crustal Motion Map and other products derived from the geodetic networks and campaign measurements.
- Research coordinated by the FARM focus group will be merged with Earthquake Source Physics focus group, thereby reducing the number of disciplinary committees from four to three.
- Rupture-dynamics simulations conducted by the current ESP focus group and the wave-propagation and site-response research of the current Ground Motion focus group will be combined into the activities of a new focus group on Ground Motion Prediction.
- Crustal deformation modeling studies now conducted by Fault Systems will be taken over by the nascent focus group on Crustal Deformation Modeling. The activities of the Borderland special project group and some of those now coor-

dinated by Fault Systems will be merged into a new Lithospheric Architecture & Dynamics focus group.

- Studies of earthquake predictability in Fault Systems will be merged into a new focus group on Earthquake Forecasting & Predictability, which will assimilate the model development and testing of the RELM project.
- The current Seismic Hazard Analysis focus group and the CEO Implementation Interface will be merged into a new CEO working group on Seismic Hazard & Risk Analysis, which will coordinate the development of SHA products and develop research partnerships with engineering organizations in end-to-end simulation and other aspects of risk analysis and mitigation.

The reconfiguration of the working groups will align the SCEC organization with the research problem areas described in the SCEC3 Science Plan. Each problem area will have a lead group (squares in Fig. 3.11). This structure will be effective in promoting complementary research activities within the working groups and effective interactions among them across the problem areas.

C. Research Initiatives

The SCEC3 Science Plan articulated in §III.A lays out a comprehensive program in system-level earthquake science and an organizational structure capable of conducting the requisite research. In this section, we describe eight initiatives that will augment this basic research program. Although none is required as a central element of our Science Plan, all will contribute in significant ways to research areas outlined the Plan, as indicated in Fig. 3.12.

SCEC3 Initiative	P1 ESP	P2 FSD	P3 EFP	P4 GMP
1. Networks as Research Tools	●	●	●	●
2. Southern San Andreas	⭘	●	●	○
3. WGCEP	⭘	⭘	●	⭘
4. NGA Project	●	○	○	●
5. End-to-End Simulation	⭘	○	○	●
6. CSEP	⭘	⭘	●	⭘
7. EarthScope Collaborations	●	●	●	●
8. International Collaborations	●	●	●	●

Fig. 3.12. Diagram showing how the eight SCEC3 initiatives will contribute to the research problem areas of SCEC3 Science Plan. P1 is Earthquake Source Physics, P2 is Fault System Dynamics, P3 is Earthquake Forecasting & Predictability, and P4 is Ground Motion Prediction. Circle strengths indicate the expected level of contribution: high (●), moderate (⭘), and low (○).

We outline each of these "add-on" initiatives in terms of its goal and objectives, its resource requirements, the expected participants and organizational partners, and the mechanisms that we will pursue to obtain additional resources to enact the initiatives. The latter is critical, because the base budget requested from the NSF and USGS provides only level funding for the Center, and our budget has already been stretched very thin by the rapid growth of the collaboration.[6] The more ambitious research program proposed for SCEC3, particularly in the realm of applied studies, will therefore require other sources of funding, which we are pursuing vigorously.

1. Networks as Research Tools

The seismic and geodetic networks of Southern California, SCSN and SCIGN, respectively, form a major part of the instrumental infrastructure for the Southern California Natural Laboratory, and SCEC scientists depend on the data they provide in much of their research. For this reason, the Center has been a leading partner in the development of SCIGN and the Southern California Earthquake Data Center (SCEDC), which serves as the SCSN database, and it has continued to support both operations throughout SCEC2.

With the inception of EarthScope and other nationalized data-gathering programs, it is clear that the relationship of the Center to these networks will be changing. About half of the SCIGN network will be incorporated into the UNAVCO-operated Plate Boundary Observatory (PBO) over the next two years; the other half will be operated by the USGS. The SCSN and SCEDC have merged into the California Integrated Seismic Network, itself part of the Advanced National Seismic System.

SCEC3 can therefore focus its efforts on enhancing the networks as research tools. The goal of this initiative will be to foster innovations in network deployments and data collection that can provide researchers with new information on earthquake phenomena. This research emphasis will complement the roles of ANSS, IRIS, and UNAVCO, and it will help to ensure that the networks do not settle into operational stasis.[7]

6 Based on current participation (see §I.B.2), we expect over 500 scientists from more than 50 research institutions to be involved in SCEC3, including a number of students and early-career researchers.

7 The ANSS National Steering Committee has recognized the need for regional efforts to upgrade networks as research tools; this initiative will support their recent recommendations (Sharon Wood, personal communication, 01/12/05) and the notion of evolutionary system architecture (Arabasz & Oppenheimer, 2004; see http://www.anss.org/tic/e/).

Specific objectives for the SCSN are to collaborate with the network operators, Caltech and the USGS, to (1) test the performance of proposed early-warning algorithms by implementing them on a real-time SCSN subsystem; (2) augmenting borehole stations with both downhole and uphole instrumentation to assess the site response and the ground coupling of built structures; (3) develop a strategy for densification of seismic instrumentation along major fault zones in Southern California to capture near-field motions; and (4) develop a strategy to search for unusual signals, such as the episodic non-volcanic tremor recently detected near the base of the crust at the northern terminus of the 1857 rupture (Nadeau, 2004).

Specific objectives for SCIGN/PBO include (1) continued production of a unified set of velocities for all geodetic stations in Southern California, through continuation of the Crustal Motion Map project; (2) the analysis of local variations in strain rate that might reveal the mechanical properties of earthquake faults, and (3) in the event of an earthquake, the analysis of permanent crustal deformation not detectable by seismographs, as well as the response of major faults to the regional change in strain.

Owing to space limitations, we cannot detail all of the projects we have in mind to achieve these objectives, but we will briefly describe one high-priority initiative that exemplifies the use of the network as a research tool.

<u>Early Warning Real-Time Demonstration Project</u>. Real-time systems developed in Southern California (e.g., ShakeMap) have been implemented on the SCSN and other regional networks in the U.S. and abroad, and they are playing an increasingly important role for post-earthquake emergency responses. The next step is "early warning," whereby the severity of seismic shaking is assessed in real time after the occurrence of an earthquake and the information is sent to locations some distance away before the damaging waves arrive. Some progress on this problem has been made, and operational systems have been deployed in Taiwan, Mexico, and Japan (Wu & Teng. 2002; Espinosa-Aranda & Rodriguez, 2003; Kamigaichi, 2004; Horiuchi et al., 2005). However, early-warning systems are far more difficult to implement than current (post-shaking) data-product systems, and assessing its feasibility will require substantial new research.

Investigators at Caltech have been developing three independent algorithms for early warning: (1) Elarms (Allen & Kanamori, 2003), (2) a τ_c method designed for on-site warning (Kanamori, 2005), and (3) the Virtual Seismologist method, which relies on Bayesian analysis (Cua & Heaton, 2004). These methods are based on different philosophies, and all of them have been extensively tested off-line.

However, since the nucleation and growth of an earthquake can be complex, the recorded waveforms can be diverse. Some methods may work better than others for identifying certain types of damaging earthquakes, but no single method is expected to work well for all earthquakes. In the operational implementation of an early warning system, it may be desirable to combine as many different methods as possible to make the overall system robust. The best way to assess the methods is to implement them on an existing system in a real-time testing mode. Large earthquakes are relatively rare and it is important to gain experience with more frequent, smaller earthquakes.

We propose a pilot implementation of the three algorithms on the on-line system of the Caltech-USGS seismic network in Southern California to test how these algorithms can jointly handle complex real-time situations. The main task involves adaptation of the codes developed for off-line testing to the on-line system and the documentation of their performance. This project is being coordinated with researchers at Berkeley and through the CISN. We intend to request additional support from the USGS external grants program.

Needless to say, the SCEC3 base budget cannot provide much support for large-scale equipment purchases or permanent instrumental deployments, but it can provide a forum for prioritizing community interests and research needs; seed funding for innovative projects; scientific coordination across the SCEC community; IT support to assist in data dissemination, product development, and incorporation of network data into the Community Modeling Environment (CME); and a mechanism for organizing large community-supported proposals to funding agencies. In the case of some activities, such as the Early Warning Real-Time Demonstration Project, the Center can also help coordinate and support international collaborations with Japan, Taiwan, and other countries with large network-based research programs (see §III.C.8).

2. *Southern San Andreas Fault*

The southern San Andreas fault, which stretches 550 km from the creeping section to the Salton trough, is recognized as Southern California's most likely source of future great earthquakes. Interdisciplinary research over the past several decades, including significant geologic work under the SCEC1 and SCEC2 programs, has improved our knowledge of the San Andreas fault system and its sub-parallel strands such as the San Jacinto and Elsinore faults (e.g., Grant & Lettis, 2002). Yet much about its long-term earthquake behavior remains puzzling and obscure, and there are major uncertainties in quantifying its seismic hazards (Weldon et al., 2004).

The goal of the southern San Andreas fault (SSAF) initiative is to mobilize a major effort on the collection and interpretation of geologic data to understand the earthquake history of the SSAF system. This initiative will coordinate research across disciplines and organizations in the following areas: (1) systematic paleoseismic investigations to develop a comprehensive rupture chronology, (2) remote sensing to obtain detailed digital topography, (3) neotectonic studies to nail down the slip-rate variations along the system, (4) deployments of near-field seismic instrumentation to capture future ground motions, and (5) coordination of the geodetic measurements and their interpretation using EarthScope's Plate Boundary Observatory. The latter two objectives couple the SSAF initiative to the networks initiative discussed above.

The major activity of the SSAF initiative will be the fieldwork and analysis needed to assemble a space-time record of all ground ruptures on the SSAF for the past 2000 years. This unique rupture record will be used to answer questions about basic fault recurrence behavior, to calibrate and test physics-based fault models, and to calculate earthquake rupture forecasts for Southern California. The current uncertainties in the rupture-sequence interpretations of data for the SSAF are illustrated in the lower three panels of Fig. 3.4. The data collected in this initiative would reduce these uncertainties and provide better information on the seismic hazards posed by large SSAF earthquakes.

This effort will require a quantum increase in the quality and quantity of paleoseismic data and a new paradigm for how the data are collected, interpreted, and integrated. As the paleoseismology community moves from individual investigators collecting site-specific data to studying multi-site ruptures, common methodologies and tools to analyze and integrate the data will have to be developed. Research sponsored by the USGS and NSF during SCEC2 has provided a new interpretive framework for these types of rupture-mapping studies (see §II.B.4 and Fig. III.A.3).

This initiative will be coordinated by R. Weldon, and the group he leads will be submitting proposals to augment SCEC base-funding support to the Tectonics Program of NSF/EAR and to the USGS external program.

3. *Working Group on California Earthquake Probabilities*

A partnership of three organizations—SCEC, the U. S. Geological Survey (USGS), and the California Geological Survey (CGS)—has established a new Working Group on California Earthquake Probabilities (WGCEP). The goal of this initiative is to develop a uniform California earthquake rupture forecast (UCERF) by combining new information with the best available methodologies for time-dependent forecasting. If this project goes as planned, the WGCEP will deliver its time-dependent UCERF during the first year of SCEC3.

The two most recent WGCEP reports, in 1995 and 2002, applied different methodologies in their treatments of Southern California and the San Francisco Bay region, and neither considered the other parts of the State. The proposed project would, for the first time, provide California with a uniform rupture forecast for all of California based on a time-dependent methodology that incorporates statewide geodetic data and geologic constraints.

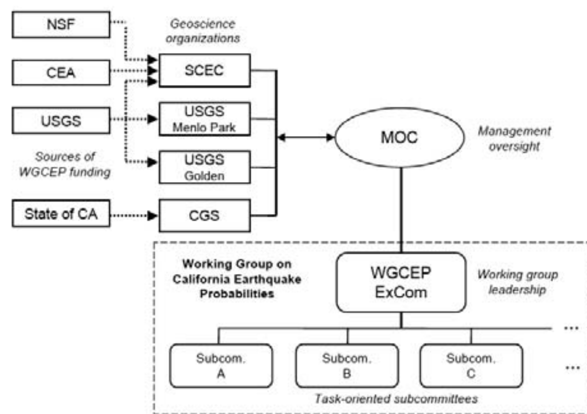


Fig. 3.13. Organization chart for the UCERF project. The geoscience organizations receive funding from multiple sources, including the National Science Foundation, the USGS, the State of California, and the California Earthquake Authority (CEA). The WGCEP will be managed by a project leader and an ExCom comprising 6 members, who will chair task-oriented subcommittees. The WGCEP will report to a Management Oversight Committee (MOC), comprising the four geoscience organizational leaders, will approve all project plans, budgets, and timetables.

