Executive Summary

This proposal requests five years of funding for the Southern California Earthquake Center (SCEC). The Center is a regionally focused organization with the mission to gather new information about earthquakes in Southern California, integrate knowledge into a comprehensive and predictive understanding of earthquake phenomena, and communicate this understanding to engineers, emergency managers, government officials, and the general public.

Rationale and Transition Objectives

Although SCEC will graduate from the NSF Science and Technology Centers (STC) Program in January, 2002, it should continue as a major center for earthquake science for three compelling reasons:

- Nearly half of the national earthquake risk is located in Southern California, with one-quarter concentrated in Los Angeles county alone. SCEC serves a population of 20 million people as its regional center for earthquake information.
- With many active faults and diverse tectonic regimes astride the rapidly moving Pacific-North America plate boundary, Southern California is a superb natural laboratory for understanding the fundamentals of earthquake processes. Data on earthquakes in this part of the world are outstanding. The integration of this information into a comprehensive and predictive understanding of earthquake behavior requires the resources of a multidisciplinary consortium capable of system-level research.
- Coordination of earthquake science in Southern California is critical to the development of the comprehensive data sets, consensus models, and consistent scientific judgements needed for public policy in earthquake risk management and mitigation.

The transition from the original STC (SCEC1) to the new, free-standing center (SCEC2) will be guided by five objectives: (1) to develop a prototype, interdisciplinary research center for NSF's EarthScope program, (2) to align SCEC2 more closely with the USGS, (3) to employ advanced information technology in system-level studies of earthquake phenomena, (4) to enhance the application of basic research to earthquake risk reduction, and (5) to facilitate the participation of a broader group of experts interested in the Southern California natural laboratory.

SCEC Accomplishments

For nearly a decade, SCEC has been the primary organization in Southern California for coordinating earthquake research. Among the most significant scientific accomplishments attained by scientists within this extended collaboration are the following:

- *Seismic hazard science:* Synthesis of seismic, geologic, and geodetic data to estimate earthquake potential. Procedure for balancing seismic and tectonic moment rates, including allowance for blind thrusts and off-fault earthquakes. Recognition of hazard-estimate sensitivity to magnitude distribution and non-Poissonian recurrence.
- *Los Angeles Basin hazard:* Fundamental reformulation of tectonics and seismic hazard of the L.A. Basin, including recognition of blind thrusts and the potential for very large (magnitude 7+) earthquakes.
- *Strong ground motion:* Improved understanding of how sedimentary basins influence earthquake ground motion—focusing effects in Santa Monica, sediment nonlinearity from the Northridge earthquake, and basin-depth effects—and the effects of surface deposits on ground shaking. Matching of low-frequency ground-motion amplitudes from Northridge using three-dimensional wave-propagation simulations.
- *Landers earthquake:* Joint inversion of multiple data sets to determine rupture history of a large earthquake. Demonstration of rupture propagation by dislocation pulse, rather than expanding crack. Detailed observations and physical modeling of post-seismic relaxation and the effects of fault segmentation during large-scale rupture.
- *Fault systems:* Paleoseismic fieldwork, geodetic observations, and integrative studies showing clustering of large earthquakes, prolonged earthquake interactions, large cascading ruptures, and general consistency with the historical record.
- *Deformation map:* Development of a detailed crustal deformation map, combining all available geodetic data, and use of this map to investigate tectonic loading of faults and post-earthquake response. Recognition from geodetic data of rapid strain accumulation in the eastern Ventura basin prior to the Northridge earthquake.
- *Evolution of stresses and slip deficits:* Modeling of stress evolution due to earthquakes, tectonic motions on faults, and stress relaxation. Demonstration that some earthquake sequences are consistent with triggering by stress interactions. Recognition of seismic slip deficits on faults in the Ventura and Los Angeles basins.
- *Los Angeles Basin structure from LARSE:* Discovery of a mid-crustal reflector (possible detachment zone) under the San Gabriel Mountains, apparent offset of the crust-mantle transi-

tion under the San Andreas Fault, and the displacement of the crustal root north of the topographic maximum. Revision of the depths of the San Gabriel and Los Angeles sedimentary basins.

- *Fault-zone waves:* Demonstration of the existence of waves trapped by fault-zone low-velocity waveguides and use of these waves in determining fault-zone properties and observing the fault-zone healing after earthquakes.
- *3D seismic velocity model:* Development of a 3D velocity model that includes geologic constraints, sedimentary basins, tomographic background velocities, a detailed geotechnical surface layer, and topography on the crust-mantle boundary. Demonstration that this model is consistent with independent gravity measurements.

These and other scientific results have been published in more than 500 scientific articles and special publications. The results have been synthesized into a "Master Model" of probabilistic seismic hazard in the Los Angeles region through a series of integrative reports:

- **Phase I**: Future Seismic Hazards in Southern California, Implications of the 1992 Landers Earthquake Sequence.
- **Phase II**: Seismic Hazards in Southern California: Probable Earthquakes, 1994 to 2024.
- **Phase III**: Accounting for Site Effects in Probabilistic Seismic Hazard Analyses of Southern California.
- **Phase IV**: RELM: Regional Earthquake Likelihood Models.

SCEC organized and obtained funding for major new facilities in Southern California. The 250-station Southern California Integrated GPS Network (SCIGN) is the world's second-largest (behind Japan), making continuous, densely spaced geodetic measurements of strain accumulation and release in the L.A. Basin and surrounding regions. The Southern California Earthquake Data Center (SCEDC) is the primary data repository and distribution center for seismic networks in the region. The Portable Broadband Instrument Center (PBIC) provides high-performance seismic instrumentation for field experiments and post-seismic response.

Along with these facilities, SCEC developed a new infrastructure that allows researchers to share data, instruments, expertise, and effort. It developed on-line data archives for all available seismic records, geodetic data, and satellite radar images for Southern California, and established the first on-line, web-based relational database for retrieving strong-motion data. It coordinated the field observations and science analysis following the 1992 Landers, 1994 Northridge, and 1999 Hector Mine earthquakes, and provided much of the expertise for post-event response to the damaging 1999 Turkey earthquakes. Indeed, SCEC's most enduring accomplishment may be the demonstration that an effective, organized collaboration among disciplines is the best way to make progress in understanding earthquakes and communicating this understanding to others.

Science Plan

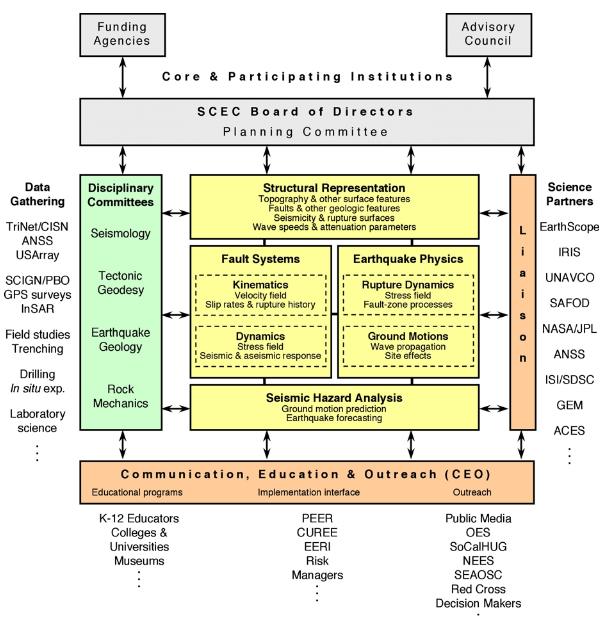
The proposed science plan is based on a fundamental research goal—to develop a physics-based understanding of earthquake phenomena in Southern California through integrative, multidisciplinary studies of plate-boundary tectonics, history and behavior of active fault systems, fault-zone processes, dynamics of fault ruptures, wave propagation, and strong ground motions. It also addresses the application of this understanding to the practical problems of improving seismic hazard analysis and reducing earthquake risk. Five-year objectives have been formulated for each of the major research areas:

- *Plate-boundary tectonics:* to determine how the relative motion between Pacific and North American plates is distributed across Southern California, how this deformation is controlled by lithospheric architecture and rheology, and how it is changing as the plate-boundary system evolves.
- *Fault systems:* to understand the kinematics and dynamics of the plate-boundary fault system on interseismic time scales, and to apply this understanding in constructing probabilities of earthquake occurrence in Southern California, including time-dependent earthquake forecasting.
- *Fault-zone processes:* to understand the internal structure of fault zones and the microscale processes that determine fault-zone rheologies in order to formulate more realistic macroscopic representations of fault-strength variations in time and space.
- *Rupture dynamics:* to understand the physics of rupture nucleation, propagation, and arrest in realistic fault systems, and the generation of strong ground motions by earthquakes.
- *Wave propagation:* to determine the structure of urbanized Southern California well enough to predict deterministically the surface motions from a specified seismic source at all frequencies up to at least 1 Hz, and to formulate useful, consistent, stochastic representations of surface motions up to at least 10 Hz.
- *Seismic hazard analysis:* to incorporate time dependence into the framework of seismic hazard analysis in two ways: (a) through the use of rupture dynamics and wave propagation in realistic geological structures, to predict strong-motion seismograms (time histories) for anticipated earthquakes, and (b) through the use of fault-system dynamics, to forecast the time-

dependent perturbations to average earthquake probabilities in Southern California.

The SCEC2 framework proposed for achieving these long-term goals is a matrix of four components. *Disciplinary committees* in seismology, geodesy, geology, and rock mechanics will be responsible for planning and coordinating data gathering and disciplinary infrastructure, including field programs, centralized data processing, and the distribution of data products. Project-oriented *focus groups* will conduct interdisciplinary research in four primary areas: (1) structural representation, to unify geologic and seismic information into a coherent picture of subsurface structure, (2) fault systems, including both their kinematical and dynamical behaviors, (3) earthquake physics, including rupture dynamics, wave propagation, and site effects, and (4) seismic hazard analysis. Much of this research will be coordinated through the development of Community Models—on-line, documented, maintained resources that can function as virtual collaboratories for knowledge quantification and synthesis, hypothesis formulation and testing, data conciliation and assimilation, and prediction.

The advanced IT infrastructure needed for this type of system-level earthquake science—computational algorithms for exploiting massively parallel computers, access to distributed computing and collaborative environments, advanced methods for code development and sharing, software libraries, distributed visualization tools, and data-management capabilities—will be developed through an *information technology partnership*. In addition to the SCEC2 institutions, the partnership will comprise USC's Information Sciences Institute (ISI), UCSD's San Diego Supercomputer Center (SDSC), the Incorporated Institutions for Research in Seismology (IRIS), and the Generalized Earthquake Models (GEM) project.



The SCEC2 matrix of activities. Disciplinary committees will coordinate data-gathering activities and infrastructure. Focus groups will organize project-oriented interdisciplinary research. Interfaces to SCEC partners will include scientific liaison and the CEO Program. Scientific planning will be the responsibility of the Planning Committee, which will prepare annual budgets for the Board of Directors.

A strategically designed, outcome-oriented *Communication, Education and Outreach* (CEO) program will continue SCEC1's successful outreach efforts with two significant enhancements: there will be a much closer collaboration with the USGS outreach program in Southern California, and the knowledge-transfer activities will be restructured to include an "implementation interface," designed to foster two-way communication with SCEC2 partners in earthquake engineering and risk management.

Management Plan

SCEC2, like the current Center, will be an institutionally-based organization governed by a Board of Directors. The structure of SCEC2 will recognize both *core institutions*, which are research organizations with major, sustained commitments to SCEC2 objectives, and a much larger number of *participating institutions*, which are self-nominating through the involvement of individual scientists or groups in SCEC2 activities. Currently, 14 core and 26 participating institutions are enrolled in the SCEC2; however, this listing may change, because the Center will be an *open consortium*, available to any individuals and institutions seeking to collaborate on the science of earthquakes in Southern California. The administrative staff will include a Center Director, who will act as the chief executive officer of the Center and will bear ultimate responsibility for the Center's programs and budget. The Center will establish an external Advisory Council to serve as an experienced advisory body to the Board of Directors. The annual budget cycle will begin with the articulation of the research plan, coordinated through a Joint Planning Committee with the USGS and approved by the Executive Committee. This research plan will form the basis for the solicitation and evaluation of "miniproposals" from SCEC2 participants, which will guide the preparation of an annual Center budget; once approved by the Board and signed by the Center Director, this budget will be submitted to the sponsoring agencies for final approval and funding.

A Proposal to NSF and USGS for Sponsorship of the Southern California Earthquake Center

I. Introduction and Overview

This proposal requests five years of funding from the National Science Foundation and United States Geological Survey for the Southern California Earthquake Center (SCEC). The Center was founded in January, 1991, to coordinate the activities of experts in academia, government, and the private sector on the scientific study of earthquakes in Southern California. SCEC is currently sponsored by NSF and the USGS under NSF's Science & Technology Centers (STC) program. In 1999, the base funding provided to SCEC by these federal agencies was about $5 million.

A. Rationale for the Center

The STC program supports individual centers for a maximum of 11 years, so SCEC is entering its last year of STC funding. There is, however, a compelling rationale and a strong consensus that SCEC should continue as a major center for earthquake science.

1. Earthquake Risk in Southern California

The need for SCEC was underscored in a report released last September by the Federal Emergency Management Agency (FEMA), which apportioned California about three-quarters of the national earthquake risk (Fig. 1.1). Nearly half of this national risk is located in Southern California, with one-quarter concentrated in Los Angeles county alone.[1] A parallel study by the California Division of Mines and Geology (CDMG) estimated that the direct economic losses due to earthquakes in six high-risk Southern California counties (Los Angeles, Orange, San Bernardino, Riverside, San Diego, and Ventura) will average $2.7 billion dollars per year.[2]

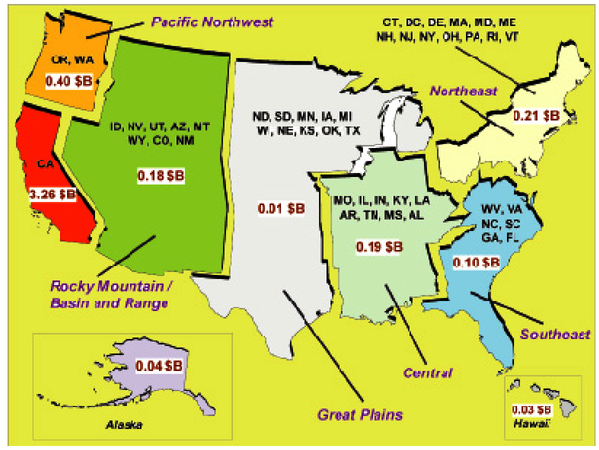


Figure 1.1. Annualized earthquake loss (AEL) for regions of the United States, estimated by FEMA using the HAZUS methodology. The total AEL for the United States is $4.4 billion/yr; 74% of this total is in California. Owing to its high urban population and dense network of active faults, Southern California accounts for nearly 50% of the national AEL. 25% is concentrated in Los Angeles county alone.

The high earthquake risk in Southern California is the product of a dense network of active faults (high hazard) and a large urban population (high exposure). This population currently exceeds 20 million and is expected to reach 24 million by 2010.[3] Southern California's gross regional product is approaching $600 billion per year—it is now one of the world's largest economies and contains a number of rapidly growing urban centers with extensive infrastructures: major harbors, airports, freeways, lifelines, heavy and light industry, and all building types.

The people in Southern California know they are at risk, and they are eager to improve their understanding of earthquake hazards. SCEC serves this public as a distributed, regional organization with the mission of discovering, integrating, and communicating knowledge about earthquakes.

1 *HAZUS®99 Estimated Annualized Earthquake Losses for the United States*, Federal Emergency Management Agency Report 366, Washington, D.C., September, 2000, 32 pp (http://www.fema.gov/pdf/FEMA366.pdf).

2 *An Evaluation of Future Earthquake Losses in California*, California Division of Mines and Geology, Sacramento, California, September, 2000, 16 pp (ftp://ftp.consrv.ca.gov/pub/dmg/pubs/Future_EQ_Losses.pdf). This estimate does not include losses associated with damage to transportation lifelines or critical facilities such as hospitals and power plants.

3 *A Landscape Portrait of Southern California's Structure of Government and Growth*, W. Fulton, M. Glickfield, G. McMurran, and J. Gin, Claremont Graduate University Research Institute, California Planning and Development Report, 2000, 36 pp. (http://www.cp-dr.com/landscape_port/landport.html)

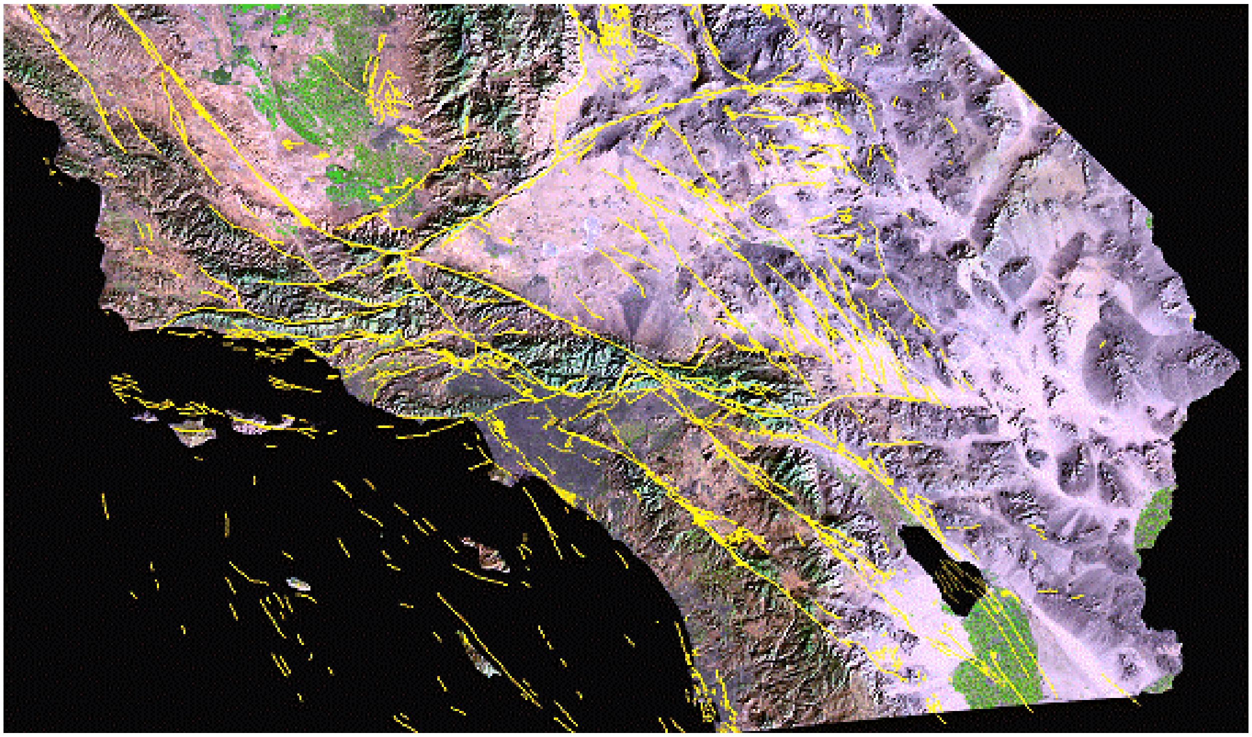


Figure 1.2. With its numerous active faults and diverse tectonic regimes astride the rapidly moving Pacific-North America plate boundary, Southern California is a superb natural laboratory for the system-level earthquake science proposed by SCEC.