The UCERF plan (see on-line Supporting Materials) identifies six major databasing tasks: (1) a fault trace/dip database; (2) a neotectonic database containing slip rates; (3) a crustal motion map based on geodetic data; (4) an instrumental earthquake catalog; (5) a historical earthquake catalog; and (6) a paleoseismic database. It also lays out five principal model-construction tasks: (A) a fault model from datasets 1, 4, 5; (B) a deformation model from model A and datasets 2 and 3; (C) an earthquake rate model from model B and datasets 4-6; (D) a time-independent UCERF based on model C; and (E) a time-dependent UCERF based on model C and datasets 4-6.

An important part of the plan is to build the consensus needed for the acceptance of the UCERF products among experts and stakeholders. In particular, the UCERF development will be tightly connected to the National Seismic Hazard Mapping Project (NSHMP), which has well-tested mechanisms for consensus-building on a national scale (USGS-Golden will be fully involved in the WGCEP). The ambitious schedule for this project will deliver a California earthquake rate model (Model C) in time for inclusion in the 2007 revisions to the national seismic hazard maps. This model will be developed according to NSHMP procedures, and it will be vetted and reviewed by the NSHMP consensus-building process. The two UCERF models (D & E) will be vetted by additional workshops and reviewed by the California Earthquake Prediction Evaluation Council (CEPEC) and National Earthquake Prediction Evaluation Council (NEPEC).

A well-articulated management structure will ensure that UCERF products can be developed on schedule and conform to the project goals (Fig. 3.13). The proposed structure is based on a Management Oversight Committee, chaired by the SCEC director and comprising the other organizational leaders who manage resources, and the WGCEP itself, which will be chaired by N. Field and will comprise experts from the participating organizations.

This project will be supported in part by the California Earthquake Authority (CEA), which provides approximately 70% of the earthquake insurance statewide. In February, 2005, the CEA Board of Directors approved $1.75 million in funding for this project, which will be managed by SCEC and will support UCERF development through 2007. Additional support will be requested from major stakeholders, such as the Pacific Gas & Electric Company and Caltrans.

4. Next Generation Attenuation Program

SCEC proposes to participate in the second phase of the Next Generation Attenuation Program (NGA-H, where H stands for *hybrid*). The first phase, NGA-E (where E stands for *empirical*), is producing a set of ground motion attenuation relations derived using an empirical approach based mainly on strong-ground motions recorded during earthquakes (see §II.C.1). The NGA-E models will be available in mid-2005. The NGA-H phase, which is expected to extend into the second year of SCEC3 (2008), will produce more reliable ground motion attenuation models that are based not only on recorded strong-motion data, but also on strong-motion simulations designed to fill critical gaps in the strong-motion database, especially in the near-field of very large earthquakes. This project, which is a partnership with the PEER-Lifelines Project and the USGS, involves improved collaborations between earthquake scientists and engineers that allow more accurate assessments of earthquake risk, and relies on the unique capabilities within SCEC to model earthquake ground motions.

A major goal of the NGA-H Project is to provide a physics-based understanding of ground motions. Using physics-based strong motion simulation techniques, the effects of individual source and fault geometry parameters on strong ground motion levels can be isolated and quantified. A surprising feature of the preliminary NGA-E models is that the ground motions from $M > 7$ earthquakes are much weaker than in previous models, in some cases weaker than those from $M < 7$ earthquakes, as indicated by the data shown in Fig. 3.7. In some of the preliminary NGA models, these effects are modeled using the magnitude or the fault aspect ratio (ratio of length to width) rather than the criterion of surface or buried faulting as in Fig. 3.7, but these three parameterizations are correlated because surface faulting earthquakes usually have large magnitudes and large aspect ratios. Since the recorded strong motion data from large magnitude earthquakes are sparse, and are mostly from outside California, there is uncertainty as to whether these NGA-E models are reliable representations of the ground motions from large earthquakes in California. An important objective of NGA-H is to use physics-based simulations to establish a physical basis for scaling ground motion intensity measures up to large magnitude.

In SCEC2, we have already made substantial progress in addressing the fundamental physics of processes relevant to the generation of earthquake rupture and strong ground motions. We will use this capability to understand the physics of how the ground motions from large earthquakes might be weaker than those from smaller earthquakes. We will also use ground motion simulations to quantify the various individual earthquake source and fault geometry characteristics on the intensity of ground shaking. The following effects will be investigated: distance and magnitude scaling, footwall/hanging wall geometry, style of faulting, directivity, buried vs. surface faulting, static stress drop (ruptured area) and other (dynamic) stress parameters, and 3D basin effects.

The NGA-H project will be managed by an executive committee comprising the SCEC director, the PEER director, the PEER-Lifelines coordinator, and the Chief Scientist of the USGS Earthquake Hazards Team. P. Somerville will act as SCEC's project manager, and N. Field will be responsible for implementing the result of this project into the OpenSHA software system.

In addition to its base funding, SCEC has received about $250K for NGA-H through a grant jointly funded by NSF/CMS and NSF/EAR (CMS-0409705); this grant will expire in September, 2007. We have also received $300K from the CEA to support NGA-H research through December, 2007. Some support for SCEC investigators will also be available from the PEER-Lifelines program, although the level is currently uncertain.

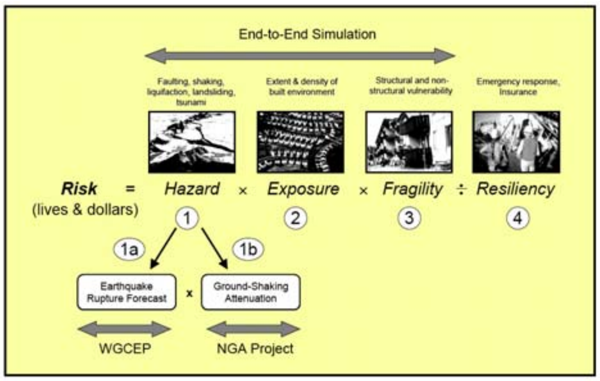


Fig. 3.14. Initiatives 3-5 presented in the context of the notional "risk equation" of Fig. 1.8. The Working Group on California Earthquake Probabilities (WGCEP) will form a major partnership with the USGS and CGS to improve earthquake rupture forecasts (1a). The NGA Project is a PEER-Lifelines/SCEC/USGS collaboration that will improve (1b) by producing the next generation of attenuation relationships. Initiative 5 is a partnership with engineering organizations such as CUREE and PEER that will improve risk assessment and loss prediction by coupling together (1), (2), and (3) in end-to-end simulations—taking risk analysis from "ruptures to rafters."

5. End-to-End Simulations: "Rupture to Rafters"

The goal of this initiative is to develop a capability for end-to-end simulation of the earthquake process that can be used for new types of risk assessment. The end-to-end approach—what we have informally dubbed "rupture to rivets" or "rupture to rafters"—is more realistic and is thus potentially more reliable than extant methodologies for earthquake damage estimation. This initiative will extend SCEC's research from its base subject of seismic hazard analysis into integrated risk analysis, as illustrated in Fig. 3.14.

Current procedures for modeling the response of structures and estimating earthquake damage and losses involve characterizing the ground motion level throughout a region using simple ground motion parameters such as intensity, peak acceleration or response spectral acceleration, and then estimating the losses for individual structures using simple correlations between ground motion level and damage. A much more rigorous procedure is to calculate the full ground motion wavefield throughout the region and put it into a nonlinear time history analysis of structural response. This integrated approach has the advantage of using a complete description of the ground motion in place of the simplified ground motion parameters common in current practice, thereby enabling realistic analysis of the nonlinear response of structures throughout an urban area. Strong-motion seismologists and engineers in the United States are beginning to collaborate on such end-to-end simulations. Pilot approaches to this kind of end-to-end simulation have been tested by SCEC (Krishnan et al., 2004) and in the SPUR Project (Park et al., 2004). End-to-end simulation from the earthquake source through to structural response offers the prospects for fully integrating earthquake science and earthquake engineering.

Under its current base funding and the NSF/CMS-EAR grant, SCEC is conducting pilot studies in end-to-end simulation. The objectives are (a) to produce more realistic earthquake ground motion scenario maps by including more realistic representations of the earthquake source, seismic wave propagation, and local site geology, and (b) to engage earthquake engineers in simulations of the structural damage to specific building types using the ground motion time histories from these scenarios. These pilot studies are focused on scenarios for the Puente Hills blind thrust system, which has only recently been characterized by SCEC scientists (Fig. 2.8) and represents a significant hazard that is not portrayed in the 1997 Uniform Building Code. The recent results of Krishnan et al. (2004) are shown in Fig. 3.8.

The SCEC3 objectives will be to establish working relations with engineering organizations such as CUREE and the EERCs to conduct collaborative studies in end-to-end damage analysis. As a first attempt, we will submit a joint proposal with CUREE to the NEESR Program in mid-March, 2005. In concept, the project plan is to (a) conduct end-to-end simulations of a model low-rise building at a few geologically typical locations in a model of the Los Angeles basin (adapted from the CVM); (b) use NEES experimental facilities to measure soil-structure interactions during the scenario earthquake; (c) demonstrate that our analytical methods can reproduce the experimental results, and then (d) vastly expand the range of the experiment by simulating the response of the building throughout the region affected by the scenario earthquake, by placing the building at a set of grid points and performing a soil-structure analysis at those points.

For this NEESR project, we will request approximately $400K/yr for four years (if funded, this project will extend into 2009). Most of these funds would be allocated to the engineers for the soil-structure interaction experiments (A. Whittaker, the current CUREE president, will act as P.I.), so that the SCEC investigators would receive only about $85K/yr if the proposal is fully funded. Additional support would be provided by the SCEC base grants.

Regardless of whether this particular project is funded, SCEC and CUREE intend to establish a long-term partnership in end-to-end damage analysis, and we propose to use some of the SCEC3 base funds to support this work. We will also seek other organizational partners in this strategic area of research.

6. Collaboratory for the Study of Earthquake Predictability

As part of our research program in earthquake forecasting and predictability (§III.A.3), we propose to develop a Collaboratory for the Study of Earthquake Predictability (CSEP). The goal is to provide a stable environment for registering earthquake predictions and conducting long-term predictability experiments that are properly characterized and can be properly evaluated. The objectives of the CSEP are to promote rigorous research on earthquake predictability, to reduce the controversy surrounding prediction experiments, and to provide the USGS, California Office of Emergency Services, and other responsible agencies with information about the feasibility and performance of earthquake prediction methodologies.

Prediction experiments need to be conducted under rigorous, highly controlled conditions and evaluated using accepted criteria, specified in advance. The process can be very complex, involving retrospective as well as prospective testing, and it requires careful evaluations of prediction skill relative to standard forecasting procedures; e.g., the time-independent forecasts of the National Seismic Hazard Mapping Project or simple time-dependent forecasts, such as the STEP model of Gerstenberger et al., 2004. The facilities available to most scientists for managing this process are inadequate for at least four reasons. (1) Scientific publications usually provide insufficient information for independent evaluation of prediction performance in either retrospective or prospective tests. (2) Active researchers are constantly seeking to improve their procedures, sometimes by tweaking their parameters, sometimes by wholesale changes to their algorithms. The predictions thus become moving targets, which makes independent evaluation very difficult. (3) Individual scientists and groups usually do not have the resources or expertise to conduct and evaluate long-term prediction experiments. (4) The data needed to evaluate prediction experiments are often improperly specified, leading to controversies about whether an earthquake satisfies a particular prediction.

These problems have a common root in poor experimental infrastructure. There have been many past instances where the lack of an adequate standards and infrastructure has led to unnecessary misunderstandings and controversy. Some of these controversies have compromised the credibility of prediction research in the eyes of both the scientific community and the general public.

Through its RELM project, SCEC has promoted a variety of experiments on earthquake predictability and is establishing procedures for conducting prediction experiments and testing prediction skill (§II.B.5). CSEP will build on this and the CME experience by creating a facility with the cyberinfrastructure adequate to support a global program of research on earthquake predictability. The collaboratory will have four key features:

- Rigorous procedures for registering prediction experiments, which will include the delivery and maintenance of closed, documented code for making and evaluating predictions.
- Community-endorsed standards for assessing probabilistic predictions, including measures of skill relative to well-defined reference forecasts.
- Access to data sets and monitoring products, certified by the agencies that produce them, for use in calibrating procedures and testing predictions.
- Software support to allow individual researchers and groups to participate in prediction experiments and update their procedures as results become available.

This project will encourage research on earthquake predictability by providing qualified researchers with adequate resources to participate in the collaboratory and the means to compare their results with other prediction experiments. A sketch of the collaboratory infrastructure is given in Fig. 3.15.

SCEC has a long history of collaboration with the USGS, CGS, California Office of Emergency Services, and other government agencies with statutory mandates to evaluate earthquake hazards and risks. For example, SCEC ran a workshop involving 40 experts in February, 2004, to evaluate a recent earthquake prediction for Southern California, issued by V. Keilis-Borok and others in January, 2004. The workshop was attended by all members of the California Earthquake Prediction Evaluation Council (CEPEC), which used the results as the basis for an official State-of-California advisory issued in early March. We will build on this experience to ensure that the activities of the proposed collaboratory help CEPEC and the reconstituted NEPEC manage public expectations about the feasibility and utility of earthquake predictions.

A preproposal for a 3-year grant to establish CSEP will be resubmitted the W. M. Keck Foundation in May, 2005. If fully funded, this grant would support the cyberinfrastructure development and an initial set of prediction experiments at a level of approximately $400K/yr through 2008.

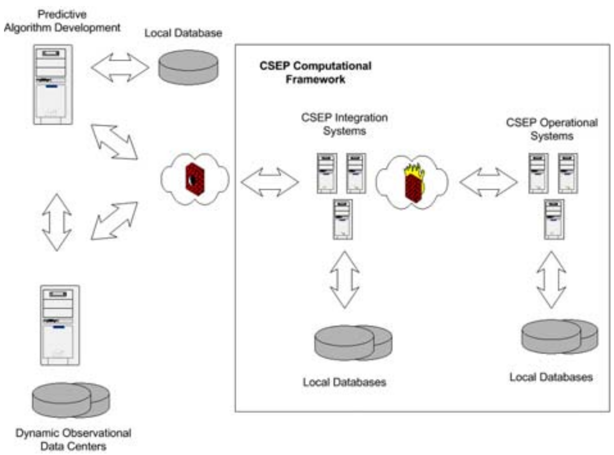


Fig. 3.15. Schematic representation of the CSEP infrastructure. Algorithms are developed on the researcher's own system. The CSEP system is partitioned into an integration environment and an operational environment. The former is used to verify proper registration of all software and data. The latter is maintained as a stable and secure operating environment under SCEC management; it will mirror the integration environment, allowing straightforward migration. Researchers will have direct access to the integration environment, but only the CSEP staff will have access to the operational environment.

7. National Collaborations Through EarthScope

SCEC is a regional earthquake center, but its community is national,[8] and its mission of achieving a comprehensive, physics-based understanding of earthquakes is a global priority, especially in the wake of recent disasters. The goal of Initiative 7 is to apply SCEC's system-level approach to other fault systems in the United States and to collaborate on a national scale in comparative studies of fault system dynamics and earthquake behavior. The particular objective is to establish partnerships between SCEC and other regional groups to participate in NSF's EarthScope program.

A major goal of EarthScope is to collect continent-wide, synoptic datasets using the state-of-the-art facilities that will be provided by USArray, PBO, and SAFOD. An equally important goal is to integrate these data sets with other information on geologic processes into a comprehensive, physics-based understanding of North American tectonics and the dynamical interactions of the continent with the deep interior. Achieving the second goal will require at least three types of capabilities in which SCEC has well-developed expertise: (a) standardized data analysis, to create high-level products from the raw EarthScope data sets, (b) regionalized structural representations, to assimilate information about geologic structure, including data on surface faulting, near-surface material properties, and crustal architecture, as well as the structural constraints from the analysis of EarthScope data, and (c) geosystem models, to capture the key interactions and system-level behaviors that govern North American tectonics.

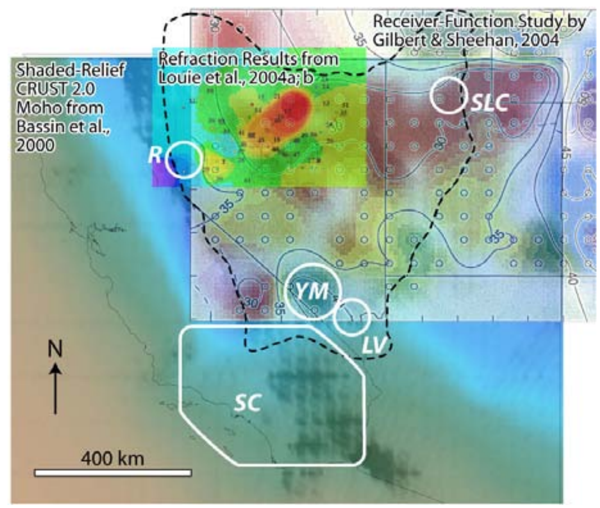


Fig. 3.16. Great Basin province (black-dashed line) showing crustal-thickness estimates at regional scales. Refraction results of Louie et al. (2004a,b) are set into color contours of crustal thickness in northwest Nevada from the CRUST 2.0 (Bassin et al., 2000). Bright red indicates crust less than 30 km thick. The color of each labeled dot keys to crustal thickness, illustrating the uneven coverage and conflicting results. J. Louie and his colleagues at UNR are developing basin-scale models for the Yucca Mtn.–NTS region (YM) and of the Salt Lake City (SLC), Las Vegas (LV), and Reno (R) urban areas that will be incorporated into a Great Basin CVM, using modeling procedures pioneered by SCEC. The Southern California Natural Laboratory (SC) is shown for comparison.

This initiative will encourage SCEC scientists to participate in multi-institutional, interdisciplinary collaborations formed under the EarthScope program, particularly those that promote regional syntheses of active fault systems in the western United States. All of the SCEC working groups will be able to engage in these collaborations, although the

[8] SCEC's core and participating institutions are located in 15 states (see Table 1.1).

Unified Structural Representation, Crustal Deformation Modeling, and Lithospheric Architecture & Dynamics focus groups will play especially important roles.

An example is a nascent partnership among the University of Nevada at Reno, the University of Nevada at Las Vegas, the University of Utah, and SCEC to build prototypes of a Great Basin Community Fault Model (GB-CFM) and a Community Velocity Model (GB-CVM), with the goal of providing a unified structural representation (GB-USR) to assimilate existing structural information and, eventually, EarthScope data (Fig. 3.16). The GB-USR is intended for use in the regional modeling of seismic wave propagation, tectonic processes, and crust/mantle interactions.

This project will familiarize scientists in the Great Basin working group with the methodologies developed by SCEC, to the benefit of both organizations. The ability to visualize the existing data with all its gaps and conflicts will focus attention on what is known and what is not known and encourage the formulation of testable hypotheses. Consolidating the existing structural information will be necessary to guide future EarthScope deployments and experiments. The establishment and refinement of the GB-USR will require a sustained, long-term effort. The capabilities for maintaining such complex modeling environments are currently being developed by the GEON and SCEC/CME projects through NSF/ITR funding. Projects of this type will help to tie these major IT developments into EarthScope.

SCEC will also play a unique role in facilitating interaction between EarthScope and NEES. In particular, SCEC will integrate information from: (1) SAFOD studies of crustal stress and fault friction to better simulate dynamic rupture, (2) PBO studies that help to determine the spatial and temporal characteristics of deformation, and (3) USArray studies that help to determine the seismic structure over a variety of length scales. Owing to its unique data-gathering facilities, EarthScope information will be critical to SCEC's strategy for estimating the nature of future earthquakes in Southern California. The goal of NEES is to lessen the impact of earthquake disasters by providing new capabilities for understanding the response of engineered structures to earthquake shaking. These facilities include shake tables, numerical simulation tools, and soil-structure interaction experimental facilities. As illustrated in Initiatives 3-5, SCEC has an obvious role in helping to define the characteristics of expected ground shaking that cause damage, and we can expect growing our collaborations with earthquake engineers to crosslink the EarthScope and NEES programs.

National collaborations through EarthScope will contribute to all four of the basic research problems outlined in §III.A. It will not be possible to initiate such collaborations without additional funding sources—EarthScope or other programs will certainly have to shoulder the costs of the non-SCEC participants—but SCEC participation can be leveraged against its base funding and existing capabilities.

8. International Collaborations

Initiatives 7 and 8 are motivated by the fact that much can be learned from comparative studies of fault systems. The Denali fault system in Alaska and the North Anatolian fault system in Turkey share many characteristics with the San Andreas fault system in California, but also manifest substantial differences (Fig. 3.17). Just as EarthScope is catalyzing integrative studies of active fault systems around the U.S., other countries are recognizing the merits of an system-level approach. For example, Taiwan has allocated about $50M for a new interdisciplinary, multi-institutional Taiwan Earthquake Center (TEC), modeled along the lines of SCEC. The goal of Initiative 8 is to enhance the understanding of earthquake causes and effects through interactions among earthquake scientists from different countries.

SCEC scientists maintain active collaborations with many foreign colleagues, and the Center has supported work in Mexico, Turkey, Taiwan, Japan, and elsewhere. However, formal organizational partnerships with interdisciplinary research groups are just now forming. In April, 2004, a SCEC group, including the Center director, attended a workshop in Taiwan, which focused on the seismic hazards of the Taipei Basin. It became clear to the workshop participants that many of the research problems pertaining to the Taipei Basin were already being addressed by the SCEC program in the context of sedimentary basins in Southern California. As a result of this workshop, four Taiwanese research organizations joined SCEC as participating institutions: the Institute of Earth Sciences of Academia Sinica, National Chung Cheng University, National Taiwan University, and National Central University. Moreover, it was resolved to explore mechanisms for a formal partnership between SCEC and the nascent TEC. Similar discussions have been underway with colleagues in Turkey, Japan, and China. For example, SCEC and the Earthquake Research Institute (ERI) of Tokyo University will convene a jointly sponsored workshop on earthquake rupture dynamics in Summer, 2005.

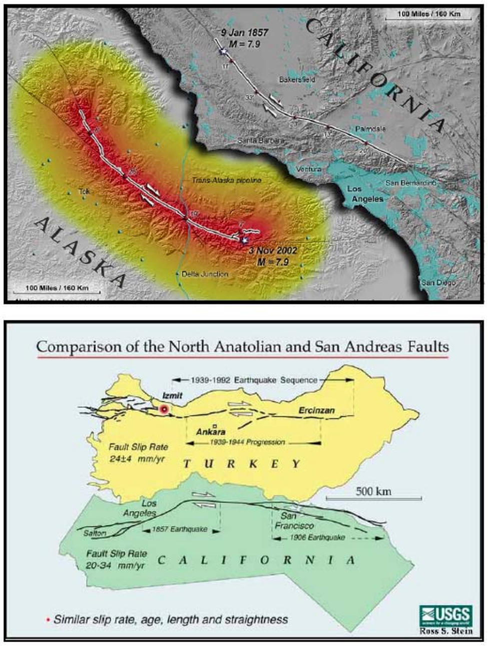


Fig. 3.17. Comparisons by R. Stein (USGS) of the 2002 Denali earthquake with the 1857 Fort Tejon earthquake (top) and the North Anatolian fault system in Turkey with the San Andreas (bottom). Initiatives 7 and 8 will provide the means for SCEC scientists to conduct comparative studies of earthquakes and fault systems with their colleagues in other parts of the U.S. and in other countries such as Turkey, Japan, and Taiwan.

The NSF recently issued a Program Solicitation from its Office of International Science and Engineering for a new center-oriented Partnerships in International Research and Education (PIRE). SCEC will respond to this solicitation with a proposal (due March 10, 2005) entitled *Multinational Partnerships in Earthquake System Science (MPRESS)*, which will include plans for center-level partnerships with Taiwan (through the TEC), Japan (through ERI), and Turkey (through a four-institution consortium led by Dr. Naci Gorur). Memoranda of Understanding have been negotiated between SCEC and these three national groups that identify the common interests in system-level earthquake science and emphasize the mutual benefits that will accrue through the international collaborations, include the societal benefits from physics-based improvements to seismic hazard analysis. Each of the foreign groups has agreed to commit substantial resources to the partnership.