2. Southern California: a Natural Laboratory for Earthquake Science

SCEC's role as a public-oriented center is complemented by its scientific mission, which is to investigate the fundamentals of crustal deformation in Southern California (Box 1.1). Many factors combine to make this natural laboratory ideal for basic earthquake research:

- Tectonic diversity. The setting comprises a wide range of tectonic styles and transitions, from extensional deformation in the Salton Trough to compression in the Transverse Ranges, and it contains a great variety of geologic structures, from granitic batholiths and core complexes of ancient metamorphic rocks to deepening basins filled with kilometers of Neogene sediments (Fig. 1.2).
- Fault-system complexity. Its geologic heterogeneity and position astride the rapidly moving (~50 mm/yr) Pacific-North America plate boundary have combined to generate a dense network of active faults (> 300), dominated by the San Andreas Fault (SAF) system. This natural laboratory has appropriate geographic dimensions for system-level studies—big enough to contain the largest SAF earthquakes (the dynamical outer scale), but small enough for a detailed analysis of seismicity and fault interactions.
- Excellent exposure. Onshore, the plate boundary deformation zone is particularly well exposed for geologic field mapping and satellite-based remote sensing. Offshore lies the California Borderlands, one of the few areas of continental wrench tectonics easily accessible to the increasingly powerful subsurface imaging methods of marine geophysics.[4]
- High seismic activity. Seismic activity in Southern California is as diverse as its geology. Young, rough faults such as the San Jacinto generate lots of small-magnitude seismicity, conforming to Gutenberg-Richter statistics,

[4] On the order of 10% of the earthquake potential in southern California may be due to offshore thrust and strike-slip faults. SCEC scientists have mapped active offshore structures from Santa Barbara to San Diego, including two large blind thrust faults between Los Angeles and San Diego that are believed to be reactivated low-angle normal faults with the potential for large (M 7.1-7.6) earthquakes; see C. Rivero, J. H. Shaw & K. Mueller, *Geology*, **28**, 891-894, 2000.

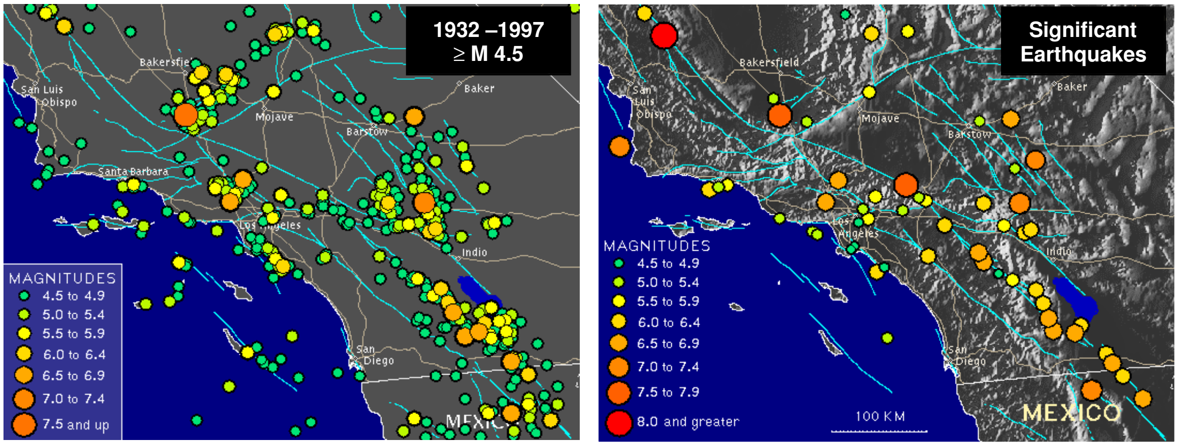


Figure 1.3. The instrumental and historical records of Southern California earthquakes document a wide variety of fault behaviors. The left panel displays the larger (M ≥ 4.5) earthquakes from a 65-year catalog of the Southern California Seismic Network; the right panel plots a selected set of epicenters for large, destructive, or unusual earthquakes since 1812.

while the more mature, smoother faults, including the San Andreas itself, release proportionately more of the strain in large-magnitude events (Fig. 1.3). Three major earthquakes have occurred in Southern California during SCEC's first decade: 1992 Landers (M7.3), 1994 Northridge (M6.7), and 1999 Hector Mine (M7.1). These are now among the best studied of all earthquakes; Northridge, the most costly natural disaster in U.S. history, yielded crucial information about earthquake damage in the urban environment.

The data on earthquake phenomena in Southern California are outstanding by all measures of quantity, quality, and variety. The 69-year catalog of the Southern California Seismic Network (SCSN) now comprises almost 500,000 instrumentally located events. For the last decade, local and regional earthquakes have been captured on digital, broadband arrays, and these records are readily available to researchers through the Southern California Earthquake Data Center at Caltech. Catalog parameters are being improved and expanded through new data analysis techniques; for example, focal mechanisms have now been determined for over 30,000 events. Strong ground motions have been recorded at hard-rock and soft-sediment sites for a series of major events, beginning with the Long Beach earthquake in 1933, and the densification of seismic instrumentation through the TriNet program will lead to further improvements in the strong-motion data base. The surface ruptures and secondary deformations of earthquakes have been carefully mapped, and the paleoseismicity of many active faults has been studied at many (177) trenching sites. Campaign GPS measurements have been collected across Southern California since 1985, and the Southern California Integrated GPS Network (SCIGN), formed in 1995 under the auspices of SCEC, is now providing continuous recording at over 235 permanent stations. The region's arid climate and low vegetation have allowed extensive mapping of fault structures and deformations by multi-spectral imaging, lidar, and interferometric synthetic aperture radar (InSAR).

SCEC provides the organizational structure for an outstanding scientific community nationwide. Some of the most accomplished researchers in earthquake science, and some of its most promising students, reside in Southern California—home to more than a dozen universities with geoscience programs, as well as the Jet Propulsion Laboratory, offices of the USGS (Pasadena) and CDMG, and respected private-consulting groups. Moreover, SCEC extends beyond Southern California. The core institutions in this proposal, listed in Table 1, include USGS offices in Menlo Park and Golden, as well as universities in Northern California (Stanford), other western states (University of Nevada at Reno), and the eastern U.S. (Columbia, Harvard, MIT). Another 18 geoscience organizations outside of Southern California have enrolled in SCEC2 as participating institutions (Table 2). A much larger, worldwide scientific community looks to the Center for collaborations in earthquake research.

3. *Coordination of Earthquake Research*

Understanding Southern California earthquakes and mitigating their impact is the focus of many organizations and individuals in government, academia, and the private sector. No single government agency can direct these diverse groups to implement a comprehensive research plan; coordina-

Box 1.1. SCEC Mission Statement and Science Goal

While the new center will differ significantly from the old in terms of scientific focus and management structure, SCEC will remain a regionally focused organization with a tripartite mission:

❶ To gather new information about earthquakes in Southern California.

❷ To integrate this information into a comprehensive and predictive understanding of earthquake phenomena as a scientific basis for seismic hazard analysis.

❸ To transfer this understanding to other communities in Southern California and elsewhere by communication with scientists, engineers, emergency managers, and government officials, and through education of the general public.

SCEC's primary science goal follows directly from statement ❷: To develop a physics-based understanding of earthquake phenomena in Southern California through integrative, multidisciplinary studies of plate-boundary tectonics, history and behavior of active fault systems, fault-zone processes, dynamics of fault ruptures, wave propagation, and strong ground motions.

tion requires a voluntary consortium. This coordination is critical to the development of (a) comprehensive data sets, (b) consensus models, and (c) consistent scientific judgements for public policy. Moreover, a broadly based consortium is well suited to the nature of the earthquake problem itself. Crustal faulting at seismogenic depths cannot be easily replicated in the laboratory and is nearly inaccessible to direct observation. The fundamental interactions are distributed over an enormous range of spatial and temporal scales. Progress in earthquake science, as in the study of many other complex natural systems (e.g. climate), requires the integration of a wide variety of observations into physics-based models capable of describing the contingent behaviors of individual events as well as the universal behaviors of many events. A primary objective of the proposed SCEC activities will be to achieve such integration.

Information technology is now furnishing the means to process massive streams of observations and, through numerical simulation, to elucidate and quantify many aspects of earthquake phenomena that have been completely resistant to standard theoretical analysis. As discussed in subsequent sections, the requirements for system-level modeling of earthquakes in Southern California lie well beyond the resources available to a single scientist or research group. The proposed SCEC effort has the twin purposes of (a) facilitating collaborations among large groups of investigators from a variety of disciplines and (b) providing an appropriate infrastructure for system-level modeling and integration. These activities are the basis for the science plan of this proposal.

B. The SCEC Transition

SCEC's graduation from the STC program presents an opportunity to reformulate its structure and improve its effectiveness. The transition from the original STC (here called SCEC1) to the new, free-standing center (SCEC2) will be guided by five tasks:

1. Develop a prototype, interdisciplinary research center for the EarthScope program.[5] Together with the many other organizations participating in EarthScope, SCEC2 will promote the integration of the various types of data into a comprehensive understanding of active deformation within the Southern California part of the Pacific-North American plate boundary zone.
2. Align SCEC2 activities more closely with those of the U.S. Geological Survey, which is planning to expand its programs related to earthquake hazards and loss mitigation in Southern California. The USGS has reiterated its support of the Center as a major partner in its scientific and public-outreach efforts.
3. Employ advanced information technology (IT) in system-level studies of earthquake phenomena. Through a partnership with several Earth-science and IT organizations, SCEC2 will develop an IT framework for research collaboration among widely distributed institutions and the dissemination of scientific results.
4. Enhance the application of basic research to earthquake risk reduction. The transfer mechanisms will include an Implementation Interface with the earthquake-engineering and risk-management communities and enhancements to SCEC1's successful Education and Outreach program.
5. Structure SCEC2 as an effective organization that can facilitate the participation of a broader

[5] EarthScope is an NSF initiative to employ new technologies for synoptic observation of the active tectonics and structure of the North American continent.(http://www.earthscope.org).

group of experts interested in the Southern California earthquake problem.

SCEC1 has been, and SCEC2 will continue to be, open to any individuals and institutions seeking to collaborate on the science of earthquakes in Southern California. The structure of SCEC2 recognizes both *core institutions*, which are research organizations with a major, sustained commitment to SCEC2 objectives, and a much larger number of *participating institutions*, which are self-nominating through the involvement of individual scientists or groups in SCEC2 activities. The nine core institutions of SCEC1 will be augmented by three universities (Stanford, Harvard, and MIT) and two additional offices of the USGS (Menlo Park and Golden). The number of core and participating institutions in SCEC2 now stands at 40 (Tables 1 & 2). For the five-year performance period of this proposal, the 11 academic core institutions have pledged over $5.5 million in direct matching funds (including overhead), as well as other valuable support such as faculty release time and space/facility usage. The commitment of University of Southern California, which will act as the managing institution for SCEC2, is especially impressive: $2.3 million in matching funds plus 11,000 square feet of renovated space in North Science Hall.[6] The new SCEC2 facility at USC will include a media center, conference room, a training center, advanced IT facilities, laboratories, office space for visitors, and the SCEC2 administrative center. This high level of commitment demonstrates that SCEC2 will be a true partnership between the core institutions and the sponsoring agencies.

C. Proposal Organization

This proposal is organized into five sections. Section II reports on the results of previous research funded by NSF and the USGS through a narrative that highlights SCEC1 accomplishments during its first decade, 1991-2000. This summary is followed by the Science Plan (§III), which discusses the major scientific issues and the proposed organizational framework. The remaining two sections describe the management plan (§IV) and the five-year budget (§V).

Table 1.1. SCEC2 Core Institutions

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, San Diego
University of California, Santa Barbara
University of Nevada, Reno
University of Southern California

Table 1.2. SCEC2 Participating Institutions

Arizona State University
Brown University
Cal-State, Fullerton
Cal-State, Northridge
Cal-State, San Bernardino
California Division of Mines and Geology
Carnegie Mellon University
Central Washington University
Florida State University
Jet Propulsion Laboratory
Lawrence Livermore National Laboratory
Oregon State University
Pennsylvania State University
Rice University
Texas A&M University
University of California, Berkeley
University of California, Davis
University of California, Irvine
University of California, Riverside
University of California, Santa Cruz
University of Colorado
University of Massachusetts
University of New Mexico
University of Oregon
URS Corporation
Whittier College

[6] The North Science Hall renovation (45,000 sq.ft.) will cost USC about $32 million, with the 11,000 sq.ft. allocation for SCEC2 representing a commitment of nearly $8 million. Phase-I construction of this facility (6,600 sq.ft.) will begin in May, 2001, and Phase-II construction (4,400 sq.ft.) will be completed by September, 2002.

II. SCEC Accomplishments

A. Overview

Since its founding in 1991, SCEC has been very successful, by all measures, as a Science & Technology Center.[1] The Center has pursued its mission through a combination of data collection and analysis, individual investigator research, model development, integrative science, and outreach. Its scientific focus has been the "Master Model," a prototype probabilistic seismic hazard model for Southern California. The Master Model has been the integrating theme for a variety of SCEC research and a series of important reports (Box 2.1).

Seismic hazard analysis is an intrinsically multidisciplinary and integrative process. In large part, SCEC's success stemmed from steady efforts to promote collaboration among its members. M. Schrage[2] has written, "Real science (the science that matters, the science that changes our views of reality) is an elaborate and inherently collaborative process of shared creation…a different task than exchanging information." Examples of how SCEC has collaborated are listed in Boxes 2.2 and 2.3.

This chapter highlights selected SCEC accomplishments. References (SCEC only) have been selected sparingly from more than 500 scientific articles and special publications (see listing at www.scec.org). These first-generation scientific and practical products raise new questions for future research.

Box 2.1. SCEC Integrative Reports

Phase I *Future Seismic Hazards in Southern California, Implications of the 1992 Landers Earthquake Sequence* (special SCEC report)

Phase II *Seismic Hazards in Southern California: Probable Earthquakes, 1994 to 2024* (BSSA)

Phase III *Accounting for Site Effects in Probabilistic Seismic Hazard Analyses of Southern California (14 papers in BSSA)*

Phase IV RELM: *Regional Earthquake Likelihood Models* (in progress)

Box 2.2. SCEC Outreach Program

From the beginning, SCEC's leaders recognized the urgent need to communicate with the multiple millions of citizens who live and work in this seismically active region. To transfer scientific results to people and organizations that will benefit, SCEC established an Outreach program with a mission to *increase earthquake awareness and knowledge so that people take actions that improve safety and reduce loss.* To accomplish this mission, SCEC's Outreach program has pursued two strategies:

- provide general and technical earthquake information, via a variety of mechanisms.
- facilitate effective dialogue and collaborative projects with engineers, Earth scientists, risk management specialists, educators, students, and the general public.

SCEC Outreach has collaborated with more than 50 other science, engineering, education, and government organizations worldwide. Examples of Outreach activities, as they relate to SCEC science accomplishments, are listed in boxes below.

B. Landers Launches the Center

Major Southern California earthquakes—the 1992 M7.3 Landers, 1994 M6.7 Northridge, and 1999 M7.1 Hector Mine events—influenced the focus SCEC's resources and stimulated collaboration. The Center responded quickly, reprogramming funds and expending considerable effort on the study of these earthquakes, each time building on experience. This added greatly to the understanding of source processes, wave propagation, and seismic hazard in Southern California. For example, the database of strong motion records built up from these events yields invaluable calibrations for deterministic ground-motion simulations.

Landers occurred shortly after the inauguration of SCEC and had a strong impact on subsequent research. Immediately after the earthquake a workshop was held to discuss its implications and SCEC's response. Following the lead of northern California after the 1989 M7.1 Loma Prieta event, SCEC planned two documents. The first (Phase I) addressed the recent seismicity in Southern California, the effects of the Landers/Big Bear sequence on nearby faults, and the potential for future ground shaking in Southern California. The second (Phase II) considered seismic hazard broadly over all of Southern California. This set much of SCEC's subsequent agenda.

[1] For example, the National Science Foundation featured SCEC's work on seismic hazard analysis in its "Nifty Fifty" of outstanding contributions to science funded by the NSF during its first fifty years as a federal agency; see www.nsfoutreach.org/htm/n50_z2/15_pg.htm

[2] M. Schrage, *Shared Minds: The New Technologies of Collaboration*" Random House, New York, 1990.

Box 2.3. SCEC Recipes for success

System-level science. By focusing on an important geosystem–the fault system of Southern California–and its human impact, the Center quite naturally defined its interdisciplinary nature.
Interactive opportunities. Interaction was carried out through a variety of forums including disciplinary working groups, over 60 workshops and seminars, field campaigns, and an annual meeting attended by over 200 scientists and students.
Shared facilities. SCEC organized and funded major facilities that allowed researchers to share data, instruments, and people. Examples include the SCEC Data Center at Caltech, the instrument center and strong motion archive at UC Santa Barbara, and the SCIGN geodetic network. The notion of full and open data exchange and readily available data was essential to Center objectives.
Advisory mechanisms: From its beginning SCEC maintained an external *Advisory Council* staffed by distinguished geophysicists and social scientists drafted nationwide, as well as several *ad hoc* advisory bodies for specific issues (e.g. Education and Outreach, product utilization).
Problem identification and consensus building. Problems were jointly identified by Center researchers and external advisors, and when necessary (e.g. hazard models), consensus was sought about final products.
Coordinating post-earthquake response. SCEC coordinated scientific investigations following the Landers, Northridge, Hector Mine, and Izmit (Turkey) earthquakes. Center core funding was immediately re-allocated to field parties in order to collect potentially perishable data.
Pooled manpower. Researchers and students from SCEC's institutions pooled efforts in major field work including post-earthquake studies, the LARSE seismic imaging transects, and the SCIGN network.
Partnerships and links with other earthquake research entities and information providers*.* As a major collaborative entity, SCEC was able to forge meaningful partnerships with other major organizations such as the USGS and the California Division of Mines and Geology (CDMG).