SCEC's proposal to the PIRE program will budget approximately $420K/yr for 5 years to support the participation of SCEC researchers, especially students and early-career scientists, in studies abroad. If fully funded, this program would extend through 2010. NSF restricts spending to be primarily for off-shore work, so these resources will not be available for research in Southern California or other U.S. territories. However, much of the work with foreign collaborators will be complementary to and supportive of the research elements in the SCEC3 Science Plan.

D. Communication, Education and Outreach

The CEO program is an essential component of the SCEC3 Science Plan through its management of external partnerships that foster new research opportunities and its delivery of research and educational products to the Center's customers, which include the general public, government offices, academic institutions, industry, and the media. In SCEC3, the Center will expand its CEO activities through partnerships with new groups, such as the EarthScope Education & Outreach Program and the NEES Education, Outreach & Training (EOT) Program. The Earthquake Country Alliance, created by SCEC in 2003, will serve as a model for the types of multi-organizational partnerships we plan to establish with in education and knowledge transfer, especially in partnership with practicing and research engineers.

SCEC3 CEO will develop new programs and also continue to manage a suite of successful evolving activities. The CEO focus areas will include partnerships in *seismic hazard & risk analysis*, primarily with research engineers; *knowledge transfer* partnerships and programs for technical professionals and government officials; *education* programs and products for students and educators; and *public outreach* activities for the general public, civic and preparedness groups, and the news media. And, as in SCEC2, CEO will organize *community development* programs for SCEC participants.

1. Working Group in Seismic Hazard & Risk Analysis

The SCEC Implementation Interface has been very successful in establishing effective research partnerships with earthquake engineering organizations such as the Pacific Earthquake Engineering Research Center (PEER), the Consortium of Universities for Earthquake Engineering (CUREE) and the Network for Earthquake Engineering Simulation (NEES). In SCEC3, we expect these partnerships to expand in several directions. Through SCEC research, physics-based methods for seismic hazard analysis are becoming a reality, as reflected in the new Working Group on California Earthquake Probabilities, which will develop a uniform, time-dependent earthquake forecast model for California (§III.C.3) and the NGA-H Program, which will take advantage of the ground-motion simulation capabilities developed by SCEC research (§III.C.4). The Center is now moving toward a new type of seismic risk analysis based on rupture-to-rafters simulations that embed built structures into realistic geologic environments (§III.C.5). These initiatives will only be possible through deeper partnerships with engineering organizations.

To bolster SCEC capabilities in these areas, we intend to merge the activities of the current Seismic Hazard Analysis focus group and the Implementation Interface into a new CEO working group on Seismic Hazard & Risk Analysis, which will coordinate the development of SHA products and develop research partnerships with engineering organizations in end-to-end simulation and other aspects of risk analysis and mitigation. This new working group, which will include engineers as well as scientists, will connect the research activities managed by the Planning Committee with the external research partnerships managed by CEO; it will oversee the development of the SCEC initiatives in seismic hazard and risk analysis, and it will help to interface external communities to the new resources provided by the SCEC Community Modeling Environment, such as the OpenSHA platform.

2. *Knowledge Transfer*

The implementation of SCEC research for practical purposes depends on effective knowledge transfer beyond engineering research and into engineering practice, emergency management, and risk mitigation. The CEO Program will in this area will focus on the following activities:

Technical Products and Programs. SCEC will organize special workshops for the insurance industry, for geotechnical firms contracted by local governments to create and revise earthquake-related policies, and for regulators of these policies. In addition, the Center will publish and distribute technical information for engineering and design professionals, the business community, planning and safety officials, and policy makers. Priorities will include increased promotion of SCEC-specific research, broader distribution of SCEC annual and technical reports, the development of community-specific summaries highlighting relevant research, and workshops based on the scientific results of SCEC3. For example, the highly successful SCEC workshops on liquefaction and landslide hazards will be continued in Southern California and initiated in Northern California. All workshops will result in a SCEC product (document, CD-ROM, software, etc.). To incentivize workshop participation, we will establish a Continuing Education Unit (CEU) program, so that technical professionals can get formal credit for attending SCEC workshops.

Local Government Partnerships. SCEC continues to explore how best to implement research at the local government level, where building codes are enacted and regulated. L. Grant and E. Runnerstrom of UC Irvine were supported by CEO in SCEC2 to study the utilization of seismic hazard data and research products by cities in Orange County, California. In particular, the study looked at the direct use of SCEC products by local-level policy-makers and staff. Preliminary analyses found that nearly all cities in Orange County relied on planning and/or geotechnical firms to prepare technical reports or Safety Elements. Therefore, in SCEC3, we will target these consultants for seismic hazard and risk information via workshops, software applications, special websites, and other resources.

SCEC will also serve local governments through its leadership of the Southern California HAZUS Users Group (SoCalHUG) to (a) train GIS professionals in HAZUS earthquake loss estimation software, (b) improve earthquake databases and inventories, and (c) develop and exercise emergency management protocols. By leading this group, SCEC is establishing strong relationships with the users of risk management tools, thus forming an effective network for promulgating the risk management tools developed by SCEC and its partners. SoCalHUG will also serve to coordinate the collection of the improved building inventory data critical for accurate loss estimation, and, using the OpenSHA platform, it will be able to produce the shaking scenarios and HAZUS loss estimates based on Uniform California Earthquake Rupture Forecast developed by the SCEC-led WGCEP. These scenario-based loss estimates will be very useful for planning, mitigation, and preparedness activities by local governments.

SCEC Associates Program. A business and industry associates program will be developed in SCEC3 to support the needs of commercial users of technical information and to couple business organizations into SCEC activities, Potential members include insurance and reinsurance companies, utilities, transportation-related organizations (railways, ports, airports, etc.), companies with significant infrastructure in Southern California, and others. Participants will have facilitated access to SCEC research results and CEO products. Special workshops for participants will explain the latest SCEC findings in an appropriate end-user context. SCEC Associates will help to identify how SCEC research can directly address the needs of the community at large.

3. *Education*

In SCEC3, education programs will be given special emphasis as resources developed during

SCEC2 become available for deployment. These resources will build upon (a) the intrinsic interest of students in their natural environment, including the "teachable moments" when earthquakes happen, and (b) the scientific and educational expertise available from SCEC institutions.

Educational Experiences. SCEC3 will use the study of earthquakes in the laboratory and field to enrich the educational experiences of students from all backgrounds and help them appreciate the excitement of basic and applied science. SCEC will expand its two summer internship programs, SCEC/SURE, and SCEC/USEIT (see section II.C.3), with support from the NSF Research Experiences for Undergraduates (REU) program These programs are the principal SCEC framework for undergraduate student participation in SCEC, and they are the Center's most effective mechanism for increasing workforce diversity in the long term (see §IV.C).

The Center's growing inventory of field-trip guides for the Los Angeles region will be adapted for high school and college class excursions. The California School Seismometer Network will be created, based on similar networks such as the South Carolina Earth Physics Project, as a part of the U.S. Educational Seismic Network.

Curricula Development and Advocacy. SCEC3 will lead the formation of an *Earthquake Education Task Force* to advocate improved K-12 Earth science education, including revised science standards that recognize the importance and value of Earth science. This group, which will be composed of representatives from the SCEC educational institutions, the CGS, and the USGS, and will include science education specialists and emergency preparedness experts, will initially be focused on earthquake education in California. Specific goals guiding these efforts will be (a) to structure these Earth-science curricula in ways that appeal to students from under-represented groups, and (b) to achieve better meshing and more continuity between K-12 and college-level Earth-science education. As part of a major new partnership with the Los Angeles Unified School District, SCEC will train teachers how to implement a new sixth-grade Earth-science curricula unit, which will include SCEC visualizations and videos such as *Earthquake Country—Los Angeles*. It now appears that this program will also be adopted in several other school districts throughout the country.

Educational Resources. SCEC3 will augment and expand the distribution of educational resources through the Electronic Encyclopedia of Earthquakes (E^3), the primary SCEC framework for presenting extensive earthquake science and engineering information, including curricular materials and technical information organized by topical areas. Curricular materials will also include video packages developed by SCEC such as *Earthquakes: Seismic Sleuths* and *Earthquake Country—Los Angeles,* which will be updated periodically. At the college level, the focus will be on developing community resources for general-education earthquake courses offered at SCEC institutions, including visualizations, lesson plans, and presentations. SCEC faculty will also be supported to spend sabbatical periods developing educational materials.

Professional Development for Educators. SCEC3 will offer workshops each year to K-12 and college-level educators that demonstrate and encourage the use of its educational resources, curricula, and field-based experiences, in accordance with established career development standards. Many of these workshops will be offered as a result of school district partnerships developed in SCEC2. Also, a new *Research Experiences for Teachers* (RET) program will be launched in SCEC3, to provide field and laboratory-based science experience for groups of teachers each summer.

4. Public Outreach

The public outreach products developed, updated, and maintained during SCEC2 represent a new capacity for providing earthquake-related information and services. During SCEC3, these resources will allow SCEC and our partners in the Earthquake Country Alliance (ECA) to provide continually updated information in a broad assortment of venues and mechanisms. The ECA is now the primary SCEC framework for maintaining partnerships and developing new products and services for the general public. In SCEC3, the ECA will be expanded with greater involvement of the news media and additional local governments preparedness officials. Activities will be organized within three primary areas, as follows.

Informational Resources. During SCEC3, *Putting Down Roots in Earthquake Country* will remain the principal SCEC vehicle for providing earthquake science, mitigation, and preparedness information to the public. The *Roots* framework extends beyond the distribution of a printed brochure and the online version. For example, the Birch Aquarium in San Diego has a new earthquake exhibit which features a "Seven Steps" display taken directly from *Roots*, and the fifteen-county Emergency Survival Program (ESP) will be basing its 2006 campaign around the "Seven Steps." SCEC participates in the ESP Coordinating Council.

The new version of the *Roots* brochure was designed to allow other regions to adopt its structure and create additional versions; it will also be produced in Spanish, and versions for other languages may be created. A reprinting in Southern California in 2005 will include a coupon for "Quakehold!" earthquake preparedness products, as part of a CEA-sponsored program.

In SCEC3, we will initiate *The SCEC Seismic Record*, an earthquake activity report with historical information, recent research results, safety and mitigation information, and links to resources and maps, which will be printed in newspapers and distributed online. Most of these resources will also be made available in Spanish and other languages.

SCEC web services will be continually updated with community participation and authorship. For example, SCEC scientists are now composing *SCEC Nuggets*, one-page descriptions of individual research projects logged on the SCEC website. In 2004 SCEC's online resources made a coordinated response possible to several public awareness issues: a mini-series about a "10.5" magnitude earthquake, a widely-reported prediction for an earthquake in Southern California, and a mass-email campaign promoting a (dangerous) alternative to the "drop, cover, and hold on" safety strategy endorsed by all preparedness groups. ECA members were able to direct their audiences to information available at the ECA website (www.earthquakecountry.info), developed and maintained by SCEC) rather than creating their own responses. This type of coordination will remain a critical role for SCEC3.

Public Presentations. SCEC3 will conduct seminars for large audiences that will provide current earthquake information, which will be broadcast live via the Internet to allow even more people to participate. Presentations for smaller audiences will also be organized in local communities through a *SCEC Speakers Bureau.* Many of the presentations may also be filmed for online viewing at a later time.

Interactive Experiences. We will update our field trip guides to local faults and earthquake-related points of interest, and organize them within the *SCEC Seismic Sites* framework, developed using the SCEC/CORE technology. These web-based field trip guides will combine individual field locations into preset guides that can be printed for individuals, families or groups to use, or enjoyed online (video footage from many locations may be included). What will be exciting is that the individual stops from separate trips can be combined to allow the public to create custom field trips according to their individual interests. In addition to these field tips, SCEC3 will organize a network of museum and science centers that host earthquake exhibits, such as those created in concert with the California Science Center in Los Angeles and Riverside County Youth Museum (KidZone), Finally, the CEO will maintain and improve the *Wallace Creek Interpretive Trail* and develop other permanent earthquake-related venues that allow the public to experience Earthquake Country.

IV. Management Plan

SCEC3 will continue to operate under the lean, flexible, and very successful management structure developed for SCEC2. The management plan described here is codified in a set of by-laws adopted in February 2002, at the transition from SCEC1 to SCEC2. In preparing this proposal, the Board of Directors voted unanimously to operate SCEC3 under the same by-laws with the University of Southern California (USC) continuing as the managing institution, and with T. Jordan, the Principal Investigator on this proposal, continuing as the Center Director.