The remoteness and desert environment of Landers made it an ideal research target. Access to the rupture zone was straightforward and the geology well exposed. In the days, weeks, and months following the earthquake, a SCEC geology team conducted extensive investigations of the surface ruptures. Within a year, the group had created a slip model from a database of approximately 1,400 sites. Concurrently, SCEC launched a comprehensive paleoseismic study of faults of the Eastern California Shear Zone (ECSZ), completing over two dozen trenches over a two-year period and demonstrating temporal clustering (Fig. 2.1).

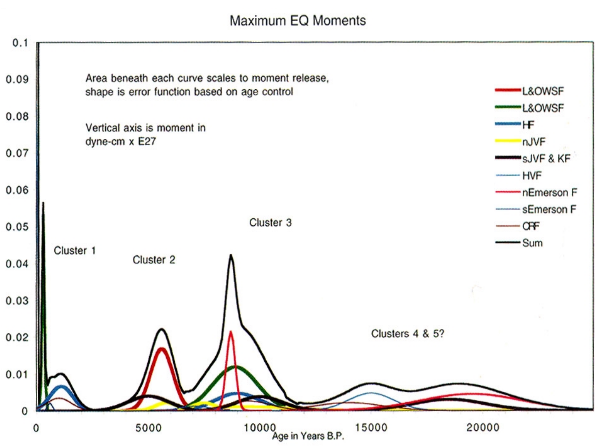


Figure 2.1. The ECSZ has had at least two clusters of large earthquakes in the past 10,000 years, Landers being the latest in a sequence begun 1,500-2,000 years ago. This suggests that ECSZ faults are mechanically linked, or that stress state changes on one fault affect adjacent faults in a "domino" effect.[3]

Aftershocks were recorded by the *TerraScope* network, and by portable instruments deployed immediately after the mainshock. The 20,000+ aftershocks and their focal mechanisms illuminated a complex faulting sequence. Other major results include:

- The seismicity along the San Bernardino, Banning, and Coachella segments of the southern San Andreas fault increased after Landers, and faulting style changed from mostly compressional to strike-slip near Banning. The seismicity rate decreased along the Mojave and Palm Springs segments. This appears consistent with predictions from Coulomb stress models.[4]
- Comparison of focal mechanisms before and after Landers showed that the mainshock changed the stress orientation along its rupture zone. The maximum stress direction rotated 7˚ to 20˚ clockwise, becoming progressively more fault normal from south to north. The complex distribution of P and T axes suggested that most of the uniform component of applied shear stress along the northern part was released in the mainshock.[5]

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[3] T.K. Rockwell *et al*., *Bull. Seismol. Soc. Am***. 90**, 1200-1236, 2000.
[4] E. Hauksson *et al*., *J.Geophys. Res*. **98**, 19835-19858, 1993.
[5] E. Hauksson, *Bull. Seismol. Soc. Am*. **84**, 917-934, 1994.

- *P*-wave travel-time tomography from 1992 and recent earthquakes shows high velocity anomalies at or near the nucleation sites of the North Palm Springs, Joshua Tree, Landers, and Big Bear events. This suggests that fault asperities may exist at these points, and that 3-D tomography may be effective for segmenting active faults at depth.[6]

The Landers sequence provided an excellent opportunity to examine the general problem of how one earthquake might trigger another.[7] In particular, the question arose as to whether Landers changed the proximity to failure on the San Andreas through static stress transfer. SCEC researchers used the Coulomb failure criterion for faults in the neighborhood of Landers with the following results:

- Aftershocks were abundant where the Coulomb stress on optimally oriented faults rose by more than 0.5 bar and sparse where it dropped by a similar amount (Fig. 2.2).
- Several earlier moderate nearby shocks raised the stress at the Landers epicenter and along much of the Landers rupture zone by about a bar, advancing the earthquake by perhaps 1 to 3 centuries.
- Landers raised the stress at the site of the future M6.5 Big Bear aftershock site by 3 bars.
- Together, the Landers and Big Bear earthquakes raised the stress along the San Bernardino segment of the southern San Andreas fault by 2 to 6 bars, hastening the next great earthquake there by perhaps a decade (Fig. 2.3).

These calculations were carried out assuming an elastic half-space. For short time periods (months to year) this is a reasonable assumption, but creep in the crust will modify the stress distribution. Clearly, the San Bernardino segment has remained dormant, so either: (a) stress in the seismogenic zone has relaxed along this segment, (b) the next great event is still more than a decade away, or (c) crustal heterogeneity obviates predictions based on a simple Coulomb failure criterion in a homogeneous elastic half-space.

The Landers data sets also provided an unprecedented opportunity to model a variable slip, finite-fault rupture history.[10] Geodetic displacements, near-field and regional strong motions, broadband teleseismic waveforms, and surface offset measurements sampled both a wide (0-0.5 Hz) frequency range and varied spatial orientations with respect to the slip and radiation patterns. These were inverted independently and in unison

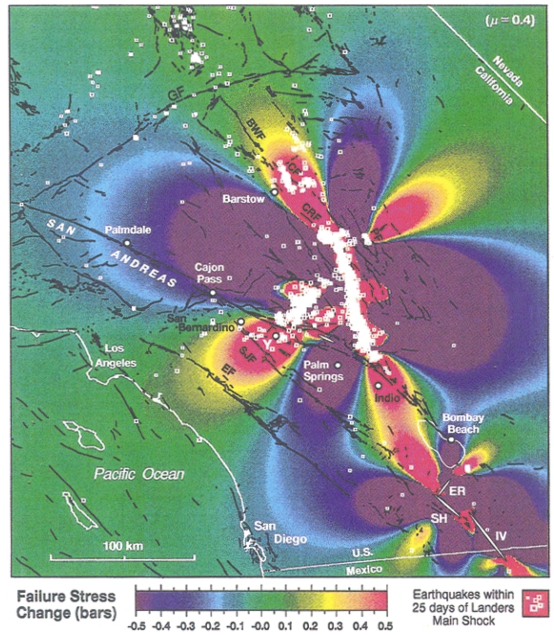

Figure 2.2. Correlation of the Landers aftershock distribution with calculated regional Coulomb stress changes.[8]

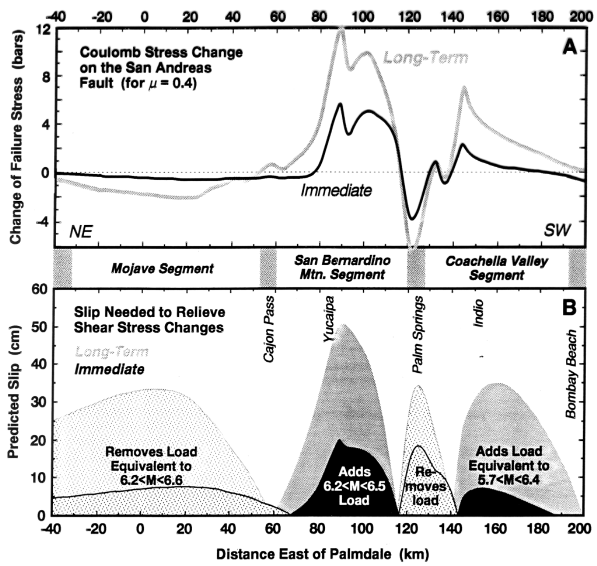

Figure 2.3. Coulomb stress change caused by the Landers and Big Bear earthquakes along the San Bernardino segment of the southern San Andreas fault.[9]

Box 2.4. Landers-Related Outreach Activities

- Over 1,500 copies of the *Phase I Report on Future Seismic Hazards in Southern California* have been distributed to Earth scientists, engineers, and technical professionals
- SCEC representatives participated in a "town hall" meeting convened by Congressman George Brown in San Bernardino in response to the Joshua Tree and Landers/Big Bear Earthquakes.

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6 J. M. Lees & C. Nicholson, *Geology* **21**, 387-390, 1993.
7 G. C. P., King, R. S. Stein & J. Lin, *Bull. Seismol. Soc. Am.* **84**, 935-953, 1994.
8 G. C. P., King, R. S. Stein & J. Lin, *op. cit.,* 1994.
9 G. C. P., King, R. S. Stein & J. Lin, *op. cit.,* 1994.
10 D. J Wald & T. H. Heaton, *Bull. Seismol. Soc. Am.* **84**, 668-691, 1994.

to generate a suite of models. Consistent features of all models included: 1) similar overall dislocation patterns and moments, 2) heterogeneous, unilateral strike slip over a fault length of 65 km and a depth of at least 15 km, although limited to shallower depths in some stretches, 3) a total rupture duration of 24 sec and an average rupture velocity of 2.7 km/sec, and 4) substantial variations in rupture velocity and slip with depth relative to measured surface offsets and segment boundaries. The importance of rupture histories in deterministic ground-motion simulations cannot be overestimated.

Trapped waves generated by aftershocks were recorded along the Landers rupture with portable seismometers.[12] Sources of clear guided waves showed a systematic distribution delineating the low velocity fault zone in three dimensions. Of particular significance was the discovery that fault step-overs and segment boundaries blocked transmission of guided waves. This strongly suggests that such features persist to considerable depth. Whether this is true only for immature faults with relatively modest displacement remains an open question.

Finally, one might say that Landers was a "geodetic earthquake." GPS and InSAR were used extensively to map co- and post-seismic regional deformation. SCEC's crustal deformation working group, working with other academic teams, USGS, and NASA derived co-seismic displacement vectors from GPS data at 97 monuments, including five continuously tracking stations. Coupled with USGS geodolite observations and two-color laser trilateration, these yielded a self-consistent geodetic data set and an elastic dislocation model of primary fault rupture planes, generally consistent with seismological and geological results (Fig. 2.4). SCEC continues to monitor post-seismic deformation from both Landers and Hector Mine. To date, post-seismic relaxation across the Landers rupture has amounted to about 100-150 cm, or 15 percent of the co-seismic value. An early phase (2-3 months) of rapid relaxation suggests afterslip at depth, while later data have been modeled with combinations of afterslip, poroelasticity, and viscoelastic relaxation in the lower crust and upper mantle.[13]

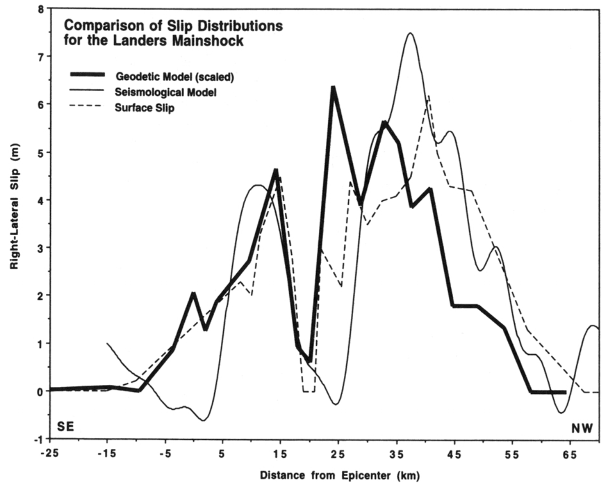

Figure 2.4. Consistency of geodetic and seismological slip models for Landers.[11]

C. Seismic Hazard Estimation – MM-1.0

When SCEC began, seismic hazard methodology was a prominent target for improvement, and Southern California was an ideal laboratory in which to carry this out: previous hazard models had not included strain (geodetic) data, little was known about the faults in the Los Angeles metropolitan area, and the major focus has been on the San Andreas fault. Recognizing this, SCEC devised the "master model," which according to the original proposal was described as follows:

> *"… the goal of SCEC is to integrate research findings from various disciplines in earthquake-related science to develop a prototype probabilistic seismic hazard model (master model) for Southern California."*
>
> *"… the master model represents a constantly updated scientific representation of seismogenic structures and earthquake processes… developed into forms applicable to earthquake hazard mitigation in the public and private sectors."*
>
> *"Through appropriate interaction and feedback, the requirements of the master model will guide data acquisition and interpretation."*

The operational approach to master model development is shown in Fig 2.5. Research results obtained by the various SCEC working groups were integrated by a master model working group, into the next-generation tools for seismic-hazard analysis, as presented in our integrative documents, resulting in version 1.0 of the *Master Model* ("MM-1.0").

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[11] K. W. Hudnut *et al., Bull. Seismol. Soc. Am.* **84**, 625-645, 1994.

[12] Y.G. Li *et al.*, *J.Geophys. Res.* **99**, 11705-11722, 1994.

[13] Z. K Shen *et al.*, *Bull. Seismol. Soc. Am.* **84**, 780-791, 1994; J., M. Deng, *et al.*, *Science* **282**, 1689-1692, 1998.

Box 2.5. Phase II - Related Outreach Activities

- 5,000 reprints of *Phase II* were distributed to Earth scientists, engineers, technical professionals, and others.
- 1.5 million copies of *Putting Down Roots in Earthquake Country,* a non-technical summary of *Phase II* results along with preparedness information, have been distributed. Portions were reprinted in the Nevada Bureau of Mines' *Living with Earthquakes in Nevada* and in KTLA-TV's *Care and Prepare* (1.5 million in English; 0.5 million in Spanish; and 0.5 million mini-booklets for children).
- In addition to the printed *Care and Prepare* booklets, SCEC and KTLA produced two half-hour earthquake specials, public service commercials, and morning news interviews featuring SCEC scientists and our partners.
- The results of the *Phase II* report have been used by the California Division of Mines and Geology (CDMG) to produce statewide urban seismic hazard maps for use by geotechnical engineers, building and safety officials, developers, homeowners, and the general public.
- Using results from *Phase II*, two insurance industry vulnerability workshops were held that focused on evaluation and upgrading of current methods used by the insurance industry in measuring exposure. Over 400 insurance industry representatives, Earth scientists and earthquake engineers attended.

Phase I related specifically to the 1992 Landers earthquake. Phase II[14] represented a first effort to integrate a wide variety of information into a "consensus" earthquake hazard forecast model. It also introduced conceptual changes in how to determine earthquake potential and how to fold this into seismic hazard estimates: a new seismic zonation model, use of geodesy, multiple segment ruptures, moment-conserving combinations of seismic, geodetic and geologic information, and determination of the relationship between faults and earthquakes.

Probabilistic seismic hazard models depend on combining a regional source model with an attenuation relationship and local site effects to estimate ground motion exceedance probabilities. In Phase II, SCEC focused on the source model for Southern California, devising a method in which historical seismicity, paleoseismic, and geodetic data could be combined into a source model that uses the rate of seismic moment as its "currency." That is, the input moment rate into the system (strain build up) must balance the output (earthquakes). Southern California was divided into several source zones with different assumptions about earthquake statistics and moment release. These assumptions are important since, on the one hand, large earthquakes control the moment, and on the other, more frequent, smaller earthquakes largely determine the hazard.

Previous probabilistic hazard estimates used the "characteristic" earthquake model in which earthquakes with the same slip and recurrence interval were assumed to repeat on a given fault segment. Phase II introduced the "cascade" model, in which multiple segments are allowed to rupture in combinations consistent with the observed geologic rate. The 1857 M7.8 Fort Tejon and 1992 M7.4 Landers earthquakes suggest that multiple segment ruptures may be the norm rather than the exception.

Two important outcomes emerged from Phase II: (1) a seismic hazard map of Southern California was produced and widely circulated (Fig. 2.6), and (2) the hazard model predicted twice as many M6-7 earthquakes than had been observed historically,

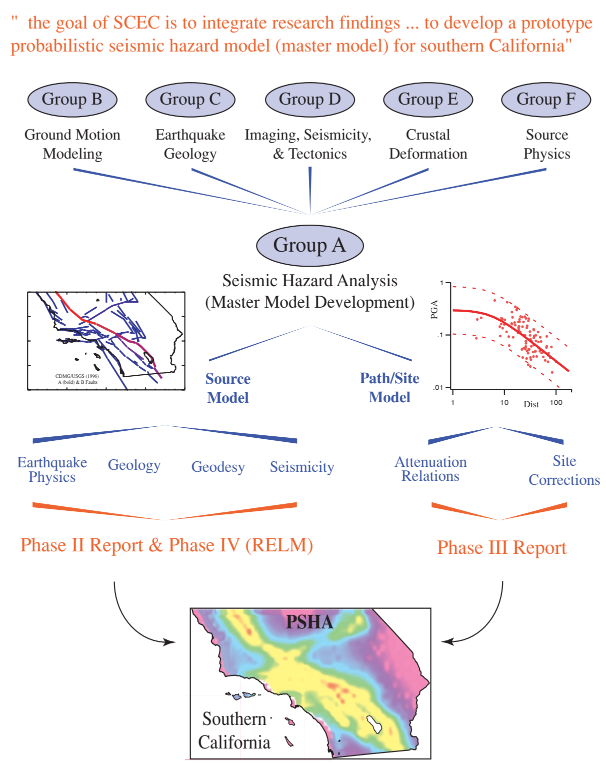

Figure 2.5. As SCEC matured, the conceptual framework for the *Master Model* evolved. This cartoon shows the latest concept emerging from SCEC.

[14] D. D. Jackson *et al*., *Bull. Seismol. Soc. Am.* **85**, 379-439, 1995.

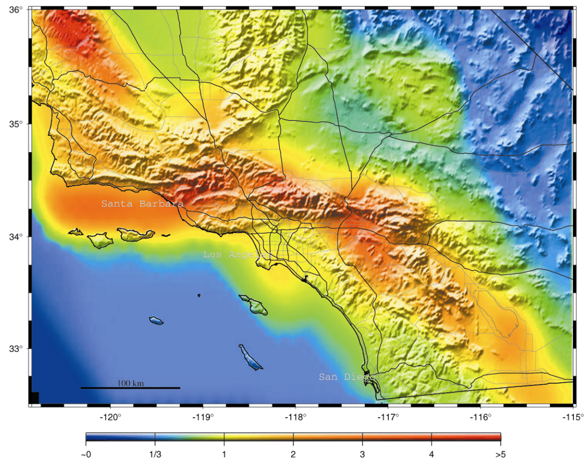

Figure 2.6. The Phase II seismic hazard map of Southern California. The probability of exceeding 0.2 g between 1994 to 2024 shows the highest hazard is associated with the Transverse Ranges, reflecting the prevalence of moderate-sized events (~M6 to M7) in this region.[16]

a discrepancy resolved in later work (Fig. 2.7).[15]

Phases III and IV reflect a fundamentally different approach. Instead of one consensus model, a range of viable source and attenuation models are being tested to evaluate their implications for probabilistic seismic hazard. The goal is to identify which parameters really matter and which do not. This is ideal for SCEC's role in testing the ingredients of hazard models and developing the databases and methodologies, leaving the consensus-building to agencies whose mission it is to develop official models (with policy implications) for public dissemination. Phases III and IV are particularly important in the evolution from *probabilistic* to *deterministic* hazard assessment through waveform modeling needed for non-linear dynamic structural analysis.

Phase III investigated site in probabilistic seismic hazard analysis. Its 14 papers hold important results:

- Most Quaternary geology maps are over-detailed for delimiting amplification levels, but a map of 30-meter-depth *S*-velocity categories used in building codes is warranted for microzonation.
- Basin depth beneath a site is an important factor in determining the level of shaking.
- Uncertainties in the attenuation relationship remain high even after making all standard site corrections and hazard estimates at a given site probably cannot be reduced by simply increasing the amount of engineering geology. This is well supported by simulations and by highly variable ground shaking patterns during Northridge, most notably in Santa Monica. Source disaggregation and waveform modeling may be a more useful input for full dynamic modeling of structures.

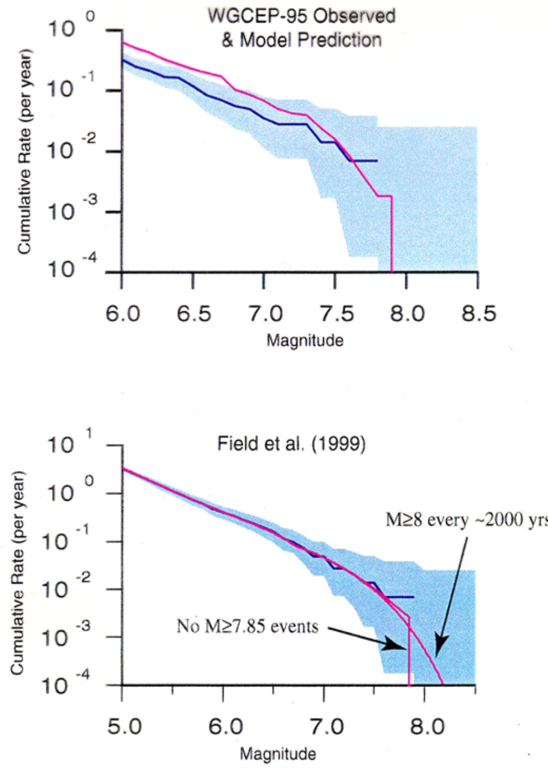

Figure 2.7. (a) The earthquake magnitude/frequency derived from the SCEC Phase II hazard model is not entirely consistent with the historic seismicity record, predicting twice as many M6-7 earthquakes than have been observed historically.[17] (b) Subsequent studies[18] showed that better agreement could be achieved by changing some assumptions and reducing errors.

Phase IV (RELM–"MM-2.0") will update the fault, geodetic, and seismicity data bases for Southern California, and evaluate a range of source models, including alternative geometries for more speculative faults, historical seismicity, geodetic observations, stress-transfer interactions, and foreshock/aftershock statistics. It will incorporate "community" interactive databases and models, available to all users, with an expected completion date to coincide roughly with the current Center's sunset date of January 2002.

[15] E.H. Field, D.D. Jackson & J.F. Dolan, *Bull. Seismol. Soc. Am.* **89**, 559-578, 1998.
[16] D. D. Jackson *et al.*, *Bull. Seismol. Soc. Am.* **85**, 379-439, 1995.
[17] D. D. Jackson *et al.*, *op. cit.*, 1995.
[18] E.H. Field, *op. cit.*, 1998.

D. The Los Angeles Basin Story

When the Northridge earthquake struck the Los Angeles (L.A.) metropolitan area with $40B in damage, attention was instantly focused on the region's seismic hazard. SCEC immediately made a strategic decision to refocus its resources, and concentrate a significant portion on the earthquake potential and shaking hazard of the L.A. basin. As Landers colored the first half-decade of SCEC, Northridge did so for the next five years. Major efforts were initiated to characterize the active faults, improve knowledge of subsurface geology and velocity structure, enhance geodetic control on strain rates across the basin, and investigate regional variability in seismically-induced ground motions, with seismic hazard analysis as the integrating activity.[19]

Despite a century of oil exploration and nearly 70 years of earthquake recordings in Southern California, little was known of the deep structure beneath the L.A. basin and San Gabriel Mountains. In order to remedy this, the *Los Angeles Region Seismic Experiments*, LARSE I and II, mapped two regional geophysical transects (Fig. 2.8). LARSE II analysis is still underway. LARSE I:

- improved the seismic velocity structure of the L.A. basin for use in ground motion simulations,
- determined that the Los Angeles and San Gabriel basins are much deeper than previously thought,
- found that the Sierra Madre thrust fault forms a buried, 2.5-km-high, north-dipping scarp between the sedimentary and volcanic San Gabriel Valley and the igneous and metamorphic San Gabriel Mountains,
- found that the Sierra Madre fault appears to sole at mid-crust into a master décollement terminating northward at the San Andreas fault, and projects southward beneath the San Gabriel Valley to the Puente Hills blind thrust fault (Fig. 2.9),
- discovered that where LARSE I crosses the San Andreas, the fault dips steeply (~83°) northward and extends at least to the Moho, contradicting suggestions of slip decoupling below the seismogenic layer,
- refined the image of a "curtain" of cold, high-velocity upper-mantle material under the Tranverse Ranges. As this curtain sinks, crust and mantle flow toward the San Andreas fault from both sides, causing compression across the plate boundary.

Although the San Andreas continues to pose a significant hazard to Southern California, examination of the Los Angeles geotectonic framework suggests that greater danger may in fact lie with infrequent, but moderate earthquakes on faults within or bounding the basin (Fig. 2.10).[20] The Whittier Narrows and Northridge earthquakes reminded us of the importance of blind thrust faults,

Figure 2.8. SCEC and USGS joined forces to image the crust along two regional geophysical transects – the *Los Angeles Region Seismic Experiments*, LARSE I and II. Both profiles involved a combination of passive teleseismic, active source reflection and refraction, and ship-to-shore wide-angle recordings. LARSE II, which passed through the epicenter of the Northridge earthquake, was completed in early 2000, yielding data from over 1,400 seismographs, 95 shotpoints, and 100 km of offshore air gun profiles.

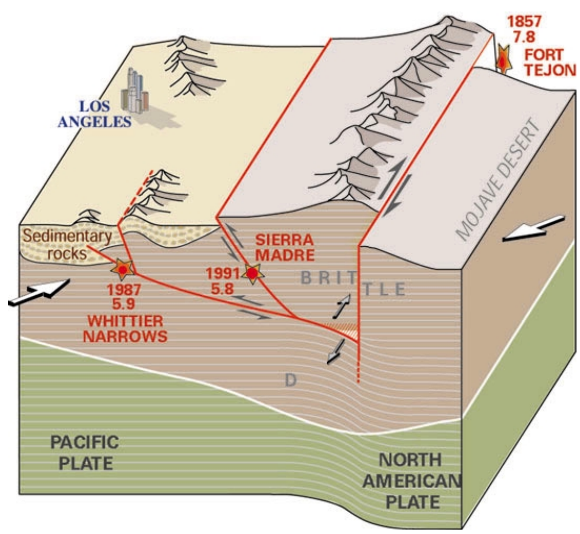

Figure 2.9. The three-dimensional relationship between the Sierra Madre fault, a lower crust décollement beneath the San Gabriel Mountains, and the Puente Hills blind thrust fault– the causative fault for the Whittier Narrows earthquake.

[19] USGS/SCEC Fact Sheet 110-99, 1999

[20] J. F. Dolan *et al.*, *Science* **267**, 199-205, 1995.

helping us focus attention on these structures beneath the L.A. basin. To illuminate these buried sources, SCEC researchers integrated results from seismicity, LARSE I, geodesy, and seismic reflection and borehole data from industry to image a major active thrust fault system under the L.A. and San Gabriel basins (Fig. 2.11 and 2.12).

The geodetic data alone are particularly intriguing. Sparsely spaced GPS measurements in the Los Angeles and Ventura basins show a convergence rate of 5-10 mm/yr. To confirm this and determine which structures might accommodate the strain, SCEC established the *Southern California Integrated GPS Geodetic Network* (SCIGN). Successful community proposals to NSF and NASA, and an invited one to the W.M. Keck Foundation supported this effort with nearly $20M. The Center expects to have 250 stations operating continuously in Southern California by the end of 2000. Many other "campaign" sites throughout the region support the permanent network. The SCEC crustal deformation working group has now produced Version 2.0 of the Southern California crustal velocity model from these data (Fig 2.13).

Having delineated sources and their geometry by integrating geologic, geodetic and seismic data, and with a rich new strong motion data set from the Northridge earthquake, SCEC initiated a major effort on ground motion prediction in the L.A. basin, leading to Phases III and IV. The first step was to improve the 3-D seismic (*P* and *S* wave) velocity and density structure for the basin. (Fig 2.14). SCEC seismologists quickly exploited it by computing synthetic ground motion time histories for hypothetical earthquakes[25] which were tested against data from Northridge and Landers.[26] These simulations demonstrated that the peak velocity amplification pattern in the basin depends on the specifics of the faulting (Fig. 2.15).

One of the more inexplicable observations from Northridge was the unusual amplification in a small region near the Santa Monica city hall. With Santa Monica close to the edge of the Los Angeles

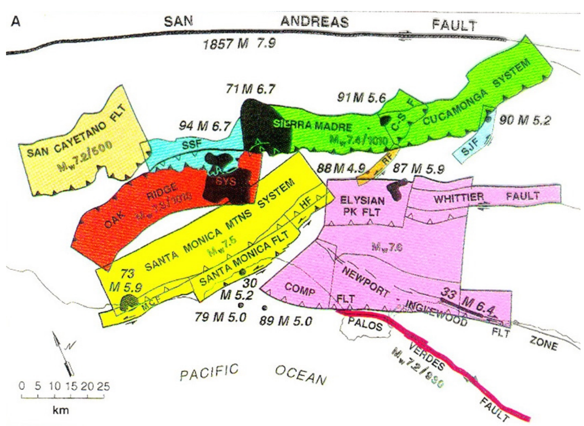

Figure 2.10. Following the Northridge earthquake, new paleoseismic investigations were carried out on L.A. area faults. A primary unanswered question was whether the faults released energy in relatively frequent Northridge-sized (M6.7) earthquakes or in major M7.0-7.5 sized events.[22] Although the issue is not yet entirely resolved, evidence suggests that significant energy is released in larger M≥7.0 earthquakes.[23]

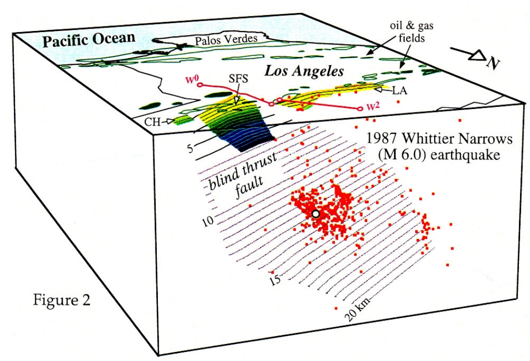

Figure 2.11. Surficial folds in the Puente Hills, an underlying blind thrust, the relocated hypocenter of the Whittier Narrows event, and the postulated décollement beneath the San Gabriel Mountains[21] are all part of a major active thrust fault system beneath the Los Angeles and San Gabriel basins.

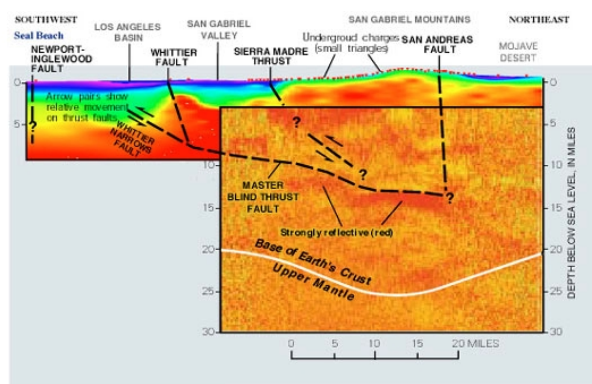

Figure 2.12. LARSE-1 image of the structure shown in Figure 2.11.[24]

[21] J.H. Shaw & P. Shearer, *Science* **283**, 1516-1518, 1999.
[22] J. F. Dolan, *op. cit.,* 1995.
[23] C.H. Rubin, S. Lindvall & T. Rockwell, *Science* **281**, 398-402, 1998.
[24] T. Ryberg & G. S. Fuis, *Tectonics* **286**, 31-46, 1998; USGS/SCEC Fact Sheet 110-99, 1999.
[25] K. B Olsen and R. J. Archuleta, *Bull. Seismol. Soc. Am.* **86**, 575-596, 1996; D. J. Wald and R. W. Graves, *Bull. Seismol. Soc. Am.* **86**, 1998.
[26] K. Olsen, R. Madariaga, and R. Archuleta, *Science* **278**, 834-838, 1997.

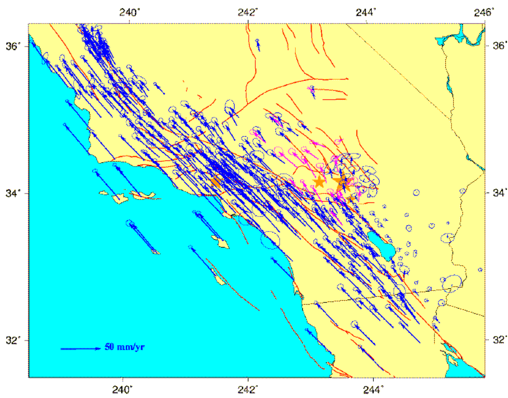

Figure 2.13. The SCEC Crustal Velocity Model, V.2.0 was derived from both surface and space geodetic observations, and illustrates the deformation across the Pacific-North America plate boundary deformation zone. Tectonic interpretations for the L.A. basin range from pure N-S convergence, to N-S convergence accompanied by E-W extension (extrusion), with structures at the northern edge of the basin playing a prominent role in both interpretations.

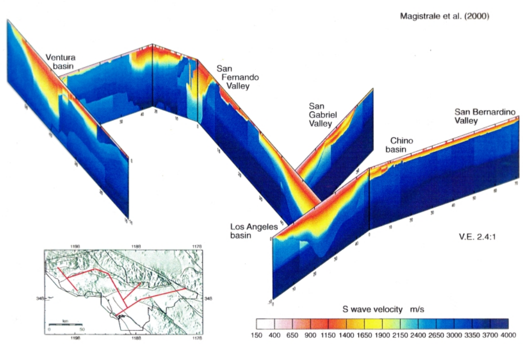

Figure 2.14. Data from geology, well logs, earthquake simulations, seismic tomography, and LARSE I and II were integrated to produce the SCEC crustal model of seismic velocity.[30]

Box 2.6. L.A.-Basin-Related Outreach

- For LARSE I and II, SCEC Outreach managed the permit process, coordinated press releases, distributed USGS/SCEC LARSE II fact sheets,[29] met with government officials, made public presentations, and represented the project to the media. Both studies received national and international news coverage.
- The California Dept. of Transportation, along with the City and County of Los Angeles, funded SCEC for studies related to strong ground motion resulting from probable major earthquakes. The project resulted in nine reports that have been distributed to geotechnical engineers, building and safety officials, and other technical professionals.
- Field trips to specific faults throughout Southern California were offered to highlight seismic hazards and SCEC research. Field guides to these faults were published.
- SCEC has conducted several workshops with the CDMG for decision makers and others, based on products developed with SCEC data that have relevance to urban areas.
- Vulnerability and seismic zonation feasibility workshops were conducted with the City of Los Angeles for engineers, building officials, and planners. Participants discussed liquefaction and landslide potential and the vulnerability of various building types, bridges, and lifelines.
- As a result of the seismic zonation workshops, a task force was formed to produce public awareness booklets on hazards posed by liquefaction and landslides, and by tuck-under parking and non-ductile concrete buildings.

basin and industry data showing the granite Santa Monica mountains thrust over sediments, it appeared that either there was a lens effect of the sediments[27] (Fig. 2.16) or a basin-edge effect.[28] Neither hypothesis accounts for the degree of amplification observed during the mainshock or in subsequent aftershock studies. LARSE II, which will provide a more detailed structure between the San Fernando Valley and Santa Monica, may help resolve the mystery.

The Los Angeles basin story is one of developing a physical seismotectonic model consistent with all geologic, geodetic and seismologic observations. Such a model can improve estimates of earthquake probabilities and expected ground motions from future events, and thus improve seismic hazard analyses. This can only be achieved by integrating results of many scientific disciplines.

[27] S. Gao, H. Liu, P. M. Davis & L. Knopoff, *Bull. Seismol. Soc. Am.* **86**, S209-S230, 1996.

[28] R. W. Graves, A. Pitarka, & P. G. Somerville *Bull. Seismol. Soc. Am.* **88**, 1998; C.M. Alex, & K. Olsen, *Geophys. Res. Lett.* **25**, 3441-3444, 1998.

[29] USGS/SCEC Fact Sheet 110-99, 1999. An online version is at geopubs/wr/usgs/gov/fact-sheets/fs110-99/

[30] H. Magistrale, S. Day, & R. Clayton, *Bull. Seismol. Soc. Am.* submitted, 2000.

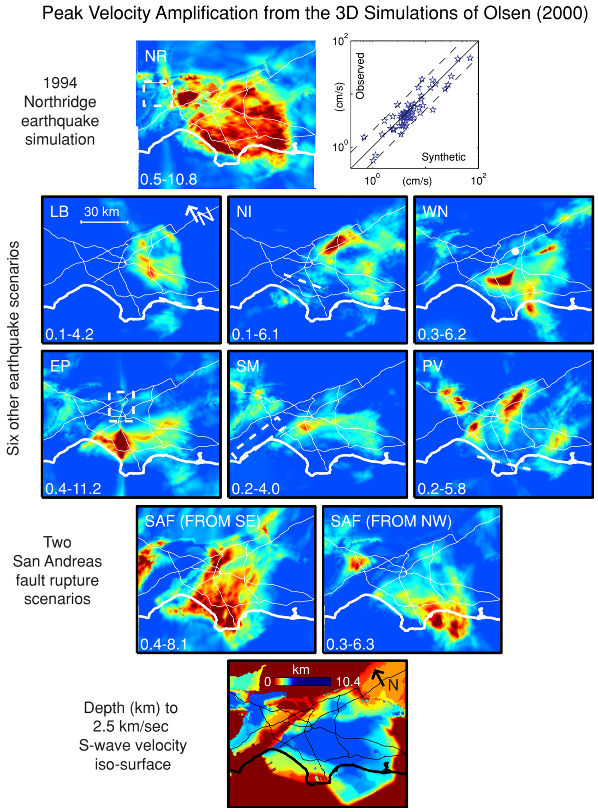

Figure 2.15. These simulations demonstrated that, the peak velocity amplification pattern in the basin depends on the specifics of the faulting. For example, two earthquakes on the San Andreas fault, the same in every respect except for the direction of propagation, can produce very different patterns of amplification depending on how seismic waves interact with basin structure.[32]

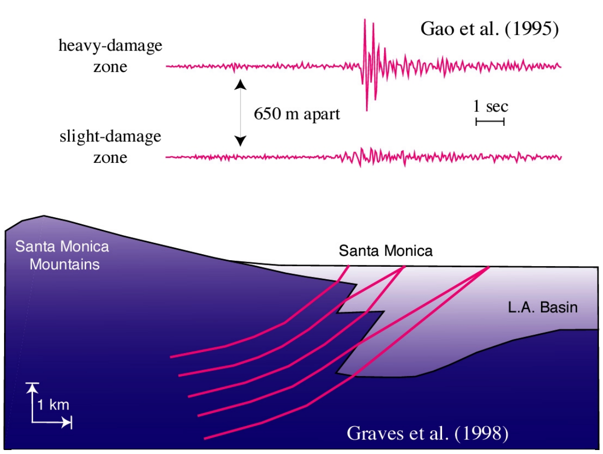

Figure 2.16. Anomalous amplification of seismic strong motions by possible basin-edge sedimentary lens effect.[31]

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[31] S. Gao *et al*., *op. cit.,* 1996.