A. Organization of the Center

Institutional Membership and Board of Directors. The Center will remain an institutionally-based organization governed by a Board of Directors (Fig. 4.1). It will recognize both core institutions, which make a major, sustained commitment to SCEC objectives, and a larger number of participating institutions, which are self-nominated through the involvement of individual scientists or groups in SCEC activities and confirmed by the Board. The 15 core and 39 participating institutions that were enrolled at the proposal submission date of March 1, 2005, are listed in Table 1.1. Membership may evolve, however, because SCEC will continue as an open consortium, available to any individuals and institutions seeking to collaborate on earthquake science in Southern California.

Each core institution will appoint one member to the Board. In addition, the Board will elect four nominees (up from the two authorized in SCEC2) from the non-core, participating institutions to serve two-year terms on the Board as members-at-large. The Board will be the primary decision-making body of SCEC; it will meet three times (February, June, and September) per year to approve the annual science plan, management plan, and budget, and to deal with major business items, including the election of an Executive Committee and an Advisory Council. There are provisions in the by-laws to allow the Board to conduct business by electronic mail. The Center Director will act as Chair of the Board. Based the institutional membership listed in Table 1.1, the Board will comprise 19 voting members (15 core institutions plus four at-large members). Non-voting members will include the Deputy Director; the Associate Director for Administration (serving as Executive Secretary); the Associate Director for Communication, Education, and Outreach; and the Information Technology Architect.

The Executive Committee will handle the day-to-day decision-making responsibilities, mainly through electronic mail. It will have five voting members, the Center Director, who will act as Chair, and four members elected for two-year terms from amongst the Board, as well as two non-voting members, the Deputy Director and the Associate Director for Administration, who will serve as Executive Secretary. The Executive Committee will have the authority to approve proposal submissions and contractual arrangements for the Center.

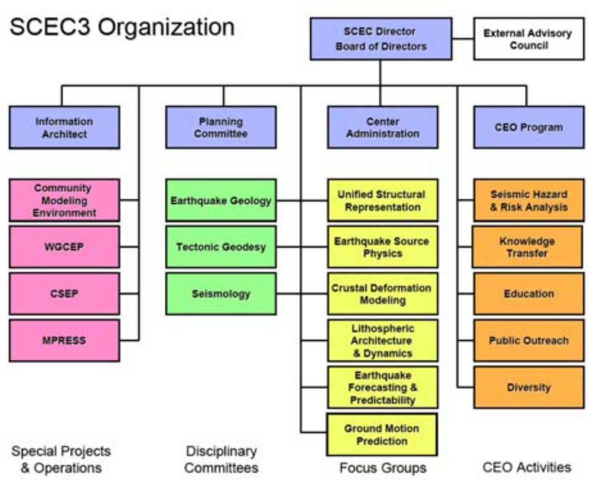


Fig. 4.1 The SCEC3 organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects & operations (pink), CEO activities (orange), management offices (blue), and its external advisory council (white). The changes in the working group structure relative to SCEC2 are described in §III.B.

Administration. The Center Director will be the Chief Executive Officer of the Center and will bear ultimate responsibility for the Center's programs and budget. The Director's responsibilities will include: (a) presiding at Board meetings and, insofar as resources permit, overseeing that orders and votes of the Board are executed; (b) devising a fair and effective process for the development of the annual science plan, based on proposals or work plans submitted to the Center, and overseeing its implementation; (c) acting as P.I. on all proposals submitted by the Center, retaining final authority to make and implement decisions on Center grants and contracts; (d) ensuring that funds are properly allocated to various Center activities; (e) appointing committees to assist in carrying out Center business; and (f) overseeing the preparation of technical reports.

The Deputy Director will serve as (non-voting) Vice-Chair of the Board of Directors. S/he will call and conduct Board meetings in the absence of the Chair, and will perform duties and exercise powers as assigned by the Center Director and Board. Among the duties of the Deputy Director will be (a) chair of the Planning Committee, (b) liaison with the SCEC science partners, and (c) chair of the annual meeting. The Deputy Director will be nominated by the Center Director for board approval in the summer of 2006.

The Associate Director for Administration will assist the Center Director in the daily operations of the Center and be responsible for managing the budget as approved by the Board, filing reports as required by the Board and funding agencies, and keeping the Board, funding agencies, and Center participants current on all Center activities through electronic mail, web postings, and written communications. J. McRaney of USC, the current SCEC Associate Director for Administration, has agreed to continue to serve in this capacity through SCEC3.

Advisory Council. The Center will have an external Advisory Council (AC) to serve as an experienced advisory body to the Board of Directors. The AC will comprise a diverse membership representing all aspects of Center activities, including basic and applied earthquake research and related technical disciplines (e.g., earthquake engineering, risk management, and computer science), formal and informal education, and public outreach. The Council will report to the Board through its Chair. Members of the Council will be drawn from academia, government, and the private sector; they will be elected by the Board for three-year terms and may be re-elected. The Council will meet once per year to review Center programs and plans and prepare a report for the Center Director. The AC chair will be advised on all major actions of the Center throughout the year. All council members will be kept informed of Center activities and will be invited to participate in all appropriate Center functions and activities. Summaries of Council reports will be made available to NSF, the USGS, and other funding agencies.

Management of Center Activities. The SCEC3 organization chart shown in Fig. 4.1 reflects the changes in working group structure described in §III.B. Standing disciplinary committees in Earthquake Geology, Tectonic Geodesy, and Seismology will coordinate the principal data-gathering activities (e.g., seismic and geodetic networks, geologic field studies, laboratory work) and the disciplinary infrastructure, as well as communal field equipment and experiments. Interdisciplinary research will be organized by focus groups in Unified Structural Representation, Earthquake Source

Physics, Crustal Deformation Modeling, Lithospheric Architecture & Dynamics, Earthquake Forecasting & Predictability, and Ground Motion Prediction. The focus groups will be project-oriented, with well-defined tasks, timelines, and products. They will be responsible for the development, verification, release, maintenance, and improvement of the SCEC Community Models. The chairs of the disciplinary committees and focus group leaders will be responsible for annual reports and will participate on the Planning Committee.

The overall framework for this data-integration and modeling effort, including the software standards for data structures and model interfaces, will be the responsibility of the SCEC Information Technology Architect. The IT Architect will report to the Center Director and will coordinate the SCEC Community Modeling Environment (CME) and other technical liaison activities. The leaders of the special project groups, which will include the CME, the Working Group on California Earthquake Probabilities (WGCEP), the Collaboratory for the Study of Earthquake Predictability (CSEP), and the Multinational Partnerships for Earthquake System Science (MPRESS), will coordinate activities in these areas and serve on the Planning Committee.

Knowledge transfer, education, and public outreach will be managed by the Associate Director for CEO, who will supervise a staff of CEO specialists. The Associate Director will act as liaison with SCEC partners in earthquake engineering and risk management. M. Benthien, the current SCEC AD for CEO, has agreed to continue in his role in SCEC3. Two-way knowledge transfer between SCEC and its engineering partners will be actively managed through the Seismic Hazard & Risk Analysis working group led by P. Somerville, who will serve on the Planning Committee. His efforts will be facilitated by a contract with URS, a SCEC participating institution involved in earthquake research and engineering implementation.

B. Budgeting Process

Planning Process. Annual and long-term budget planning will be the responsibility of the SCEC Planning Committee (PC). The PC will be chaired by the Deputy Director and comprise representatives from each of the working groups; the CEO Associate Director and the IT Architect will serve as non-voting members. The annual budget cycle will begin with the articulation of the research plan by the Planning Committee. The draft research plan will be presented to the SCEC community and discussed at the SCEC annual meeting in September. Following the annual meeting, the Planning Committee will finalize the science plan and present it to the Board and Director for approval. This research plan will form the basis for the Annual Collaboration Solicitation released in early October each year. SCEC participants submit proposals in response to the solicitation in late November. All proposals will be independently reviewed by the Center Director, the Deputy Director, and the chairs and/or co-chairs of three relevant working groups. Review assignments will avoid conflicts of interest.

The PC will meet in January of each year to review all proposals and construct an Annual Collaboration Plan. The objective of this plan will be a coherent science program consistent with SCEC's basic mission, institutional composition, and budgetary constraints that can achieve the Center's short-term objectives and long-term goals. The Deputy Director (and Planning Committee chair) will combine the PC's recommendation with requests from the Associate Director for Administration, CEO Associate Director, and the IT Architect and submit the Annual Collaboration Plan together with a coordinated Center budget to the Board of Directors. The annual budget will be approved by the Board, signed by the Center Director, and submitted to the sponsoring agencies for final approval and funding.

Proposal Evaluation Criteria. In constructing the Annual Collaboration Plan, proposals will be evaluated according to the following criteria: (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 P.I. and institution to the SCEC mission; (f) value of the proposed research relative to its cost; and (g) the need to achieve a balanced budget while maintaining a reasonable level of scientific continuity given funding limitations. With respect to criterion (b), we note that a major SCEC goal is to improve the diversity of its community and encourage early-career scientists; therefore, its resources will be distributed accordingly.

Joint SCEC/USGS Planning Committee. A major objective of SCEC is to maintain a close alignment of the Center's activities with the USGS Earthquake Program. The Center relies on three mechanisms: (a) accountability required by USGS funding of SCEC activities, (b) memberships on the Board of Directors by the three USGS offices now enrolled as SCEC core institutions, and (c) a Joint SCEC/USGS Planning Committee (JPC). The latter combines the SCEC Planning Committee with a group of program leaders designated by the USGS. This coordination mechanism has worked very well in SCEC2 and will be continued in

SCEC3. USGS members of the JPC will continue to participate in the annual PC meeting that reviews SCEC proposals and to have direct input in the formulation of the Annual Collaboration Solicitation and the Annual Collaboration Plan.

C. Diversity Plan

SCEC and its leadership are committed to the growth of a diverse scientific community. A Diversity Working Group of the Board of Directors was established at the beginning of SCEC2 (February, 2002) to formulate policies for increasing diversity. This working group, which is chaired by R. Wesson, conducted a diversity assessment to identify issues and suggest strategies. Its report focused on four major areas:

1. The leadership of SCEC, including the Officers and the Board, has been predominantly white and male. Currently, 15 of the 17 Board members are appointed by the core institutions; they should be encouraged to consider diversity in these appointments of Board members. Diversity should be considered in electing members-at-large.
2. The Planning Committee has significant power in SCEC2 and serves as a crucible for developing leadership. Diversity should be a major criterion for PC appointments.
3. Although many women and minority students are involved in intern and other programs at the undergraduate level, successively smaller numbers of women and minorities are involved at the graduate student, post doctoral, junior faculty and senior faculty levels. Because SCEC has little control in hiring scientists and staff, and in admitting students, diversity goals can be encouraged but not mandated. However, diversity should be included in the criteria used to evaluate proposals and construct the Annual Collaboration Plan.
4. The current situation is not unique to SCEC, but reflects historical trends in the earth and physical science communities. SCEC can be most effective in changing these trends by promoting diversity among its students and early-career scientists; i.e., by focusing on the "pipeline problem". The SCEC internship programs may be the most effective mechanism for this purpose.

This diversity assessment has provided the Center with effective guidance during SCEC2, and we propose to continue to advance diversity in SCEC3 through the mechanisms identified in this plan.

Some tangible progress has been made in populating SCEC leadership positions with outstanding women scientists. Three women now serve on its Board of Directors (out of 17). Four women have been appointed as working group leaders or co-leaders and have participated visibly in the SCEC2 Planning Committee process. Several women also have key roles in SCEC administration and CEO; D. Coyle will be assuming an even greater role in SCEC3 administration, and I. Cooper and M. Maynard (also Latina) are Education Specialists.

Some progress has also been made in terms of participation of minorities in SCEC leadership positions; both the current SCEC Deputy Director (R. Archuleta) and the SCEC Board representative for SDSU (S. Day) are Latino.

Recognizing that diversity is a long-term issue which requires continuing assessments and constant attention by the leadership, the Center has taken a number of concrete steps to improve its understanding of the composition and evolution of its community. Using the new CORE databasing system developed by the CEO Program (see §V.C), we can now assess the demographics of the SCEC community and track the career trajectories of our students and early-career scientists.

Of the 580 participants in SCEC2 (some no longer are involved), diversity levels generally reflect historical trends, with much greater diversity among students than senior faculty. In terms of gender, women account for 42% of SCEC undergraduates, 36% of graduate students, 27% of non-faculty researchers, 42% of administrative staff, and 15% of faculty researchers. Participation of under-represented minorities is very low, again reflecting the Earth Sciences at large: 25 of the 580 SCEC2 participants identify themselves as Latino, 10 are Native American, 3 are Black, 2 are Pacific Islander, 105 are Asian, 413 are White, and 32 have not reported.

Table 4.1. Student participation in the SURE and UseIT intern programs in the three years of SCEC2.

# in Program:	32 SURE		43 UseIT	
#Female, #Male:	16 F	16 M	13 F	30 M
Asian	0	3	2	8
Asian/White	1	0	1	0
Black/Latino	0	0	1	0
Latino	4	1	1	1
Middle Eastern	0	1	0	0
Pacific Islander	0	0	0	1
White	11	11	8	19

A bright spot in our diversity efforts is the SCEC intern program (Table 4.1). White males have constituted only 40% of SCEC2 interns (30 of 75), compared to 71% for the Center population as a whole. We believe that the key to increasing the diversity of SCEC participants in the future is to involve, interest, and retain students of diverse backgrounds such that they continue into research careers at SCEC institutions. We are vigorously pursuing this strategy. Our recruitment activities now include active participation in regional minority science meetings around the country, such as the Florida-Georgia Louis Stokes Alliance for Minority Participation Expo held each year in Orlando, Florida, and the distribution of recruitment information to historically black colleges and other minority-serving undergraduate institutions nationwide. These recruitment activities and others will be expanded in SCEC3.

Other plans include the establishment of a Sounding Board, a committee of SCEC participants who could serve as informal counselors, holding evening sessions at the annual meetings where diversity issues can be aired, developing mentoring programs at the graduate student, post doc and junior faculty levels, and identifying successful diversity practices of other large science organizations. These and other activities will support the career advancement of all members—and potential members—of the SCEC community.

D. Operations Following a Major Earthquake

Major Southern California earthquakes—1992 Landers (M7.3), 1994 Northridge (M6.7), 1999 Hector Mine (M7.1), 2002 San Simeon (M6.5), and 2003 Parkfield (M6.0)—have been important events for focusing SCEC research and stimulating collaboration. The Center's management structure, as articulated through its working groups, has been able to respond quickly in coordinating field programs with the USGS and other organizations to capture perishable data and conduct post-earthquake studies. Much has been learned about earthquake processes through these efforts.[9]

SCEC will continue to play a central role in coordinating the scientific response to major earthquakes in Southern California. Through its cooperative agreements with the NSF and USGS and its contractual arrangements with its core and participating institutions, SCEC provides a well-organized conduit for the funding of investigations in the critical period immediately following the event. Overall post-earthquake scientific response will be managed by the USGS in coordination with the California Office of Emergency Services (OES) and the California Geological Survey (CGS). The SCEC components of this response, including coordination with the NSF, will be managed by the Center Director and staff, and plans will be executed through the SCEC working groups and special teams. SCEC geologists will move quickly to resolve the scope of surface rupture, which will require immediate access to necessary equipment, clearance, and transportation, including helicopters and aerial photography. SCEC geodesists may quickly install temporary GPS receivers to track post-earthquake slip and coseismic slip during aftershocks, in addition to processing data from SCIGN and other networks (soon PBO). SCEC seismologists will immediately deploy seismometers from SCEC's Portable Broadband Instrument Center into the epicentral region to record aftershocks, resolve the properties of the fault rupture, and help assess the potential for additional large events. All these efforts will require coordination with data center seismologists who will be revising real-time information on source properties and ground motions. As observations are reported from the field, the CEO office will help coordinate an effective media response with the USGS, Caltech, and other organizations.

In SCEC3, post-earthquake response will build on new technology to shorten response times and improve modeling of potential damage. Key SCEC centers (USC, Caltech, UCSD, UCSB, USGS) will be connected with satellite phones and dedicated internet lines. Large regional earthquakes will provide important tests of early warning algorithms (see §III.C.1) and will help to calibrate SCEC research in end-to-end simulation.

All post-earthquake activities will require close coordination among earthquake science and engineering organizations. In 2002, the USGS developed *A Plan to Coordinate NEHRP Post-Earthquake Investigations* to provide guidance to coordinate post-earthquake investigations supported by the National Earthquake Hazards Reduction Program (NEHRP). The USGS plan addresses coordination of the NEHRP agencies—Federal Emergency Management Agency (FEMA), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), the U.S. Geological Survey (USGS)—and their partners such as SCEC. Part of the plan is devoted to operations of a post-earthquake clearinghouse and recognizes that the State of California has "formalized the process for establishing a clearinghouse." SCEC is a leader in the California Post Earthquake Information Clearinghouse with USGS, CGS, OES, EERI, and many others. Representatives of participating organizations meet quarterly to discuss plans and develop resources for effective response. M. Benthien, the CEO Associate Director, chairs the Clearinghouse IT working group and has led the effort to update and maintain the formal Clearinghouse planning documents. SCEC now hosts a members-only website with contact information, responses protocols, and access to online

[9] A special study by ISI Essential Science Indicators of earthquake science for the period 1993-2003 ranked 4 publications on the 1992 Landers earthquake among the top 5 in number of citations worldwide (see http://www.esi-topics.com/earthquakes/papers/). Notably, four of the top five institutions in earthquake publication citations were SCEC-affiliated (USGS, Caltech, USC, and UCLA).

data and photos being collected by Clearinghouse participants. These activities will continue in SCEC3.

V. Facilities and Resources

A. SCEC Headquarters

SCEC operates as a center because it is funded to do so by the NSF and USGS. It is not a corporation like IRIS, UNAVCO, or CUAHSI, so it depends on the support and integrity of its host institution—the University of Southern California (USC). USC's administration has made a major commitment to SCEC by renovating 11,000 square feet of space in 2001-2002 at a cost of $12M. This facility, in Zumberge Hall of Science, contains administrative offices, offices for visitors, scientists, and students, computer facilities, a media center, and an undergraduate intern laboratory.

B. Resources of the Core and Participating Institutions

The core and participating institutions provide the SCEC community with significant resources, including major facilities, computing and information resources, student support, and faculty and researcher salaries. In addition, several of the core institutions host major shared facilities. A more complete description is given in *SCEC3 Shared Experimental Facilities* as part of the Facilities Section. Here we illustrate these facilities with four examples:

Southern California Earthquake Data Center, operated by Caltech. The mission of the SCEDC is to maintain an easily accessible, high-quality, searchable archive of earthquake information for research in seismology and earthquake engineering. The Data Center archives and provides public access to earthquake parametric and waveform data gathered by the Southern California Seismic Network (SCSN), as well as other sources of earthquake related information.

SCEC Borehole Instrumentation Program, operated by the University of California, Santa Barbara. This program maintains 12 existing borehole stations and facilitates the installation of new borehole stations in collaboration with other agencies responsible for earthquake monitoring in Southern California. The borehole instrumentation is used to gain a better understanding of the near-surface effects on ground motions, to improve our ability to account for these effects in simulations of ground motion, and to get a more detailed observation of the earthquake source by avoiding the near-surface layers that typically attenuate high frequency radiation.

Portable Broadband Instrument Center, operated by the University of California, Santa Barbara. The PBIC provides researchers working on problems in southern California with year-round access to a pool of high-resolution, digital seismic recording equipment and serves as a RAMP facility in the event of significant earthquakes. In addition to the data loggers and sensors, support equipment such as solar panels, charge controllers, and batteries are also maintained.

Age-Dating Facilities. SCEC attempts to provide all paleoseismic and geologic projects with state of the art AMS ^{14}C, cosmogenic ^{10}Be, and ^{26}Al, and OSL chronological control. SCEC consolidates the chronological efforts of multiple projects in order to provide greater efficiency and cost savings. Consolidation of dating efforts also provides more coherent and more accurate paleoseismic chronologies across the many SCEC field investigations that require AMS and/or OSL dating. The SCEC chronology efforts are coordinated at the Lawrence Livermore National Laboratory.

C. Cyberinfrastructure

Community Modeling Environment. SCEC provides significant computing and data management facilities to SCEC researchers. Existing SCEC facilities and resources have been augmented through the activities and developments of the SCEC Community Modeling Environment (SCEC/CME) Project (see Figs. 1.5 & 1.6 and online at www.scec.org/cme). The SCEC computing facilities are a shared, heterogeneous, and distributed computing environment with significant computational, networking, visualization, and storage capabilities. In addition, SCEC has established grid-based computer resource sharing system through the SCEC/CME that provides SCEC researchers with access to additional computing capabilities including access to High Performance Computing (HPC) facilities at USC, the San Diego Supercomputing Center (SDSC), the Pittsburg Supercomputing Center (PSC), the Information Sciences Institute (ISI)

The SCEC/CME system hosts a collection of geophysical simulation codes. These codes are accessible through the SCEC/CME computational testbed system. Programs available in the current SCEC/CME system include probabilistic seismic hazard calculation programs, automatic meshing tools, geophysical model codes such as velocity modeling codes, as well as wave propagation software that has been developed by SCEC researchers. The SCEC/CME system provides access to these codes as well as access to the computing facilities needed to run geophysical simulations using the codes.

The SCEC/CME is developing extensive libraries of simulation-based data sets. For example, 96,000 synthetic seismograms for 70 Los Angeles region earthquake scenarios are stored with appropriate metadata in a SCEC digital library system located at the SDSC. These simulation results are accessible through web-based access tools.

The SCEC IT resources include collaborative tools such as SCEC-wide and Project-specific web sites, group email lists, web forums, and web logs hosted on UltraSPARC-based Solaris and Intel-based Linux computers. SCEC has a computing laboratory at USC for use by SCEC researchers and the SCEC UseIT intern program with 30 PCs are configured to support software development activities, video-editing, and animation. This lab also includes Geowall 3D visualization projection equipment and Linux visualization computers with fiber-optic network cards, large disks, and high-end graphics cards for visualization of volumetric data sets.

The SCEC facilities at USC now include a computer server room with high data-rate network connections, including a 1-GB multi-mode fiber optic link to the USC High Performance Computing and Communication (HPCC) center, and uninterruptible power supply, computer racks for SCEC servers and more than 10 TB of disk storage. The Solaris and Linux servers are available for software development and for computational work by SCEC researchers, and they host suites of scientific application programs such as Seismic Analysis Code (SAC), Generic Mapping Tools (GMT), and MATLAB. The SCEC server room also includes a small (9-node) Linux cluster to help SCEC researcher develop and test of high performance parallel simulation codes. SCEC also has dedicated access to 32 Xeon 32-bit computing nodes, 48 Opteron 64-bit computing nodes, and over 25 TB of storage on the USC HPCC system, and it has been granted large (>10^5 CPU-hr) group allocations on the large-scale USC HPCC computing facilities. This allocation is currently utilized by several SCEC research groups external to USC.

Community Organized Resource Environment (CORE) and Community Information System (CIS). CORE is SCEC's content development and management system, originally developed for the Electronic Encyclopedia of Earthquakes (E3) project (see §II.C.4) and now used to create dynamically the web pages such of the SCEC main website (www.scec.org), the Earthquake Country Alliance website (www.earthquakecountry.info), the online *Putting Down Roots in Earthquake Country* (www.earthquakecountry.info/roots), SCEC "Nuggets", and EERI's online Mitigation Center. CORE is also being used to create and review print resources (*Roots*, field trip guides, and other documents) and to organize materials for SCEC teacher workshops, exhibits, and other educational activities.

The SCEC CIS is a databasing system first implemented to facilitate registration for the 2002 SCEC Annual Meeting, and it has since been used for registration for most SCEC workshops and meetings, for tracking SCEC publications, maintaining demographic information, managing e-mail lists, processing SCEC intern applications, and providing access to contact information for each of the 750+ members of the SCEC Community. One of the most successful applications of the system has been to streamline the process for submitting and reviewing SCEC proposals each year, saving SCEC leadership time and allowing more information to be tracked for assessments. For example, SCEC CEO can track research projects with potential CEO applications more efficiently, and distribution of funding can be more easily analyzed.

As a service, similar CIS interfaces have been developed for other communities associated with SCEC using the same system. These include the California Post Earthquake Information Clearinghouse, the Earthquake Country Alliance, the Earthquake Information Providers (EqIP), and soon others. Members of multiple communities can access their systems using a single password and update their information in one location, a major efficiency.