E. Fault System Behavior

SCEC has contributed to a decade of outstanding progress in our understanding of fault system behavior, which SCEC2 will build upon. Highlights of that progress include the understanding of earthquake triggering by static and dynamic stress changes, development and refinement of the critical state concept for earthquake occurrence, characterization of complexity of ruptures and earthquake sequences, and detailed mapping of fault-zone fine structure, including damage zones, segmentation, and time-dependent healing.

Numerical modeling has advanced the understanding of how static and dynamic stress changes induced by one earthquake affect the timing of subsequent earthquakes. For example, modeling indicates that the Landers-Big Bear earthquake sequence represents mainshock triggering by stress transfer. Moreover, the distribution and focal mechanisms of Landers aftershocks appear to be controlled by stress transfer from the mainshock. This is well illustrated by the successful inference of the mainshock slip distribution from the aftershocks pattern (Fig. 2.17), which agrees with independent estimates from kinematic and dynamic modeling of seismic radiation. Similar event interactions operate over much longer time scales as well.[33] Paleoseismic studies in Imperial Valley, Eastern California Shear Zone, and L.A. basin suggest that clustering may be the operative space-time seismicity pattern for large earthquakes in Southern California (Fig 2.1). Dynamic earthquake

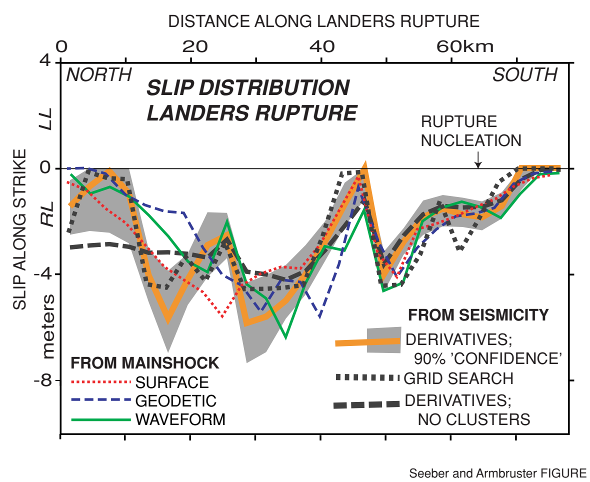

Figure 2.17. Slip distribution for the 1992 Landers rupture derived from subsequent seismicity, assuming stress triggering by mainshock. Shown for comparison are independent estimates obtained directly from the mainshock.

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[32] K.B. Olsen, *Bull. Seismol. Soc. Am.,* in revision, 2000.
[33] T.K. Rockwell *et al., Bull. Seism. Soc. Am.* **90**, 1200-1236, 2000.

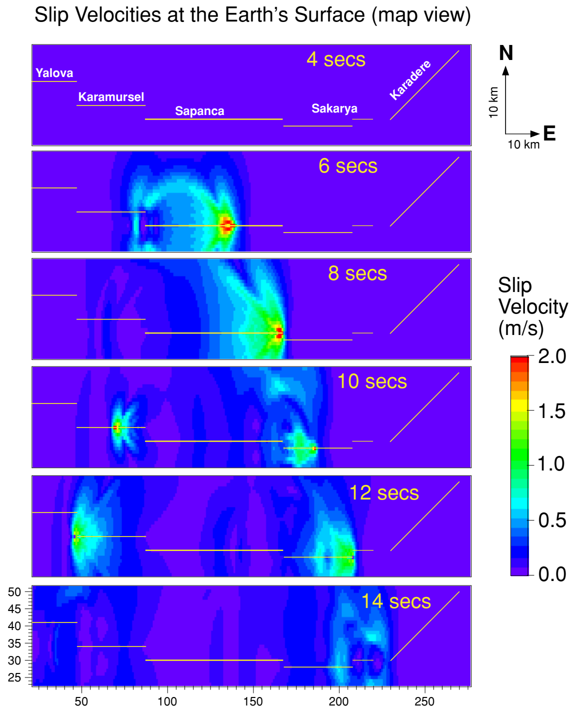

Figure 2.18. Slip velocities at earth's surface from a 3D numerical simulation of the 1999 Izmit, Turkey, earthquake. The simulated earthquake dynamically triggers numerous segments delimited by stepovers with 1-2 km of separation, mimicking the behavior of the Izmit event.[35]

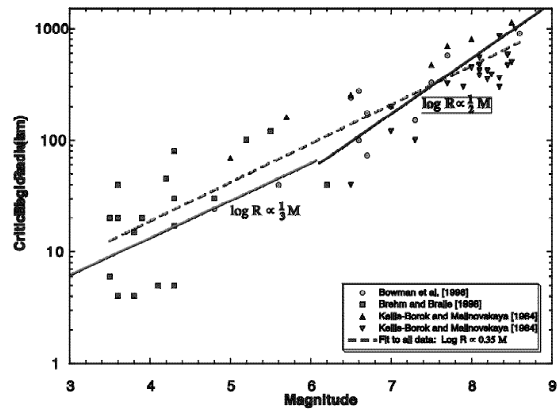

Fig. 2.19. Scaling of size of region of accelerating moment release with size of subsequent mainshock. Observations of for large Southern California earthquakes are compared with results from several related studies.[36]

models show that rupture can grow large rather easily by jumping between fault segments separated by up to several kilometers.[34] Landers dramatically demonstrated this process, as did the Izmit, Turkey, earthquake (Fig 2.18). These new models and observations have brought into question the strict segmentation approach in hazard modeling.

The Center also has explored system-level fault interaction from a statistical point of view, leading to the hypothesis that large earthquakes only occur when the regional fault network is in a "critical state" characterized by long-range spatial correlation of the regional stress. This view holds that regional tectonic loading combined with stress transfer from many small earthquakes progressively smoothes the regional stress field, making it increasingly likely that an earthquake, once nucleated, will jump to other highly stressed segments and grow larger. Observational support for this hypothesis includes a power-law increase in seismic moment release as a function of time remaining until the largest earthquakes, and an increase of intermediate-size events just prior to large earthquakes. If regional seismicity reflects a critical point phenomenon, then mathematical techniques such as the renormalization group, originally developed to describe critical-point transitions in chemical and magnetic systems, can be used to describe regional seismicity.

SCEC researchers have been at the forefront of efforts to refine the observational basis for the critical state hypothesis, finding that the size of the region of accelerating moment release preceding mainshocks scales with event size in a physically sensible way (Fig 2.19). This offers a possibility for a physically-based, intermediate-term, prediction method. Similar ideas are emerging for individual earthquakes from independent lines of evidence: dynamic modeling of individual events such as Landers suggests that rupture occurs when the stress state achieves a critical level, which represents a sensitive balance between energy release rate and rupture resistance.[37]

Observational and theoretical research by the Center has contributed to a greatly improved understanding of the space-time complexity of both individual ruptures and long-term seismicity. Center researchers have found complex patterns of rupture velocity and heterogeneous slip from high-resolution imaging of of slip history. When slip images are converted to images of stress drop, a picture emerges of regions of relatively high stress drop interfingered with regions of low stress drop,

[34] R. A. Harris, R. J. Archuleta, & S. M. Day, *Geophys. Res. Letters* **18**, 893-896, 1991; R.A Harris, J.F. Dolan, R. Hartleb, & S.M. Day, *Bull Seism. Soc. Am.,* in review, 2000.

[35] R.A. Harris *et al*, *Bull Seism. Soc. Am.,* in review, 2000.

[36] D. Bowman *et al*., *J. Geophys. Res.* **103**, 359-372, 1998.

[37] S. Peyrat, K. Olsen, & R. Madariaga, *J. Geophys. Res*., submitted, 2000.

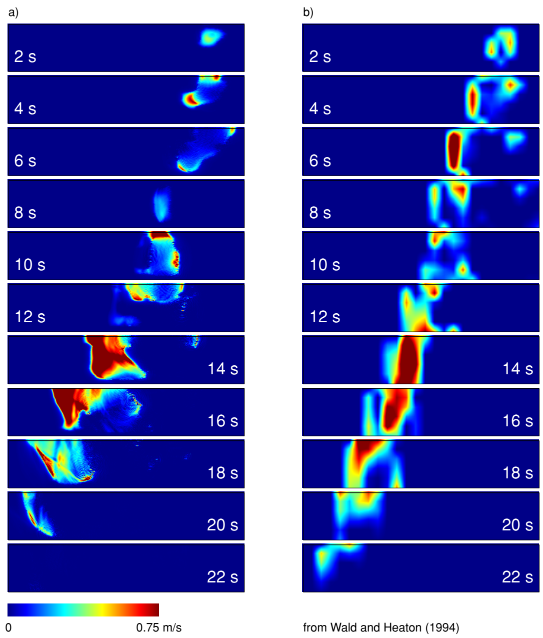

Figure 2.20. Comparison of the rupture history for the Landers earthquake, for the (a) dynamic and (b) kinematic model by Wald and Heaton.[41] The snapshots depict the horizontal slip rate in 2-second time slices.

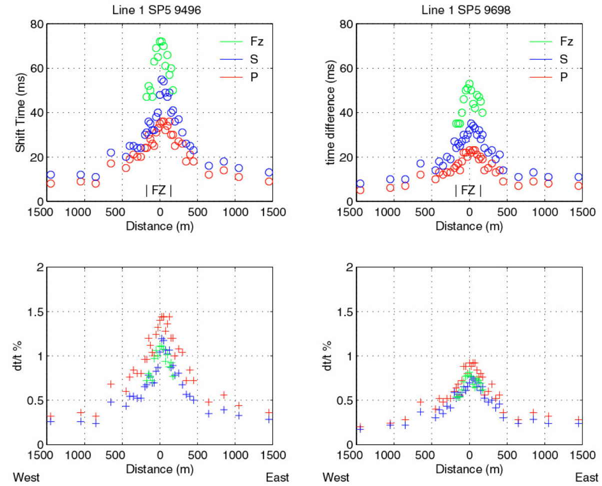

Figure 2.21. Travel-time shifts and inferred seismic velocity increases in the shallow fault zone of the Landers earthquake, over a 2-year period.[40] The velocity increases are interpreted as evidence of healing of rupture-induced damage.

or even of stress increase.[38] Numerical models of heterogeneous fault planes show the same smoothing of the stress field before large events hypothesized for regional seismicity above. Statistical models for heterogeneous faults predict a "mode-switching" behavior in which a fault randomly switches between periods in which it produces only small events to periods in which it produces many large events.[39] This phenomenon can be understood in terms of the smoothness (correlation length) of the stress field and offers another explanation for the observed temporal clustering of large earthquakes.

Dynamic models for rupture and slip on heterogeneous faults are now able to reproduce strong motion recordings from earthquakes at least as well as kinematic models (Fig 2.20). While challenges remain, dynamic modeling should eventually provide an improved physical basis for predictive simulations of earthquake ground motion.

How much of fault heterogeneity results from fluctuations in stress produced by prior events, how much is due to physical asperities associated with geometrical complexity or variations in friction, and how much is inherent in the nonlinear dynamics of frictional sliding has yet to be determined. Theoretical work by SCEC has shown that nonlinear dynamics of frictional sliding, even in the absence of geometrical disorder, can lead to space-time complexity, although only for a restricted range of frictional parameters.[42] But recent accurate locations of repeating microearthquakes argue for persistent asperities, which likely correspond to physical heterogeneity of fault zone rheology.

The relationship between fault fine structure and seismicity has been illuminated by guided waves trapped in the low-velocity damaged zone adjacent to faults.[43] Its thickness seems to vary, but is typically of the order of 100 m., with *S*-velocity degraded by 30% to 50%. The depth extent of the low velocities is still a matter of debate, but may encompass much or all of the seismogenic range. A series of ongoing active source experiments along the fault over a several-year period since the Landers earthquake suggests a healing process, in the sense that *P*- and *S*-wave velocities near the fault have been observed to increase with time since the event (Fig. 2.21). The evolving wave velocity ratio, consistent with crack closure, hints tantalizingly at the governing physics.

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[38] K.B. Olsen, R. Madariaga & R.J. Archuleta, *Science* **278**, 834-838. 1997; S.M Day, G. Yu, & D.J. Wald, *Bull. Seism. Soc. Am.* **88**, 512-522, 1998.

[39] Y. Ben-Zion, K. Dahmen, V. Lyakhovsky, D. Ertas & A. Agnon, *Earth Planet. Sci. Lett.* 172, 11-21, 1999.

[40] Y. G. Li *et al*, *Science* **279**, 217-219, 1998.

[41] D. Wald & T. Heaton, 1994; comparison from S. Peyrat, K. Olsen, & R. Madariaga, 2000.

[42] B. E. Shaw & J. R. Rice, *J. Geophys. Res.* **105**, 23,791, 2000.

[43] Y.-G. Li, K. Aki, D. Adams, A. Hasemi & W. H. K. Lee, *J. Geophys. Res.* **99**, 11,705-11,722, 1994; Y.-G. Li, K. Aki, J. E. Vidale & F. Xu, *J. Geophys. Res.* **104**, 20,257-20,275, 1999.

F. Data and Facilities

SCEC's success with integrating the science of many disciplines has been fueled by an open data policy, coupled with the advent of convenient web access. Data collection, distribution and archiving were key enabling functions in dealing with the voluminous data sets associated with earthquakes during SCEC's first decade. Technological revolutions (e.g., broadband seismology, continuous GPS, InSAR, cosmogenic isotope dating) have also increased the need for advanced data management. To foster the development of these new technologies, SCEC has funded several data centers and instrumentation networks (see Box 2.8.). Further, through SCEC-supported integrative activities, all data collected over prior years of NEHRP funding have been brought together and combined into new products, made available through the web for others to use in novel ways. Thus seismologists enjoy access to the seismicity catalog, phase data and seismograms, as well as the 3-D velocity model. Geodesists combine EDM, VLBI, and early GPS results with continuous GPS data from PGGA and SCIGN into the SCEC Crustal Motion Model. The databases have also been used to combine disciplinary research synergistically (geology and geodesy with InSAR and ALSM, seismology and geodesy with high-rate GPS, etc.), resulting in improved source and hazard modeling.

Mass-storage technology improvements and cost reductions, bandwidth increases, and automation, enable a new world of global communication in science. SCEC presaged the communications revolution by embracing the novel concept of a "center without walls" and succeeded by attaining a functional realization thereof. SCEC2 will further extend this model.

Box 2.7. Data Center Education Tools

- SCEC's Regional Seismicity and Geodesy Web education modules based on data from the SCEC data center and SCIGN network, are used by high school and basic undergraduate students and teachers.
- A middle school education module, "Whole Earth," is under development and will also link to SCEC data.

Box 2.8. SCEC Databases and Facilities

- The **Southern California Earthquake Center Data Center** (www.scecdc.scec.org) at Caltech made an important step in putting the earthquake catalog, phase data, and seismograms online for the research community, as well as other seismic data such as from the LARSE I and II seismic imaging projects. The SCEC 3-D velocity model (Figure 2.14) is also available from the Data Center. More recently, the Data Center has set new standards with its Relational Database Management System (RDBMS) which allows powerful web-based data searching and access. This groundwork has proven the feasibility of similar new systems to be used for the California Integrated Seismic Network (CISN). The SCEC Data Center has also incorporated GPS data from GPS campaigns and SCIGN, as well as SAR interferometry data from the WInSAR consortium.
- The **Southern California Integrated GPS Network (SCIGN)** (www.scign.org), operated by JPL, UCSD, and USGS under the aegis of SCEC, is an array of Global Positioning System (GPS) stations distributed throughout Southern California with emphasis on the greater Los Angeles metropolitan region.
- The **Scripps Orbit and Permanent Array Center (SOPAC)** (lox.ucsd.edu/) at Scripps Institution of Oceanography is funded in part by SCEC. Its role is to support high precision geodetic and geophysical measurements using GPS.
- The **Western North America InSAR (WInSAR) Consortium** is a collection of universities and public agencies under the aegis of SCEC that was created to manage the acquisition and archiving of spaceborne InSAR data over western North America.
- The **Portable Broadband Instrument Center** (www.crustal.ucsb.edu/scec/pbic/) at UC Santa Barbara was established by SCEC to provide researchers with year-round access to a "pool" of high-resolution, digital seismic recording equipment.
- The **Strong Motion Database-** (smdb.crustal.ucsb.edu) at UC Santa Barbara was established by SCEC to provide access to strong ground motion recordings. It also contains strong motion data gathered from a number of other countries, agencies and organizations.
- The **Empirical Green's Functions Library-** (egfl.crustal.ucsb.edu) at UC Santa Barbara is a relational database and data repository established by SCEC containing 84,641 seismograms from 1500 Southern California earthquakes. The purpose of this site is to provide fast and easy access to recordings of small earthquakes that might be used as Green's functions for predicting the ground motion from larger earthquakes.