VI. References

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Letters of Support from Partner Organizations

This section of supporting documents includes letters from SCEC partner organizations as follows:

1. American Red Cross
2. California Earthquake Authority
3. California Geological Survey
4. Consortium of Universities for Research in Earthquake Engineering (CUREE)
5. Earthquake Engineering Research Institute (EERI)
6. Incorporated Research Institutions for Seismology (IRIS)
7. Pacific Earthquake Engineering Research Center (PEER)
8. NEES Consortium
9. County of Los Angeles Emergency Management Agency
10. Southern California Edison Company

American Red Cross
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February 28, 2005

Dr. Thomas Jordan, Director
Southern California Earthquake Center
3651 Trousdale Parkway, Suite 169
Los Angeles, CA 90089-0742

Dear Dr, Jordan:

I am writing in support of SCEC's proposal for continued funding. The results of the Center's research, education, public information, and knowledge transfer programs have been of great benefit to the American Red Cross and the public that we serve, and we look forward to the continuation of the Center and our partnership in many of its projects and programs.

As the designated liaison to SCEC for the 19 Southern California chapters of the American Red Cross, I would like to inform the National Science Foundation and the United States Geological Survey of the great value that we have gained from the development of a regional model of multi-disciplinary earthquake science, and the public information and education programs that accompany that model.

From the collaboration on the original 1995 version of "Putting Down Roots in Earthquake Country", through the news conferences and seminars that SCEC has hosted to transfer new scientific findings, through the coordination of events to recognize and capitalize on the 10^{th} anniversary of the Northridge earthquake and the creation of the Earthquake Country Alliance, to the collaboration on the design and contents of the new "Roots", Red Cross has gained enormously from our participation and partnership. A major program of the American Red Cross is disaster preparedness education. Initially, our work with SCEC provided us with the latest scientific information on which to base that education. Participation in SCEC seminars and workshops helped us define better ways to reach and educate our target audience. And, most recently, our 19 chapters received more than 50,000 copies of the new "Putting Down Roots in Earthquake Country", at no cost, that gave us an opportunity we rarely have to provide "concise, vital information that is well presented, easy to read, with everything from earthquake fundamentals to steps to prepare and recover". This quotation is from our Inland Empire Chapter, based in San Bernardino, who has used the 2004 wildfires and subsequent floods and mudslides as a springboard to increase their communities' preparedness for earthquakes.

SCEC plays a vital role in Southern California as a clearinghouse for education, public information, and knowledge transfer. Recently, when erroneous and potentially dangerous information about how to survive an earthquake was widely circulated on the internet and found its way into print, it was through SCEC that the many agencies involved in public education were able to come together and formulate a plan to counteract the misinformation. Having correct information disseminated by an organization with SCEC's status and breadth made an impact on the public that none of us partner agencies could have made on our own.

The similar role that SCEC took as the clearinghouse agency for information on events commemorating the 10th anniversary of the Northridge earthquake was equally valuable. In a place as heavily populated as Southern California, with the number of academic, governmental, and non-profit agencies who are involved or interested in earthquake science, preparedness and education, the importance of such a "central expert" role cannot be over-emphasized. It has been clearly shown that when the public receives conflicting information from different agencies, they will take no precautionary or protective actions. SCEC serves a vital role by serving as a "central expert" with connections to and information from the broad academic, scientific, and public policy community. This gives partner agencies such as the American Red Cross a strong foundation on which to stand as we work to educate the "average resident" and motivate him/her to understand and mitigate against the hazards of earthquakes in his/her life.

Given that the FEMA HAZUS study showed that California carries 50% of the economic risk from earthquakes in the United States, it seems clear that the money that funds the Southern California Earthquake Center is one of the most cost-effective programs in the country. The more that SCEC learns and shares, the more we can reduce the potential losses from the inevitable future quakes.

Sincerely,

Peggy L. Brutsche

Peggy L. Brutsche
Response Services Officer
American Red Cross
Greater Long Beach Chapter

CALIFORNIA EARTHQUAKE AUTHORITY

February 24, 2005

Thomas Jordan, Ph.D.
Director, Southern California Earthquake Center
3651 Trousdale Parkway, Suite 169
Los Angeles, CA 90089--0742

Dear Dr. Jordan:

The California Earthquake Authority values the opportunity to collaborate with the Southern California Earthquake Center and salutes your organization's contributions in advancing earthquake science and elevating public awareness of earthquake risks. Through its research and collaborative development of educational materials, SCEC has played a vital role in enabling the CEA to meet a number of its key strategic objectives.

The popular booklet, *Putting Down Roots in Earthquake Country*, is an important component of our mutual goal to educate Californians on earthquake preparedness. Additionally, the video and curriculum project, *Written in Stone: Earthquake Country Los Angeles*, takes earthquake preparedness lessons into the classroom, which serves to educate the next generation of homeowners.

SCEC's work on these and other projects is second-to-none – we greatly appreciate opportunities to collaborate with you and together, encourage the widest possible distribution of these valuable educational products. The CEA thanks you and your team for creating tools that enable communities to learn and better understand the unique risks of living in earthquake country, and we look forward to future opportunities to work with you.

In addition, we are enthusiastic about supporting the new ventures SCEC plans to launch during 2005. We are confident the work of the new "Working Group on California Earthquake Probabilities" will create new horizons in earthquake research that will benefit the CEA and its policyholders, and indeed, all Californians. And as well, we consider the "Unified California Earthquake Rupture Forecast," the NGA product, and "End-to-End Simulations" to be important elements in advancing seismic science and residential structural engineering. These endeavors will substantially enhance the CEA's ability to understand, estimate, and adjust earthquake losses, and we believe the results of these projects will be quite helpful to the CEA in its rate-making processes.

Thank you, Tom, for your and SCEC's leadership in helping to build productive and meaningful collaborations between earthquake scientists and engineers and organizations such as the CEA, all of which lead directly to greater and more accurate assessment of earthquake-related risks – this is a true public benefit. Your efforts in advancing science and building knowledge continue to play a key role in enabling the CEA to fulfill its mission, and for that reason, we salute SCEC's contributions, support its endeavors, and look forward to continuing to learn together.

Sincerely,

Elaine Bush
Chief Executive Officer

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February 23, 2005

Dr. Thomas Jordan, Director
Southern California Earthquake Center
3651 Trousdale Parkway Suite 169
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Dr. Thomas Jordan:

On behalf of the California Geological Survey, I wish extend our gratitude and support for the Southern California Earthquake Center Since its inception, the relevance of SCEC research has transcended the academic/basic science domain to application, becoming increasingly important to seismic safety policy in California. Particula examples include the Seismic Hazards Mapping Act special advisory committees formed to assist the City and County of Los Angeles implement their mandates, and more recently, the Working Group o California Earthquake Probabilities.

Products of the WGCEP, and its predecessors, have significantly improved understanding of seismic hazard in California, having foun application to design and construction decision-making via the California Building Standards Code, and in provision of fair and equitable earthquake insurance by providing a basis for independent reviewing rate setting by the California Earthquake Authority. SCEC lead role in the new WGCEP will be an important step in continuing t valuable service to the citizens of California.

We hope to continue our cooperative work with SCEC in the role as principal liaison for science and technology transfer to state government policy. We particularly look forward to collaboration on the new WGCEP initiative to develop a statewide time-dependent earthquake hazard model. These collaborative efforts can perhaps b made most effective by incorporating our agency in the proposed co membership for SCEC3. We look forward to discussing that opportunity in the near future.

Sincerely,

Michael S. Reichle
Acting State Geologist
California Geological Survey

CUREE Consortium of Universities for Research in Earthquake Engineering

CUREE, a non-profit organization established in 1988, is devoted to the advancement of earthquake engineering research, education, and implementation.

February 18, 2005

Dr. Thomas Jordan, Director
Southern California Earthquake Center
3651 Trousdale Parkway Suite 169
Los Angeles, CA 90089-0742

Subject: Support Letter for SCEC Renewal Proposal

Dear Dr. Jordan:

I am pleased to provide this CUREE statement of support for the 2007-2012 SCEC renewal proposal. In addition to CUREE's strong general desire to see the Center continue to develop its research program, I can comment briefly on three specific examples of past or current SCEC-CUREE collaboration. I cite these as "data points" that support the extrapolation that innovative and successful earth science-engineering collaboration will continue to occur over SCEC's next five-year timespan.

First, for the benefit of other readers of this letter involved in your proposal's review, the "EE" (Earthquake Engineering) in CUREE's name translates into "engineering applied to the subject of earthquakes," and our organization essentially draws its strength from the civil engineering departments of our 28 university members. The deans of the school of engineering of a university member selects the Representative to CUREE, and almost all our 350 individual members are structural or geotechnical engineering professors (with about 10% being past or current practicing engineer members of our Board of Directors). We don't claim to represent earth scientists or have a research capability in that discipline. Thus, SCEC and CUREE have non-redundant capabilities that form a geoscience-engineering bridge, and this has been very useful.

Rupture-to-Rafters Simulation

This catch phrase of the future-oriented SCEC program and its underlying conceptual basis have met with a very positive response from the engineering community. CUREE is currently collaborating with SCEC to assemble a research proposal to NSF for the NEES (Network for Earthquake Engineering Simulation) program, and we are using SCEC's end-to-end simulation goal as the project's framework. As a means to organizing a research project and its detailed tasks, this framework is very useful. It also gives structural, geotechnical, and risk engineering an advanced objective that mobilizes the current intellectual talent pool and helps to attract bright young minds to the field. The results flowing from such a research project also have great practical utility for building codes and engineering practice. In effect, what researchers call simulation is what practicing engineers do when they design and analyze structures, so advances in simulation have a direct path to implementation in the practice of engineering.

Electronic Encyclopedia of Earthquakes

This ongoing collaboration between our two organizations (CUREE has been a subaward to SCEC through several renewals of this NSF-funded project) is an example of the fruitful educational applications of engineering-earth science collaboration. The Electronic Encyclopedia of Earthquakes digital library collection deals with all aspects of earthquakes. A particular topic such as aftershocks or attenuation obviously has a geoscience basis, and at the same time it has engineering aspects related to criteria in building codes and post-earthquake structural safety inspections. The Encyclopedia keeps the multi-disciplinary nature of the underlying phenomenon intact and mixes material from different disciplines as appropriate. In terms of the educational use of the digital library collection for a high school or college level math course, both geoscience and engineering have relevant content to offer to challenge students' minds. If an educator needs research-quality data and methods annotated and sorted to be relevant for a particular class, say introductory algebra, it is foolish to make them search out resources at one website devoted only to geoscience aspects of earthquakes and another to find some interesting earthquake engineering applications. Thus the multi-disciplinary SCEC-CUREE collaboration has proven valuable in education as well as research.

CUREE-SCEC Course on the Earth Sciences - Engineering Interface in Seismic Design

Several years ago in Los Angeles this short course in Los Angeles brought together presenters from the disciplines of earth science (Tom Henyey, Kerry Sieh, Susan Hough, Mark Petersen, Tom Heaton) and engineering (C. Allin Cornell, Charles Kircher, Helmut Krawinkler, Farzad Naiem). While the quantitative capability today in both fields has considerably advanced beyond five years ago, the premise of that course identified the theme that still challenges and unifies the two disciplines: "At present, the two fields are converging on a capability to develop integrated earth science-engineering models of how a building or other structure at any particular location, or an entire urban region, will behave in future earthquakes." This "wide angle" science vision is easier said than done. Continuing the SCEC program another five years will push this effort forward, rather than plough over already-tilled ground.

Again, CUREE strongly endorses the SCEC continuation proposal and wishes it the best of luck.

Sincerely,

Reitherman

Robert Reitherman
EXECUTIVE DIRECTOR

cc: Professor Andrew Whittaker, University at Buffalo-SUNY
CUREE President

February 25, 2005

Professor Thomas Jordan
Director
Southern California Earthquake Center
3651 Trousdale Parkway, Suite 169
Los Angeles, CA 90089-0742

Dear Tom:

I am pleased to know that SCEC is seeking renewal for the period of 2007–2012. SCEC is well recognized in the scientific community for its many vital contributions to advancing earthquake science and improving basic understanding of the physics of the earth. It is critical that the Center be funded adequately to ensure that your excellent work at so many universities and in collaboration with USGS be allowed to continue and to prosper. Not only is SCEC a unique research institute, but the support that SCEC has shown to the next generation of scientists, through its active involvement with and support of graduate and undergraduate students, is superb and will enrich the field for decades to come. This alone should justify SCEC's renewal.

However, there are many other unique aspects of SCEC that certainly call for its continued support. Over the years, SCEC has come to play an extremely critical role in bringing together members of the engineering research community and members of the earth science community. This is essential to ensuring that the most current scientific research is incorporated into tools that can be used by design professionals to reduce earthquake risk. By working closely with members of the engineering community, SCEC scientists are gaining a better understanding of the types of information that engineers need to economically design and build earthquake-resistant structures. I appreciate that much of this is a result of the personal commitment you have shown to bringing our communities together. Both research and practice will benefit from this collaboration.

EERI looks forward to continued collaboration with various SCEC programs in the coming years. As you know, we are currently working closely with Mark Benthien as he and his Education and Outreach staff develop the digital library project to create an electronic encyclopedia of earthquakes. We expect this project to have an enormous impact on the education of school children and others in the non science public, but we also anticipate that it will prove of great value to those in our own engineering and design fields, who are not earth science specialists but need access to current and reliable scientific information in a form they can share with their clients and colleagues. We look forward to making our own web-based Mitigation Center an important element within this digital library platform.

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a nonprofit corporation

Finally, EERI values the assistance SCEC has provided to the EERI Southern California Chapter, hosting meetings, helping to promote multidisciplinary earthquake educational efforts, and helping to promote and host a range of EERI programs, including our post-earthquake reconnaissance briefings. Mark Benthien has been a stalwart of the chapter and a major contributor to chapter activities. We look forward to working with him for many years to come.

On behalf of EERI, we sincerely wish you the most favorable reviews as you seek renewal of support for SCEC.

Sincerely,

Susan K. Tubbesing
Executive Director

cc: Board of Directors

the IRIS CONSORTIUM

March 2, 2005

Dr. Thomas Jordan
Director
Southern California Earthquake Center
3651 Trousdale Parkway Suite 169
Los Angeles, CA 90089-0742

Dear Tom

The Southern California Earthquake Center has emerged as the preeminent focus of research on earthquakes and earthquake hazards in Southern California. We are pleased to see that plans are underway to build a healthy future for the intellectual, technical and educational resources that SCEC has created.

Over the past decade, the complementary nature of SCEC and IRIS has lead to a solid base for cooperation between our two organizations. IRIS/PASSCAL instruments have been used by SCEC researchers in active source experiments such as LARSE and in aftershock studies for almost all of the significant earthquakes in recent years in Southern California. The IRIS Data Management System has worked closely with SCEC to coordinate procedures for data exchange and to establish open access to a variety of seismological data through interactions related to the Community Modeling Environment. The research community benefits from participation in SCEC and IRIS Workshops and our Education and Outreach programs are coordinating on the development of materials and activities as part of the E3 encyclopedia development. Close interactions between staff and in planning activities can ensure that effective use is made of our resources in areas of mutual interest.

We will be pleased to continue and expand these areas of cooperation as part of IRIS and SCEC core activities. Interactions between SCEC, IRIS and EarthScope/USArray will help ensure that these developments build on immediate SCEC interests, but also serve the broad regional and national goals of IRIS and USArray.

We wish you success in your proposal and look forward to continued and productive collaboration in the future.

Yours sincerely,

David W. Simpson
President

Thorne Lay
Chair, IRIS Board of Directors

INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY
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Pacific Earthquake Engineering Research Center
1301 S. 46th Street, Bldg. 451-RFS
Richmond, CALIFORNIA 94804
TEL: (510) 231-9554

3 March 2005

Thomas H. Jordan
Director, Southern California Earthquake Center
University Professor and W. M. Keck Professor of Geophysics
Department of Earth Sciences, 3651 Trousdale Parkway, Suite 166
University of Southern California, Los Angeles, CA 90089-0742
phone: 213-821-1237; fax: 213-740-0011; email: tjordan@usc.edu

Professor Jordan:

I am writing to provide my strong endorsement of your proposal to the NSF and USGS for support of the Southern California Earthquake Center (February 1, 2007 through January 31, 2012). The proposal continues and advances the excellent work of SCEC, which I have followed closely over the past decade. The proposal reflects the evolution in earthquake science made possible by SCEC, and proposes the appropriate next steps for continued work. In my view, it is critical that the work be funded so that progress in this field can continue to accelerate.

The outstanding contributions of SCEC to earthquake science and its applications are well cited in the proposal and well known in the earthquake science and engineering communities nationally and internationally. Its importance as a national and international center of excellence is evident by the broad participation in SCEC activities. The community of involved scientists and engineers is continually growing and making possible ever more rapid advances in earthquake science and its application in engineering. The center has reached a vital stage in its development that should be promoted through continued financial support.

As an engineer and director of the Pacific Earthquake Engineering Research Center (PEER), I have benefited greatly from SCEC's work and our affiliation with them. The collaboration interface implemented by SCEC has been very effective in promoting collaboration between SCEC and the engineering community, and is evidence of SCEC's continuing commitment to development and promotion of useful products.

SCEC has been an active contributor to the Next Generation Attenuation Relation program, a multi-agency effort to bring together the leading experts to develop improved attenuation relations with consensus among the community. SCEC has provided financial support for this program that is essential to its successful completion; SCEC's contribution is leveraged with significant contributions from other agencies, maximizing the utilization of available funds. In addition to financial support, SCEC researchers are providing key technical contributions through ground motion simulations that are augmenting the gaps in the available records, especially for large magnitudes and close distances. SCEC's current proposal includes the NGA-H program, which will make much greater use of simulation techniques. From the engineering seismology perspective, the recently past, ongoing, and proposed work must be counted among the most significant contributions in the past decade.

The ability to simulate regional ground shaking is one of the fundamental building blocks for regional loss estimation, which in its most scientifically rigorous form is sometimes referred to as “rupture to rivets” simulation. The engineering, emergency response, and public policy communities are depending on SCEC’s contributions to these simulations, so we are very pleased to see that SCEC is making this one of the foci of its continuing work. PEER and SCEC are planning a collaborative effort using this approach to understand the collapse risk posed by older existing concrete buildings. We believe that by using advanced simulation procedures, including simulation of regional ground shaking and simulation of structural response, we can better understand the mitigation needs of these buildings and develop a range of incentives and regulations that expands, not restricts, the ways mitigation is approached. PEER is proposing to do this work with funding from the NSF Network for Earthquake Engineering Simulation (NEES) program, as well as other funds supporting its program. This collaboration with SCEC will leverage available funds and merge science and engineering in the interest of developing effective public policy to address a serious regional and national threat.

In light of the excellent science and collaborative contributions of SCEC, I urge your support of this SCEC proposal.

Respectfully,

Jack Moehle

Jack P. Moehle
Professor and Director
Pacific Earthquake Engineering Research Center

February 18, 2005

Dr. Thomas Jordan, Director
Southern California Earthquake Center
3651 Trousdale Parkway Suite 169
Los Angeles, CA 90089-0742

Dear Tom:

I am pleased to have this opportunity to express strong support of the Southern California Earthquake Center's (SCEC's) interest in pursuing inter-disciplinary research collaborations with NEES-affiliated earthquake engineers as you develop and propose SCEC's strategic vision for years 2007-2012 to the National Science Foundation and the United States Geologic Survey.

As you well know, reliable prediction of the performance of the built infrastructure during earthquakes requires excellent capabilities to model both ground motions and the engineering response of built facilities with a high degree of fidelity. The NEES engineering research program is focused on developing a rich archive of experimental data to characterize the inelastic behavior of elements and subassemblies of the built infrastructure for purposes of improving capabilities to numerically simulate the seismic performance of a complete facility. However, consideration of a single response to a single ground motion is wholly insufficient to capture real behavior in the field since facility performance during an earthquake is highly stochastic in nature. To truly characterize system response, many combinations of ground motions and facility-specific response must be considered.

SCEC has a distinguished history of accomplishment, and continues to be a recognized leader in the development and coordinated application of advanced ground-motion simulation techniques. These simulation capabilities have enabled systematic exploration of a wide range of seismological conditions for which the empirical ground-motion archive is poorly populated. SCEC's continuing efforts to refine both these simulation techniques and the geosciences data demanded by these models are essential elements of future capabilities to predict overall seismic performance of the built infrastructure.

An emerging and critical vision which we share is to use advanced numerical simulation capabilities to systematically bridge the gap between the earth sciences and engineering disciplines, and thus enable a more complete consideration of seismic vulnerability of built facilities. Sensitivities of facility response to wide ranges of realistic input motions must be explored, and differences between the response of systems to empirical and synthetic motions must be understood and eliminated. These and other interdisciplinary research topics must be systematically addressed, and this important work will be neither simple nor quick. Rather, it will take a deliberate and sustained effort of both communities to engage the capabilities, and understand the limitations, of the other. I firmly believe that SCEC and NEES are the ideally positioned to be partners in assuming a leadership role to develop this dialog and execute a sustained effort to improve underlying capabilities needed for improved seismic hazard mitigation practices.

Best of luck with your proposal, and I look forward to a sustained inter-disciplinary dialog with SCEC.

Sincerely

Clifford J. Roblee, Ph.D., P.E.
Executive Director

COUNTY OF LOS ANGELES
Office of Emergency Management
1275 North Eastern Avenue
Los Angeles, California 90063
(323) 980-2260

David E. Janssen
Chief Administrative Officer

Constance Perett
Administrator

March 2, 2005

Dr. Thomas Jordan
Director
Southern California Earthquake Center
3651 Trousdale Parkway, Suite 169
Los Angeles, CA 90089-0742

Dear Dr. Jordan:

LETTER OF SUPPORT

I am pleased to submit this letter in support of the Southern California Earthquake Center's (SCEC) proposal to the National Science Foundation and the United States Geological Survey for funding for the next five years.

Los Angeles County has had an extremely beneficial partnership with SCEC for many years. We are grateful for SCEC's assistance with our local Hazard Mitigation Plan process last year and for the many technical and educational workshops that SCEC has hosted over the years. These workshops, meetings, trainings and seminars were attended by numerous County agencies and have helped to enhance the Los Angeles County Operational Area's earthquake preparedness efforts.

SCEC is also an active participant in the County's Emergency Survival Program (ESP) public education campaign. Mark Benthien has been an outstanding member of the fifteen-county ESP Coordinating Council for several years. He willingly shares his expertise and provides valuable information and assistance to ESP in our public outreach endeavors throughout the United States and in other countries.

Los Angeles County is fortunate to have SCEC as one our most valued educators. We look forward to a long-lasting partnership with you.

I highly recommend that SCEC be funded by the National Science Foundation and the United States Geological Survey for the next five years (2007-2012). Please contact me at (323) 980-2261 or by email at cperett@lacoeoc.org if you have any questions.

Sincerely,

for Constance Perett

CONSTANCE PERETT, CEM
Administrator

CP:JH:jl

SOUTHERN CALIFORNIA
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March 2, 2005

Dr. Thomas Jordan
Director
Southern California Earthquake Center
3651 Trousdale Parkway, Suite 169
Los Angeles, California 90089-0742

Dear Dr Jordan:

I am writing to acknowledge the considerable synergy that exists between the earthquake planning and preparedness activities of Southern California Edison and the Southern California Earthquake Center. Our long-standing partnership has become an important element of our employee education program and our executive awareness efforts.

Edison has been an enthusiastic supporter of the 2004 Earthquake Country Alliance programs, including the January 17 anniversary events hosted by California Institute of Technology, the 2004 revision of the 1995 publication, *Putting Down Roots in Earthquake Country,* and the development of an outstanding public information tool, the *EarthquakeCountryInfo* website. We were pleased to purchase a copy of *Roots* for every Edison employee, with the objective of making our important workforce among the most earthquake-ready in California.

When we began development of an executive-level tabletop exercise for our Chief Executive Officer and senior executives this January, we turned with confidence to SCEC for advice and presentation materials to make the sobering potential of the Puente Hills Fault understandable to our leadership. Our needs were met and exceeded.

SCEC's importance as a scientific and policy resource to the private sector must not be underestimated. The Business and Industry Council for Emergency Planning & Preparedness (BICEPP), of which Edison is an active participant, was honored to collaborate with SCEC in sponsoring a luncheon for civic and business decision-makers last January, as part of the Northridge anniversary activities.

Please consider this letter our contribution to the many voices speaking out to encourage the continued funding of this important center for earthquake research, education, public information and knowledge transfer. We appreciate, in particular, the leadership and collaboration of Mark Benthien, who brings SCEC programs to its outreach clients with professionalism, perseverance and passion.

Cordially,

Janet Workman

Janet R. Workman
Emergency Planning & Preparedness

8631 Rush Street, Room 101
Rosemead, CA 91770