Box 2.9. Additional Education and Outreach Activities

An important measure of SCEC's success has been the breadth of its outreach activities. As listed in the boxes above, many of these products and programs have been related to specific research activities of the center. Other activities, especially in the education and public awareness areas, have been very successful at transferring SCEC science *in general:*

- SCEC's main webservice - www.scec.org - presents the research of SCEC scientists, provides links to SCEC institutions, research facilities, and databases, and serves as a resource for earthquake information, educational products, and links to other earthquake organizations.
- The *SCEC Quarterly Newsletter* featured articles written by SCEC scientists and staff about research and activities sponsored by the Center; a publications listing; and a calendar of events.
- The newsletter was replaced by the SCEC INSTANeT News Service (www.scec.org/instanet) which features general earthquake information, in-depth coverage of earthquake research, meeting announcements and online registration, and downloadable workshop presentations. Since its inception in March, 2000, over 1300 people have subscribed to e-mailed news "bytes" which announce new articles.
- The SCEC Undergraduate Internship Program has provided opportunities for 69 undergraduate students (including 36 women and 10 minority students) to work alongside 47 SCEC scientists.
- The SCEC Post-Doctoral/ Visitors Program has supported 28 post-doctoral fellow and 11 senior visitors over the past 10 years.
- SCEC has worked with many museums to develop activities, such as the California Science Center (Los Angeles) "Track the Quake" program, and the Riverside County Youth Museum "ShakeZone" exhibit.
- The San Francisco Exploratorium's Faultline Project featured live remote interviews with SCEC scientists at research sites along the San Andreas fault. See www.exploratorium.org/faultline/
- NSF has funded SCEC to revise the *Seismic Sleuths* earthquake curriculum to reflect advances in science and technology, especially the use of geodesy in Earth science (under development).
- *Earthquakes: Seismic Sleuths* educational video will accompany the curriculum materials and also air on the Discovery Channel in the spring of 2001 (under development).
- *LA Underground* aired on KFWB radio and featured SCEC scientists and researchers in one-minute segments.
- SCEC manages the education and outreach element of the CUREE-Caltech Woodframe Project funded by FEMA. Activities have included the production of three videos, a newsletter, and interaction with the media.
- SCEC, CUREE and IRIS have been funded by NSF to develop a pilot project for an Electronic Encyclopedia of Earthquakes, in the context of the Digital Library for Earth Systems Education (DLESE- www.dlese.org).
- SCEC is a member of the EqIP (Earthquake Information Providers) group which connects information specialists from most earthquake-related organizations. SCEC managed the development of www.eqnet.org, EqIP's website which provides a database of descriptions of over 250 organizations with links to their websites.
- The *Wallace Creek Interpretive Trail* will open in 2001 with permanent signs describing features of the San Andreas fault at this former paleoseismic research site. A printed trail guide and website will also be developed.

III. Science Plan

SCEC is a regionally focused center deeply involved in science applications and public outreach, but the heart of the SCEC program is interdisciplinary[1] basic research: to gather new information about earthquakes in Southern California using the methodologies of many scientific disciplines and to integrate this information into a comprehensive and predictive understanding of earthquake behaviors.

- A comprehensive understanding must include all aspects of earthquake phenomena, from the small-scale <u>fault-zone processes</u> that act during milliseconds in earthquake ruptures to large-scale <u>plate-boundary tectonics</u> evolving over many millennia. This goal requires *system-level* basic research.
- A predictive understanding implies the ability to extrapolate earthquake behaviors beyond what have been directly observed. This goal requires a *physics-based* approach to three main problem areas: <u>fault systems</u>, <u>rupture dynamics</u>, and <u>wave propagation</u>.

The scope of these fundamental issues justifies a center-based effort. Moreover, this type of interdisciplinary basic research is well aligned with the practical goals of <u>seismic hazard analysis</u>, which is a research topic in its own right.

Section III.A of this science plan outlines the major scientific issues, organized according to the six problem areas underscored above, while §III.B presents the "SCEC Framework", a strategy for multidisciplinary data integration and physics-based modeling of earthquake-related phenomena. An essential component of the SCEC Framework is a vigorous Communication, Education and Outreach (CEO) program.

A. Major Science Issues

The discussion of each of the six problem areas lays out the long-term (five-year) goals for basic research and the key scientific questions, outlines the requisite data-gathering efforts and modeling resources, and states the short-term (one-year) objectives.

1. Plate-Boundary Tectonics

The tectonic complexity of Southern California is the product of a long geological history. The last 200 million years have been dominated by interactions among the North American continental lithosphere, its accreted terrains, and the oceanic lithosphere of the Farallon and Pacific plates. These interactions have created a broad zone of deformation that extends from the California Borderlands to the edge of the Colorado Plateau. The right-lateral San Andreas system is the "master fault" of this plate-boundary zone, but the tectonic styles cover the full range, from extension in the Salton Trough to contraction in the Transverse Ranges. Over the last ten years, SCEC scientists have learned a great deal about the structure and kinematics of the region; however, the mechanics responsible for the overall pattern of deformation—e.g., the puzzling Eastern California Shear Zone (ECSZ) and the intricacies of the Los Angeles Basin and Transverse Ranges—are by no means fully understood. Tectonic complexity combined with dense, diverse, and steadily improving observations make Southern California an excellent natural laboratory for investigating the dynamics of continental plate-boundary zones.

Long-Term Goal: To determine how the relative motion between Pacific and North American plates is distributed across Southern California, how this deformation is controlled by lithospheric architecture and rheology, and how it is changing as the plate-boundary system evolves.

Key Questions:

1. How does the complex system of faults in Southern California accommodate the overall plate motion? To what extent does distributed deformation (folds, pressure-solution compaction, and motions on joints, fractures and small faults) play a role within the seismogenic layer of the crust?
2. How does inelastic deformation accumulated over repeated earthquake cycles give rise to landforms and geologic structures? How can this type of geomorphic and geologic information be used to constrain recent deformation rates and structural geometries?
3. What is the deep structure of fault zones? Are major strike-slip faults such as the SAF truncated by décollements or do they continue through the crust? Do they offset the Moho? Are active thrust faults best described by thick-skin or thin-skin geometries?
4. What rheologies govern deformation in the lower crust and mantle? Is deformation beneath the seismogenic zone localized on discrete surfaces or distributed over broad regions? How are these deformations related to those within the seismogenic zone?
5. What lateral tractions drive the fault system? What are the directions and magnitudes of the basal tractions? How do these stresses compare with the stresses due to topography and variations in rock density? Do they vary through time?

[1] In this proposal, the term *interdisciplinary* is used to connote research that is both *multidisciplinary* and *integrative*.

6. How is the fault system in Southern California evolving over geologic time, what factors are controlling the evolution, and what influence do these changes have on the patterns of seismicity?

Data and Modeling Requirements: SCEC scientists are now working with others to formulate plans for denser and more complete geodetic coverage of Southern California as part of the Plate Boundary Observatory (PBO) in NSF's EarthScope program.[2] Under EarthScope, the geodetic studies will be continued using SCIGN and expanded with additional permanent GPS stations and campaign-style observations. The objectives relevant to plate-boundary tectonics include separating secular deformations from transient signals and filling in the gaps in the existing SCEC velocity field. The SCEC infrastructure will support SCIGN and PBO geodesy and provide capabilities for data analysis and model-based integration. SCEC will use also its infrastructure to support the dissemination and use of InSAR data. A good start has been made with the WInSAR consortium, but a dedicated science mission with free access to InSAR data is needed to complement PBO and SCIGN, and to exploit the advantages of spatially contiguous InSAR data in deformation studies, as planned by EarthScope. SCEC will work with NSF and NASA to define where it can contribute to such a mission.

Geologic field work, combined with precise accelerator mass spectrometer (AMS) dating using ^{14}C and cosmogenic isotopes (^{36}Cl, ^{10}Be, ^{26}Al), is necessary to quantify late-Pleistocene and Holocene slip rates on major faults. Similarly, deformation rates at longer (Quaternary to Tertiary) time scales, as delineated by $^{40/39}$Ar, fission-track, and U-Th-He dating, are required to resolve the evolution of slip and rock-uplift rates. Despite the SCEC and USGS efforts in neotectonics and paleoseismology, there are only a handful of well constrained Holocene slip rates along the entire length of the SAF, and most of these cover just the last 2000-3500 years. The slip rates of most major faults in Southern California are either unknown or are determined at only one or two sites. Data are especially lacking in structurally complex regions such as the Transverse Ranges and Coastal Ranges contractional provinces, where many questions still remain about how strain is partitioned among the major faults and between seismogenic faults and aseismic folding. New techniques in tectonic geomorphology could play a major role in addressing these issues. The evolving geomorphic character of former depositional surfaces inferred by combining detailed field mapping and geochronology with a precise digital elevation model (DEM) are particularly powerful in assessing the patterns of deformation associated with blind thrust faults, where the absence of surface ruptures confounds the traditional paleoseismic approaches. Such studies yield data on rates of strain at Holocene to Quaternary time scales, on the geometry of hanging-wall deformation, and, when combined with geodesy and modeling, on the magnitude of off-fault strain[3]

Understanding the tectonics of this plate-boundary zone will require data from regions other than Southern California. For example, key inferences about the deep structure of the SAF have been made from investigations of similar exhumed faults, both inside[4] and outside of Southern California.[5] Studies of exhumed fault zones are likely to contribute new insights into how the modes of deformation vary with depth, as well as critical evidence on secondary deformation near a slip surface and important details on the role of fluids.[6] The study of seismogenesis in stable, high-strength continental regions offers interesting comparisons with weaker plate-boundary zones for understanding the fundamentals of tectonic and earthquake processes. The wide geographic distribution of SCEC participating institutions will encourage lively debate about the significance of such cross-regional comparisons.

Progress on the major issues of plate-boundary tectonics will be facilitated by the construction of SCEC community models[7] that can assimilate the various types of geologic, geodetic, and geophysical data. A proper interpretation of these data must begin with a detailed representation of the active structural elements; in particular, it will be necessary for SCEC to expand its efforts to quantify the

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2 *Proceedings of the 2nd Plate Boundary Observatory Workshop*, J. Freymueller (chair), Southern California Earthquake Center, October, 2000.

3 D. W. Burbank, A. Meigs, & N. Brozovic, *Basin Research* **8**, 199-223, 1996; L. B.Grant, K. J. Mueller, E. M. Gath, H. Cheng, R. L. Edwards. R. Munro, & G. L. Kennedy, *Geology* **27**, 1031-1034, 1999; J. Lavé & J. P. Avouac, *J. Geophys. Res.* **105**, 5735-5770, 2000.

4 J. L. Anderson, R. H Osborne, & D. F. Palmer, *Tectonophys*. 98, 209-251, 1983; L.-J. An & C. G. Sammis, *Pure Appl. Geophys.* **143**, 203-227, 1994; F.M. Chester, J.P. Evans & R.L. Biegel, *J. Geophys. Res.* **98**, 771-786, 1993.

5 M. A. Forster and G. S. Lister , in U. Ring, M. T. Brandon, G. S. Lister, & S. D. Willett (eds.), *Geological Society Special Pub.* **154**, 305-323, 1999.

6 See S. Hickman, R. Sibson & R. Bruhn, *J. Geophys. Res.* **100**, 12,831-12,840, 1995, and references therein.

7 In this proposal, the term "community model" designates an on-line, documented, maintained resource accessible to SCEC and other investigators for knowledge quantification and synthesis, hypothesis formulation and testing, data conciliation, and prediction; see §III.B.3.

representation of major faults throughout Southern California in all three spatial dimensions. Further objectives of the proposed research are to:

- integrate other information—in particular, the 3D seismic velocities used in the recovery of earthquake source parameters and the simulation of ground motions—into a unified structural representation of Southern California;
- use this 3D representation as the basis for combining all available data on geodetic velocities and fault slip rates into kinematically consistent (4D) models of the plate-boundary deformation zone; and, eventually,
- extend the kinematical representation to a fully dynamical model that incorporates realistic rheologies, boundary tractions, and body forces.

This program of data integration and modeling will require good data access, substantial IT resources, and the development of novel techniques. For instance, geologic inferences about geometries and kinematics of blind faults could be used as *a priori* information in a Bayesian framework for analyzing geodetic data for fault slip rates, orientations, and locking depths.[8]

Short-Term Objectives:

1. Use existing geologic, seismic, and other data (e.g. well-logs, DEMs) to depict major faults in Southern California in three dimensions and integrate this model with other information (e.g., seismic velocities) to create a unified 3D structural representation.
2. Develop an updateable SCEC community model that combines geologic slip rates on faults and geodetic velocities with the unified structural representation to describe fault-system kinematics.
3. Improve knowledge of fault slip and uplift rates using geologic, geomorphic, geodetic, and seismic methods. Systematically study how the surface expression of blind faults relates to rates of shortening and structural geometries.
4. Using a Bayesian framework, carry out inversions to compare the long-term and short-term rates, and determine what information is most needed to resolve any inconsistencies.[9]
5. Collaborate with EarthScope working groups and UNAVCO to initiate plans for improving measurements of the secular crustal velocity field in Southern California using the extended GPS and strainmeter instrumentation of the Plate Boundary Observatory (PBO).

[8] Shen, Z-K, D. D. Jackson, & B. X. Ge, *J. Geophys. Res.* **101**, 27,957-27,980, 1996.

[9] Discrepancies between slip rates determined by geologic methods and inferred from GPS geodesy have been discussed by D. F. Argus et al., *Geology* **27**, 703-706, 1999.

2. Fault Systems

While significant questions regarding distributed, aseismic deformation remain unanswered, moment-balance and slip-rate calculations indicate that most of the motion in the upper 15 kilometers of the Southern California plate-boundary zone occurs as earthquakes on active faults.[10] In this discussion of fault systems, emphasis is placed on phenomena that occur on the “interseismic” time scales relevant to fault interactions, seismicity distributions (including earthquake cyclicity, aperiodicity, and clustering), and the long-term aspects of the post-seismic response. The underlying dynamics of fault systems is highly nonlinear, and the study of this subject from the perspective of dynamical systems theory, which focuses on scaling behaviors and universality, has led to fundamental insights about how certain types of nonlinear systems may behave in general.[11] Fault dynamics involves interactions among a number of mechanical and chemical processes—fault friction and rupture, poroelasticity and fluid flow, viscous coupling, etc.—and sorting out how these different processes interact to govern the cycle of stress accumulation, transfer, and release is a major goal. Moreover, progress on the problem of seismicity as a cooperative behavior within a network of active faults has the potential to deliver huge practical benefits in the form of improved earthquake forecasting. The latter consideration sets the direction for SCEC’s long-term efforts.

Long-Term Goal: To understand the kinematics and dynamics of the plate-boundary fault system on interseismic time scales, and to apply this understanding in constructing probabilities of earthquake occurrence in Southern California, including time-dependent earthquake forecasting.

Key Questions:

1. What are the limits of earthquake predictability, and how are they set by fault-system dynamics?
2. Which aspects of the seismicity are scale-invariant, and which are scale-dependent? How do these scaling properties relate to the underlying dynamics of the fault system? Under what circumstances is it valid to extrapolate results based on low-magnitude seismicity to large-earthquake behavior?
3. Are there patterns in the regional seismicity of Southern California that are related to the past or

[10] R. S. Stein & T. C. Hanks, Bull. Seismo. Soc. Am., 88, 635-652, 1998; B. Shen-Tu, W. E. Holt, & A. J. Haines, J. Geophys. Res., 104, 28927, 1999.

[11] P. Bak, *How Nature Works: the Science of Self-Organized Criticality*, Springer-Verlag, New York, 1996, 212 pp.; .J. Langer et al., *Proc.Nat. Acad. Sci*, **93**, 3825, 1996; B. E. Shaw & J. R. Rice, *J. Geophys. Res.* **105**, 23,791, 2000.

future occurrence of large earthquakes? For example, are major ruptures on the SAF preceded by enhanced activity on secondary faults, temporal changes in *b*-values, or local quiescence? Can the seismicity cycles associated with large earthquakes be described in terms of repeated approaches to, and retreats from, a regional "critical point" of the fault system?[12]

4. What are the statistics that describe seismic clustering in time and space, and what underlying dynamics (e.g., mode-switching[13]) control this episodic behavior? Is clustering observed at particular sites on the SAF due to repeated ruptures on an individual fault segment, or to rupture overlap from multiple segments? Is clustering on an individual fault related to regional clustering encompassing many faults?
5. What systematic differences in fault strength and behavior are attributable to the age and maturity of the fault zone, lithology of the wall rock, sense of slip, heat flow, and variation of physical properties with depth? Is the mature SAF a weak fault? If so, why?
6. To what extent do fault-zone complexities, such as bends, changes in strength, and other "quenched heterogeneities" control seismicity? How applicable are the "characteristic-earthquake" and "slip-patch" models in describing the frequency of large events? How important are dynamic cascades in determining this frequency? Do these cascades depend on the state of stress, as well as the configuration of fault segments?
7. How does the fault system respond to the abrupt stress changes caused by earthquakes? To what extent do the stress changes from a large earthquake advance or retard large earthquakes on adjacent faults? How does stress transfer vary with time?[14]
8. What controls the amplitude and time constants of the post-seismic response, including aftershock sequences and transient aseismic deformations? In particular, how important are fault-healing effects, poroelastic effects, and coupling of the seismogenic layer to viscoelastic flow at depth?

Data and Modeling Requirements: Understanding fault systems requires integrative modeling of seismologic, geodetic, and earthquake geology data. As with plate-boundary tectonics, the study of fault systems relies heavily on the information supplied by earthquake geology, particularly paleoseismology. A good example is the long-standing problem of regional earthquake clustering,[15] an issue crucial to earthquake forecasting that is poorly constrained by the limited catalogs of instrumental seismology. After the 1992 Landers earthquake, SCEC and USGS scientists undertook a collaborative effort to define the paleoseismic history of the southeastern Mojave region, which showed that many faults failed in large earthquakes within a 1000–2000-yr period, followed by a quiescence lasting up to several thousand years.[16] The ECSZ is an excellent but poorly documented natural laboratory for further work on this problem, as is the San Andreas fault itself. Although the SAF is perhaps the best studied fault in the world, with over 20 paleoseismic sites distributed along its trace through Southern California, improved data—especially better chronologies—will be necessary to pin down event correlations among sites with the precision to answer key questions (4) and (6) above. A different perspective can be obtained through study of fault systems for which earthquakes are less frequent, but can be well dated (e.g., ECSZ or Basin and Range), or for which unique sets of data on historical earthquakes and paleoseismicity are available (e.g., the Middle East[17]).

Seismologic data are also essential. Modeling seismicity on a fault network relies on an accurate and complete seismic catalog for the recognition of spatial-temporal-magnitude patterns in regional seismicity. Maintaining the earthquake catalog is an operational responsibility of the network operators (primarily Caltech and the USGS), although SCEC has supported research for improving the cataloged locations and moment tensors and will continue to encourage the development of new seismological products.[18]

[12] C. Sammis & S. Smith, *Pure Appl. Geophys.* **155**, 307-334, 1999; S. Jaume & L. Sykes, *Pure Appl. Geophys.* **155**, 279-306, 1999.

[13] Y. Ben-Zion, K. Dahmen, V. Lyakhovsky, D. Ertas & A. Agnon, *Earth Planet. Sci. Lett.* 172, 11-21, 1999.

[14] R. A. Harris, *J. Geophys. Res.* **103**, 24347-24358, 1998.

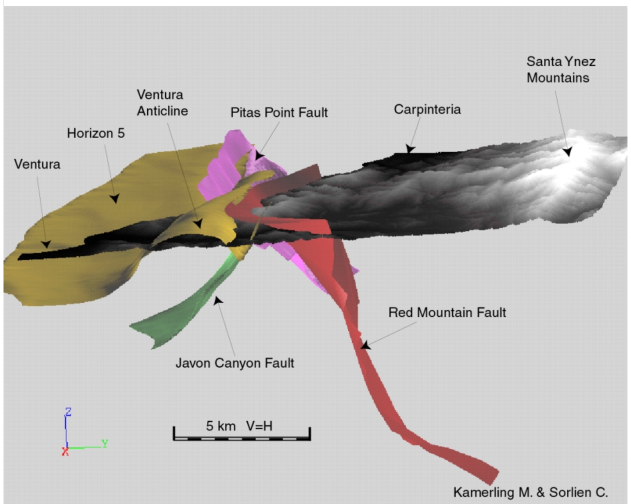
[15] Arguments for regional clustering were initially based on historical earthquakes in Asia (by C. Allen) and the Great Basin (by R. Wallace). Paleoseismic data for clustering of large events on the San Andreas system have been summarized by T. K. Rockwell & K. E. Sieh, *Proceedings of the Workshop on Paleoseismology*, Marshall, CA, United States, p. 161; L. B. Grant & K. Sieh, *J. Geophys. Res.* **99**, 6819-6841, 1995.

[16] A new paleoseismic study of the Garlock fault, which bounds the Mojave province on the north, has also demonstrated clustering behavior (Rockwell et al., 2000). The long-term slip rate for the Garlock fault (about 7 mm/yr) is substantially higher than for any individual Mojave fault, but preliminary data indicate that its earthquakes are in phase with the Mojave events. If this unexpected inference is not an artifact of sampling bias, earthquake clustering may operate on a much larger scale, perhaps associated with large-scale variations in driving stresses.

[17] S. Marco, A. Agnon, M. Stein & H. Ron, *J. Geophys. Res.* **101**, 6179-6191, 1996; N. N. Ambraseys & M. Barazangi, M., *J. Geophys. Res.* **94**, 4007-4013, 1989.

[18] For example, broadband waveform data from smaller events (M4-5) could be used to invert for source dimensions, durations, and directivity, as now possible

Figure 3.1. Development of a Community Fault Model will receive a high priority as part of the SCEC2 effort towards a unified structural representation. Shown here is a 3D perspective of faults near the California coast between Ventura and Carpinteria, viewed from east of Ventura to the west. The image shows surface topography in gray (USGS DEM), Red Mountain fault in red (Huftile and Yeats, 1995), Pitas Point fault in purple, and the offshore part of the Javon Canyon fault in green. Surface in yellow is Horizon 5 (~1 Ma) of Yeats (1981) modified by C Sorlien; it and the Red Mountain fault are projected above the present topography. The Red Mountain fault was defined by well penetrations down to 3 km, and the deeper part of the fault was delineated by earthquake hypocenters. (Courtesy of Mark Kammerling.)



Better structural data are needed on fault segmentation, as well as an improved mechanical understanding of the role of segmentation in fault rupture. Work on fault-zone complexity suggests fundamental differences in behavior between mature faults, such as the San Andreas, and immature faults, such as the San Jacinto or Elsinore.[19] If segment boundaries play a key role in the termination of ruptures, then highly segmented faults may tend to be more characteristic in their behavior, or at least more predictable in the lateral extent of future ruptures. A long, smooth fault such as the SAF may not have any "hard" segment boundaries, making the size of ruptures more sensitive to time-dependent stress heterogeneities.

Changes in Coulomb stress parameters resulting from large earthquakes have been invoked as a quasistatic mechanism for modifying seismicity rates.[20] If such dynamical interactions significantly affect the timing of earthquakes on nearby faults, then they must be accounted for in any model of earthquake recurrence. An important issue is the role of time-dependent phenomena, such as fault-healing, poroelasticity, and viscoelasticity, in stress transfer.[21] A SCEC-sponsored workshop on stress triggering produced three numerical codes with tutorials and manuals that are now in wide usage (10 posters at the 2000 SCEC Annual Meeting employed these codes), and there is an opportunity to build on this community modeling capability by adding viscoelastic and poroelastic modules.

The expansion of SCEC activities in the numerical modeling of fault-system dynamics will be done in collaboration with the Generalized Earthquake Models (GEM) project (see §II.B.3).

Short-Term Objectives:

1. Compile and categorize all paleoseismic data available for Southern California, with emphasis on determining the earthquake history of the SAF and ECSZ. Improve knowledge of the timing of large earthquakes by precise dating of selected samples from existing paleoseismic sites, and assess potential sampling bias of previous work on earthquake clustering by field work at several well-targeted new sites in the northeasterly ECSZ.
2. In collaboration with the USGS, use the paleoseismic data base and other information (including seismicity simulations[22]) to design a new plan for geologic studies of the SAF and other faults in Southern California directed at the fundamental issues of fault-system behavior.
3. Integrate existing information on fault structure and segmentation into the unified structural representation of Southern California to improve the geologic basis for seismicity simulations (e.g. Fig. 3.1).
4. Use earthquake statistics or other observables to test proposed models of earthquake clustering, including foreshocks and aftershocks.
5. Develop statistically valid evaluations of spatiotemporal variations in seismicity rate. Evaluate the effect of stress transfer in predicting rates of future seismicity. Compare the relative effectiveness of changes in shear stress, normal stress, and Coulomb stress.

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in teleseismic analysis (J. McGuire, L. Zhao & T. H. Jordan, *Bull. Seismol. Soc. Am..*, in press, 2000). Resolving the fault-plane ambiguity by this method would allow smaller earthquakes to be employed in delineating patterns of faulting and fault dips.

[19] S. Wesnousky, *Nature* **335**, 340-342, 1988.

[20] K. W. Hudnut, L. Seeber & J. Pacheco, *Geophys. Res. Lett*. **16**, 199-202, 1989; R. A. Harris & R. W. Simpson, *Nature* **360**, 251-254, 1992; G. C. P. King, R. S. Stein & J. Lin, *Bull. Seismol. Soc. Am* **84**, 935-953, 1994; R. S. Stein, A. A. Barka, & H. D. Dieterich, *Geophys. J. Int*. **128**, 594-604, 1997.

[21] R. A. Harris, Stress Triggers, Stress Shadows, and Implications for Seismic Hazard, Introduction to the Special Issue, *J. Geophys. Res*. **103**, 24347-24358, 1998.

[22] S. N. Ward, *J. Geophys. Res*. **101**, 22,393-22,418, 1996.

6. Add afterslip, viscoelastic, and poroelastic modules to existing codes for modeling stress transfer between faults following moderate to large earthquakes.

3. Fault-Zone Processes

In theoretical studies of fault systems and rupture dynamics, earthquakes are usually approximated as propagating dislocations on idealized, friction-bound fault planes. In reality, earthquakes involve a complex sequence of events that lead to rheological breakdown and damage within zones of finite width. Damage zones can be investigated on large scales by seismological field experiments using fault-zone trapped waves, a research area pioneered by SCEC scientists,[23] as well as by gravity and electromagnetic methods. On smaller scales, processes of rock failure can be studied in the laboratory and their effects observed by field work on exhumed faults.

Thus far, the latter areas of inquiry have not been priorities for SCEC research. However, the move toward physics-based modeling of earthquake phenomena dictates that more attention be placed on relating small-scale processes within fault zones to the large-scale dynamics of earthquakes and fault systems. Earthquakes have many scale-invariant and self-similar features, yet numerical simulations must assume some smallest length scale in a grid or mesh, as well as a shortest time step, in order to discretize the computational problem. The problem then becomes how to capture the wealth of processes that occur on sub-grid scales through judicious parameterizations.

Long-Term Goal: To understand the internal structure of fault zones and the microscale processes that determine fault-zone rheologies in order to formulate more realistic macroscopic representations of fault-strength variations in time and space.

Key Questions:

1. Which small-scale processes—pore-water pressurization and flow, thermal effects, geochemical alteration of minerals, solution transport effects, contact creep, microcracking and rock damage, gouge comminution and wear—are important in describing the earthquake cycle of nucleation, dynamic rupture, and post-seismic healing?
2. What fault-zone properties determine velocity-weakening vs. velocity-strengthening behavior? How do these properties vary with temperature, pressure, and composition?
3. How does fault strength drop as slip increases immediately prior to and just after the initiation of dynamic fault rupture? Are dilatancy and fluid-flow effects important during nucleation?
4. What is the nature of near-fault damage and how can its effect on fault-zone rheology be parameterized? Can damage during large earthquake ruptures explain the discrepancy between the small values of the critical slip distance found in the laboratory (< 100 microns) and the large values (> 100 millimeters) inferred from the fracture energies of large earthquakes?
5. How does fault-zone rheology depend on microscale roughness, mesoscale offsets and bends, variations in the thickness and rheology of the gouge zone, and variations in porosity and fluid pressures? Can the effects of these or other physical heterogeneities on fault friction be parameterized in phenomenological laws based on rate and state variables?
6. How does fault strength vary as the slip velocities increase to values as large as 1 m/s? How much is frictional weakening enhanced during high-speed slip by thermal softening at asperity contacts and by local melting?
7. How do faults heal? Is the dependence of large-scale fault healing on time logarithmic, as observed in the laboratory? What small-scale processes govern the healing rate, and how do they depend on temperature, stress, mineralogy, and pore-fluid chemistry?

Data and Modeling Requirements: Laboratory-derived friction models have been effective in explaining a number of seismic phenomena, furnishing a theoretical basis for numerical simulations of fault-system behaviors and dynamic ruptures.[24] Continued experimentation at the SCEC-affiliated rock-mechanics laboratories (USGS Menlo Park, Brown, Penn State, Columbia) will provide additional data to address several of the key questions. For example, laboratory experiments are beginning to access the frictional properties of rock surfaces and gouge zones at high slip velocities. This is a challenging task experimentally, because a combination of large slip, rapid slip rates, and elevated normal stress are all required to reproduce rupture conditions during earthquakes. The primary role for SCEC will not be to support such experiments directly, but to bring experts together to formulate laboratory-based models that are testable with field-scale data.

Studies of exhumed faults in Southern California and other regions have furnished constraints on fault-zone structure and processes. For example, R. Sibson found gouge "explosion" structures that implied a sudden drop in confining pressure during faulting; F. Chester and J. Chester found that most

[23] Y.-G. Li, K. Aki, D. Adams, A. Hasemi & W. H. K. Lee, *J. Geophys. Res.* **99**, 11,705-11,722, 1994; Y.-G. Li, K. Aki, J. E. Vidale & F. Xu, *J. Geophys. Res.* **104**, 20,257-20,275, 1999.

[24] J. Dieterich, *J. Geophys. Res.* **99**, 2601-2618, 1994.; *Tectonophysics* **211**, 115-134, 1992.

of the slip on the Punchbowl fault occurred on a very narrow planar "slip surface".[25] Further work should be encouraged to explore the mechanical importance of such shear localization structures and to look for evidence of fluids and local melting.

The most exciting prospects for direct observations of fault-zone processes are from the fault-drilling component of the EarthScope Project—the San Andreas Fault Observatory at Depth (SAFOD)—which will drill, sample, and perform *in situ* experiments to 4-km depth at Parkfield, California. SAFOD, which will be jointly managed by Stanford University and the USGS, is completely independent of SCEC, but the addition of both Stanford and Menlo Park as SCEC core institutions will facilitate collaborations between the SAFOD and SCEC science teams.

Because the earthquake problem cannot be fully addressed at the laboratory scale or by direct field observations, it is important to have rigorous physical modeling that begins with testable microscale processes, and carries out the appropriate multi-scale analyses to understand the implications for natural events. Much research has recently been done on the microscale physics of fault zones using numerical lattice and particle models.[26] Although SCEC does not propose a major effort in microscale simulations, this type of modeling is a central activity of the ACES international collaboration, in which both SCEC and GEM participate.[27] As described below, SCEC modeling activities will be concentrated in fault-system and rupture dynamics and coordinated with GEM.

Short-Term Objectives:

1. Develop deeper collaborations between laboratory researchers who study rock mechanics and scientists who study the large-scale phenomena of earthquakes and fault-system dynamics.
2. Use dynamical simulations to assess the discrepancies between laboratory-based friction laws and observed fault-system behaviors (e.g., earthquake productivity, post-seismic response) and seismological data on large earthquakes (e.g., fracture energies, particle velocities and accelerations).
3. Expand SCEC participation in ACES and connections to the SAFOD Program.
4. Study exhumed fault zones to determine the relationship between fault structure and fault mechanics, with special emphasis on determining the width of the primary sliding zone.

4. Rupture Dynamics

A comprehensive, predictive understanding of earthquake ground motion will require much better knowledge of the physics of rupture propagation and frictional sliding on faults. The same is probably true for earthquake forecasting, because of the dynamical connection between the evolution of the stress field on interseismic time scales and the stress heterogeneities created and destroyed during earthquakes. SCEC scientists have been research leaders in rupture dynamics (see §II), and this research will continue as a major focus in SCEC2.

Long-Term Goal: To understand the physics of rupture nucleation, propagation, and arrest in realistic fault systems, and the generation of strong ground motions by earthquakes.

Key Questions:

1. What is the magnitude of the stress needed to initiate fault rupture? Are crustal faults "brittle" in the sense that ruptures require high stress concentrations to nucleate, but, once started, large ruptures reduce the stress to low residual levels?
2. How do earthquakes nucleate? What is the role of foreshocks in this process? What features characterize the early post-instability phase?
3. What is the nature of fault friction under slip speeds characteristic of large earthquake ruptures? How can data on fault friction from laboratory experiments be reconciled with the earthquake energy budget observed from seismic radiation and near-fault heat flow?
4. How much inelastic work is done outside a highly localized fault-zone core during rupture? Is the porosity of the fault zone increased by rock damage due to the passage of the rupture-tip stress concentration? What is the role of aqueous fluids in dynamic weakening and slip stabilization?
5. Do minor faults bordering a main fault become involved in producing unsteady rupture propagation and, potentially, in arresting the rupture? Is rupture branching an important process in controlling earthquake size and dynamic complexity?
6. Are strong, local variations in normal stress generated by rapid sliding on nonplanar surfaces or material contrasts across these surfaces? If so, how do they affect the energy balance during rupture?
7. What produces the slip heterogeneity observed in the analysis of near-field strong motion data? Does it arise from variations in mechanical properties

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[25] R. Sibson, *J. Geophys. Res.* **85**, 6239-6247, 1992; F. M. Chester & J. S. Chester. *Tectonophysics* **295**, 199-221, 1998.

[26] P. Mora & D. Place, *J. Geophys. Res.* **103**, 21,067-21,089, 1999; E. Aharonov & D. W. Sparks, *Phys. Rev. E* **60**, 6890-6896, 1999; C. Thornton, in *Constitutive Modelling of Granular Materials* (ed. D. Kolymbas), Springer-Verlag, 2000, pp. 193-208.

[27] ACES is the APEC Cooperation for Earthquake Simulation, which draws its participating institutions from the countries of the Asia-Pacific Economic Cooperation (http://shake2.earthsciences.uq.edu.au/ACES/)

(quenched heterogeneity) or stress fluctuations left in the wake of prior events (dynamic heterogeneity)?

8. Under what conditions will ruptures jump damaged zones between major fault strands? Why do many ruptures terminate at releasing step-overs? How does the current state of stress along a fault segment affect the likelihood of ruptures cascading from one segment to the next?
9. What are physical mechanisms for the near-field and far-field dynamical triggering of seismicity by large earthquakes?

Data and Modeling Requirements: The most important data for constraining and testing dynamic earthquake models are ground-motion recordings near earthquake ruptures and GPS measurements and InSAR images of the near-fault deformation field. To make effective use of this information in the study of rupture physics, SCEC scientists will also need:

- Detailed 3D models of seismic wave-speed structure, in order to account for propagation effects in the waveform data.
- Fine structure of fault zones from geologic mapping and remote sensing, seismicity information, and trapped-wave studies of low-velocity zones and anisotropy.
- Access to experimental data on rock friction at high sliding velocities and large slips.
- Better understanding of fault-zone fluid processes from geologic observations on exhumed faults and, eventually, *in situ* observations from SAFOD and other drilling experiments.
- Constraints on the state of stress, including a better characterization of past earthquake history and stress-transfer mechanisms.

Numerical simulations are central to research in rupture dynamics, because they provide the physical basis for linking laboratory experiments and field data on small-scale fault-zone processes with large-scale observations of seismic waveforms and geodetic deformation fields. Full 3D dynamical simulations are needed to address issues regarding fault-zone complexities (e.g., non-planarity of fault surfaces, step-overs, and branches in fault networks) and the selection among competitive rupture paths. Codes for such simulations are just becoming available (see §III.B.2), and their use will require extensive access to "terascale" computing capabilities. Owing to the wide separation between the inner scale of faulting (e.g., frictional breakdown at the rupture front, as small as ten meters) and its outer scale (e.g., total rupture length, up to hundreds of kilometers), the computational difficulties are truly enormous.

Rupture modeling involves nonlinear processes and geometrical complexities on various length scales, and there is no consensus methodology optimal for all aspects of the problem (see §III.B.2). A desirable simulation framework, therefore, would allow user-supplied rupture modules to be embedded in, and coupled to a fast, simple 3D wave-propagation model (e.g., a finite-difference code). With appropriate links to the community structural model for Southern California, this approach would furnish a framework for comparing waveform computations with recorded seismic data from past events, and thus for improving the models, as well as the predictive simulations for future earthquake scenarios.

Short-Term Objectives:

1. Establish a set of "reference earthquakes" in Southern California, including Landers, Northridge, and Hector Mine, by (a) improving the analysis and availability of geologic, geodetic and seismologic observations, especially strong-motion data, on these events, and (b) collecting more data on the 3D structure and properties of the faults that ruptured.
2. Initiate the development of a community modeling infrastructure for rupture-dynamics computations by defining the data structures and interfaces needed for the exchange of information and computational results.
3. Undertake the systematic validation of existing rupture-dynamics codes using the reference earthquakes as a basis for the comparison.
4. Develop techniques for the assimilation of seismic and geodetic data into the rupture-dynamic models.
5. Apply high-resolution location techniques to resolve the spatiotemporal distribution of microearthquakes on active faults in Southern California and compare with similar studies on creeping sections of the SAF in central California.

5. Wave Propagation

Earthquake damage is primarily caused by seismic waves. In Southern California, seismic shaking is heavily influenced by the details of how seismic waves propagate through complex geological structures. In particular, strong ground motions can be enhanced by resonances in sedimentary basins and wave multipathing along sharp geologic boundaries at basin edges, as well as by amplifications due to near-site properties. While near-site effects such as liquefaction can be strongly nonlinear, most aspects of seismic wave propagation are linear phenomena described by well-understood physics. Therefore, if the seismic source could be precisely specified and the wave velocities, density, and intrinsic attenuation were sufficiently well known, it would be possible to predict strong motions by a forward calculation.

This topic is complicated by the fact that source excitation and wave propagation are intimately coupled, both as forward problems (inertial effects are important in rupture dynamics) and as inverse problems (excitation and propagation must be untangled to interpret seismograms). The coupling becomes stronger as the ground-motion frequencies get higher. At present, K. Olsen's simulations using the most recent version of the SCEC's 3D Community Velocity Model can model the peak amplitudes of low-frequency motions (< 0.5 Hz) from events such as the 1994 Northridge earthquake with moderate success. Extending these calculations to the higher frequencies needed for engineering applications (> 1 Hz) will require much better seismological imaging of both the rupture process and crustal structure.

Long-Term Goal: To determine the structure of urbanized Southern California well enough to predict deterministically the surface motions from a specified seismic source at all frequencies up to at least 1 Hz, and to formulate useful, consistent, stochastic representations of surface motions up to at least 10 Hz.

Key Questions:

1. How are the major variations in seismic wave speeds in Southern California related to geologic structures? How are these structures best parameterized for the purposes of wavefield modeling?
2. What are the contrasts in shear-wave speed across major faults in Southern California? Are the implied variations in shear modulus significant for dynamic rupture modeling? Do these contrasts extend into the lower crust and upper mantle?
3. How are variations in the attenuation parameters related to wave-speed heterogeneities? Is there a significant dependence of the attenuation parameters on crustal composition or on frequency? How much of the apparent attenuation is due to scattering?
4. In what ways do near-fault ground motions for reverse faulting differ from those of strike-slip faulting? In thrust faulting, how does energy trapped between the fault plane and free surface of the hanging-wall block amplify strong ground motions?
5. Are fault-parallel, low-velocity waveguides deep-seated features of faults? How continuous are they along strike and dip? Can studies of fault-zone trapped waves constrain the effective rheological parameters of the fault zone, such as effective fracture energy?
6. Are the poor predictions of some components of strong ground motion by theoretical models dominantly due to (a) heterogeneity in source excitation, (b) focusing by geologic structure, or (c) wavefield scattering by small-scale heterogeneities?
7. What role do small (sub-grid scale) heterogeneities and irregular interfaces play in wave propagation at high frequencies? How do they depend on depth, geological formation, and tectonic structure? How important is multiple scattering in the low-velocity, uppermost layers? Can stochastic parameterizations be used to improve wavefield predictions?

Data and Modeling Requirements: The SCEC 3D Community Velocity Model, which is currently limited to the Greater Los Angeles region, will have to be extended to the offshore regions and other parts of Southern California. Future improvements will include attenuation factors and a stochastic parameterization of small heterogeneities. An extensive library of seismic waveforms is available from the Southern California Earthquake Data Center to attack these problems, and the data will continue to get better as TriNet/CISN is densified and upgraded and eventually integrated with the USGS's Advanced National Seismic System (ANSS). A major new source of structural data will come from the USArray component of the EarthScope Project, which will make its initial deployments in the southwestern United States, including Southern California. SCEC will collaborate with IRIS to optimize USArray for recovery of 3D structure. In addition to the regional deployment of the "Big Foot" array, SCEC, IRIS, and the USGS will use the high-density "flexible" array for active-source studies of specific features, thus continuing the high-resolution crustal studies begun under the LARSE initiatives. Portable aftershock arrays may yield valuable information on fault waveguides for constraining crack density, continuity of fault planes, and evolution of fault strength through the seismic cycle. Portable arrays recording background seismicity will also shed light on the effect of basins and basin edges on ground motion.

Crustal and uppermost mantle structure will be resolved using waveform data from local and regional earthquakes recorded on permanent and temporary stations to supplement active-source imaging. High-priority targets include the investigation of fault-related offsets of major structural features, such as the Moho discontinuity, which would shed light on the rheology of the lower crust and would connect observed surface motions with underlying mantle flow. A better knowledge of Moho topography would also improve the prediction of strong motions from *SmS* reflections at ranges of 50-150 km.[28]

As richer seismic data sets are collected, the primary challenge for SCEC will be to set up a computational framework for (a) the systematic refinement of 3D wave-speed models and (b) the

[28] Moho reflections were partially responsible for the strong ground motions that damaged San Francisco after the 1989 Loma Prieta earthquake (Somerville. P.G. & J. Yoshimura, *Geophys. Res. Lett.* **17**, 1203-1206, 1990).

use of these models in the calculation of synthetic seismograms. This framework will be based on a unified structural representation (USR) that includes not only seismic propagation parameters but also geologic, gravimetric, and other information on major features—in particular, faults. The creation of a USR extends the rationale for SCEC/IRIS cooperation in EarthScope and will contribute substantially to reaching the nationwide science objectives of USArray (see §III.B.3).

Developing flexible and feasible methods for assimilating wavefield observations into updated 3D structural models—the structural inverse problem—will be a conceptual and computational challenge of the highest order. In principle, the inversion can be set up as a linearized perturbation to an initial 3D structure, and the Fréchet sensitivity kernels appropriate to various data functionals can be computed numerically. In practice, the huge computational requirements will require substantial IT infrastructure and some clever theoretical work. Solving this problem will contribute to the success of USArray, which will need to employ regional-scale imaging methods in other parts of the U.S.

Improved regional models will provide for more accurate separation of source and propagation effects, facilitating more accurate hypocenter locations, focal mechanisms, and higher-order source parameters, including better imaging of rupture kinematics. The latter will be significant in initializing the stress field for fully dynamic ruptures. As the structures used in waveform simulations improve, the need for "site effects" to correct for incomplete descriptions of wave propagation should be reduced, which will help to isolate the true near-surface site effects associated with nonlinear soil response. Nonlinear site effects, including liquefaction and slumping, are a major research topic constrained by only a few *in situ* observations.

Short-Term Objectives:

1. Add attenuation parameters to the SCEC Community Velocity Model (CVM), and make available a community code for wavefield simulation in this model. Compute the wavefield in this model for a variety of earthquakes to elucidate probable patterns of ground motions across Southern California.
2. Use the CVM to relocate cataloged events in the Los Angeles basin and improve the kinematic representations of the SCEC reference earthquakes.
3. Use broadband seismic data to explore structures in the lower crust and upper mantle and their relationship to surface faulting, with an emphasis on detecting fault-related offsets in the Moho discontinuity, anisotropy, and velocity variations.
4. Emplace portable arrays to explore basin edge effects, fault-zone properties, and other wave-propagation phenomena.
5. Initiate the development of computer codes for assimilating wavefield observations to update the CVM through establishment of the necessary working groups and development of pilot projects. Estimate the uncertainties in all CVM parameters.
6. Collaborate with the USGS, IRIS, and EarthScope working groups to initiate plans for high-resolution imaging of crustal structure in Southern California using the extended assets of USArray and the CISN/ANSS.

6. Seismic Hazard Analysis

Seismic hazard analysis (SHA) involves the characterization of potential earthquake activity and associated ground motions in a form, either probabilistic or scenario-based, that is useful for earthquake engineering and emergency management. The SCEC Master Model was originally conceived as a probabilistic seismic hazard model for Southern California, and SCEC1 accomplishments include major improvements in the scientific basis for probabilistic seismic hazard analysis (PSHA) through (1) the incorporation of new types of geodetic and geologic data into seismic hazard characterization and (2) a better understanding of the geological controls on strong ground motions. The SCEC2 program will continue to emphasize the transfer of basic research results into SHA methodology, and it will build on SCEC1 by moving toward a formulation of SHA that explicitly accounts for the dependence of earthquake phenomena on time. SCEC2 will also establish an Implementation Interface, through which it will provide seismic hazard inputs for use in earthquake engineering research and practice and risk management.

Long-Term Goals: To incorporate time dependence into the framework of seismic hazard analysis in two ways: (a) through the use of rupture dynamics and wave propagation in realistic geological structures, to predict strong-motion seismograms (time histories) for anticipated earthquakes, and (b) through the use of fault-system dynamics, to forecast the time-dependent perturbations to average earthquake probabilities in Southern California.

Key Questions:

1. Do recognizable segment boundaries limit rupture propagation? How valid are the cascade and characteristic-earthquake models? What magnitude distribution is appropriate for Southern California?
2. Are large events Poissonian in time? Can PSHA be improved by incorporating non-Poissonian distribu-

tions? What distributions of recurrence intervals pertain to faults in Southern California?

3. Can physics-based scenario simulations produce more accurate estimates of ground-motion parameters than standard attenuation relationships? Can they be used to reduce the high residual variance (factor of ~1.5 at one-sigma) in current ground-motion models?
4. What is the nature of near-fault ground motion? How do fault ruptures generate long-period directivity pulses? How do near-fault effects differ between reverse and strike-slip faulting? Can these effects be predicted for scenario earthquakes?
5. What are the earthquake source and strong ground motion characteristics of large earthquakes (magnitudes larger then 7.5), for which there are few strong motion recordings? Can the shaking from large earthquakes be inferred from smaller events?
6. How does the nonlinear seismic response of soils depend on medium properties, amplitude, and frequency?

Data and Modeling Requirements: Previous studies organized by SCEC have opened questions regarding earthquake activity in the Los Angeles metropolitan region. Within the L.A. Basin, several moderate-sized earthquakes (up to M6.7) have occurred during the past century, but these are far too few to account for the GPS-observed shortening rates between JPL and Palos Verdes Peninsula.[29] One explanation is that the strain is released in larger (M7.0-7.5) earthquakes. Alternatively, the strain release may occur in clusters of more frequent, moderate earthquakes with several centuries of intervening quiescence, or even in clusters of larger events separated by a thousand years or more. No paleoseismic evidence has been exposed for any earthquake over M7 in the L.A. Basin during the last thousand years, although there is clear evidence for several large earthquakes on various faults prior to that time. Resolving this highly important seismic-hazard issue should be a major focus for SCEC efforts.

Surprisingly, the thrust faults in the Los Angeles basin appear to have lower-than-expected slip rates and some strike-slip faults are more active than previously believed. For instance, SCEC-funded research this past year on the Raymond fault has resolved the first well-constrained slip rate on a northeast-striking left-lateral fault in the Basin at a minimum of 1.5 mm/yr. Slip rates and timing of earthquakes on other northeast-striking left-lateral faults is critical in understanding the current structural framework of the L.A. region, and resolving likely future seismic sources. Similarly, much more work is needed on the rate and activity of the Newport-Inglewood fault, the timing of past earthquakes on the Palos Verdes, Whittier, Chino, Santa Monica and Hollywood faults as well as the myriad of smaller structures that account for substantial surface strain in the transition region between the strike-slip and reverse-faulting regimes. An effective strategy for coordinating SCEC and USGS efforts may be to focus teams on one or two structures each year to resolve the current uncertainties and ambiguities in existing information.

SCEC efforts in SHA are currently focused in the joint SCEC/USGS project called Regional Earthquake Likelihood Models (RELM).[30] This Phase-IV activity builds on Phase II, although the approach is fundamentally different. Rather than construct one "consensus" model, the aim is to develop and evaluate a *range* of viable models based on variety of assumptions and information types; e.g., geological fault information, alternative geometries for more speculative faults, historical seismicity, geodetic observations, stress-transfer interactions, and foreshock/aftershock statistics. Developing and testing a range of models will allow more flexibility when attempts are made to export the methodology to another region where the options are more limited. The RELM approach conforms with SCEC's role as a research organization and will leave "policy" decisions, such as weights on a logic tree, to the USGS and CDMG, whose mandate it is to produce official hazard maps.

Few recordings of strong ground motions from earthquakes greater than M7 are available for earthquake-engineering research.[31] Consequently, ground-motion models may not adequately represent the damage potential of large earthquakes. For example, the response spectrum, which is the most common representation of ground motion for engineering design, is not very sensitive to the duration of strong motion, which may be significantly longer for large earthquakes. Also, the response spectrum may not provide an adequate representation of the damage potential of long period ground motions from large earthquakes. Large long-period ground motions place very large deformation demands on flexible frame buildings. These buildings are designed to withstand deformations that extend as much ten times beyond the elastic limit. The design of these buildings for nonlinear response is critically dependent on the reliability of the ground-motion level used for design, especially at the longer periods which scale strongly with earthquake magnitude. In particular, there is an

[29] Z-K Shen, D. D. Jackson & B. X. Ge, *J. Geophys. Res.* **101**, 27,957-27,980, 1996.

[30] http://www.scec.org/research/RELM/

[31] A notable exception is the excellent data set collected by the Taiwan Central Weather Bureau from the 1999 Chi-Chi, Taiwan, earthquake (M7.6).

urgent need for an improved representation of the near-fault rupture directivity pulse for use in earthquake engineering, because the response spectrum does not provide an adequate representation of pulse-type motions.

Performance-based earthquake engineering will make increasing use of ground motion time histories to represent the shaking input into structures, enabling the dynamic nonlinear response of the structure to be rigorously modeled. Providing ground-motion time histories for performance based design forms a natural interface between SCEC2 and earthquake engineering research organizations such as the Consortium for Research in Earthquake Engineering (CUREE), the Network for Earthquake Engineering Simulation (NEES), and the Pacific Earthquake Engineering Research Center (PEER). Reliable procedures for simulating ground-motion time histories have been developed, and have been applied to some extent in earthquake engineering research and practice. Through rigorous testing of these methods against recorded strong motion data, SCEC2 aims to develop methods that can be applied routinely with a high level of confidence in earthquake engineering research and practice. SCEC2's program of fundamental research on rupture dynamics and wave propagation will provide further enhancements of existing ground motion simulation methods.

Seismic hazard analysis uses many of the data sets described under the major science issues. The structure of the RELM Project requires that these data sets be available as Community Models, since alternative earthquake source models cannot be rigorously compared unless they are based on common sets of data such as earthquake catalogs, GPS velocity vectors, and fault geometries and slip rates. Similar requirements exist for the strong motion data sets and seismic velocity models that are used in the development and validation of ground-motion prediction models. These community data sets and models should be readily accessible on line, and traceable back to the original sources. A computational infrastructure is needed to allow real-time, dynamic access to current data that reside at an appropriate host institution.

Short-Term Objectives:

1. Establish the infrastructure for the RELM project (community data bases and PSHA hazard code), present first generation earthquake forecast models, evaluate their hazard implications, and identify geophysical data needed for conclusive testing of models.
2. Resolve strain-deficit discrepancies in the Los Angeles region, and explore hazard implications of alternative fault geometries.
3. Establish a working group to begin long-term systematic development and validation of strong-motion simulation techniques, using the results of fault dynamics studies, broadband strong-motion simulations using kinematic source models, data from the recent Turkey and Taiwan earthquakes, and new near-fault data from precarious rocks.
4. Use existing waveform simulation codes to assess (a) near-fault effects, (b) ground motions from large earthquakes, and (c) basin and basin-edge amplification effects.
5. Participate in the FEMA/CUREE Near Fault Seismic Risk Project.
6. In collaboration with PEER, identify and provide sample seismic hazard inputs needed by PEER Field Laboratories in Southern California, such as older existing concrete buildings, newer concrete bridges, and the Port of Los Angeles.
7. Participate in PEER's Program of Applied Earthquake Engineering Research for Lifeline Systems.
8. In collaboration with PEER, identify and provide seismic hazard inputs needed by PEER's Thrust Areas, such as suites of ground motion time histories for performance-based seismic engineering.
9. Interface with the NEES Systems Integration Project.
10. Assist FEMA in developing a HAZUS Users' Group in Southern California, and provide example seismic hazard inputs for use in HAZUS and other loss-estimation methodologies.

B. The SCEC Framework

The science issues articulated in §III.A are well aligned with the expertise and interests of the SCEC community, and many are under active investigation. Achieving the long-term goals set forth in this discussion will clearly require vigorous data-gathering and analysis activities across the major disciplines—earthquake geology, seismology, tectonic geodesy, and rock mechanics.[32] Equally critical to this progress will be enhanced capabilities for data integration and system-level analysis to deal with the complex interactions inherent to active deformation processes. A new framework is thus proposed for the organization of SCEC2 interdisciplinary earthquake science. This framework, which will replace the current working-group structure, is a matrix of four components: (1) standing committees for disciplinary coordination and infrastructure, (2) project-

[32] As the scale of earthquake observations is refined through detailed field studies, high-resolution imaging, and especially deep drilling of faults with its capabilities for *in situ* measurements (e.g., SAFOD), at least two other disciplines—hydrology and geochemistry—will become more important in the study of active faulting. A goal of SCEC2 is to incorporate these disciplines into the collaborative framework of Southern California earthquake science.

oriented focus groups for interdisciplinary research, (3) an information technology partnership to develop an advanced IT infrastructure, and (4) a Communication, Education and Outreach (CEO) program. The technical aspects of these components are briefly described here, while the mechanisms for orchestrating their functions in concert are presented in the Management Plan (§IV).

1. Disciplinary Coordination and Infrastructure

Although SCEC is not the principal organization for earthquake data-gathering in Southern California,[33] the Center has provided, and will continue to provide, disciplinary coordination and infrastructure. For example, SCEC1 has worked with NASA, JPL, and the USGS to establish two important regional organizations in geodesy, SCIGN and WInSAR. In seismology, it has coordinated the LARSE program and assisted many experiments with deployments of seismometers from the Portable Broadband Instrument Center (PBIC). Working Group C has acted as the main planning group for a very active program in paleoseismic studies and age dating, as well as many other field-based activities by earthquake geologists. SCEC1 has also supported the consolidation of disciplinary observations into web-accessible data bases and the analysis of raw data to produce high-level data products.

SCEC2 will sustain disciplinary science through standing committees in seismology, geodesy, geology, and rock mechanics. These committees will be responsible for planning and coordinating disciplinary activities relevant to SCEC2 objectives, and each will make periodic recommendations to the Planning Committee regarding the support of disciplinary infrastructure (see §IV.D).

Seismology. The Seismology Committee will coordinate SCEC2's efforts in seismology-related activities, including its involvement with the existing regional networks (TriNet, Anza), as well as its participation in the USGS's ANSS initiative. This committee will also oversee the consolidation of disciplinary observations into accessible data bases and the analysis of raw data to produce high-level data products.

The Southern California Earthquake Data Center[34] and Strong-Motion Data Base[35] will continue to be supported under SCEC2. SCEDC and SMDB will provide SCEC scientists with access to important observations for research studies in the areas of Earth structure, seismicity, and earthquake source processes. For example, understanding the coupling of forces between mantle flow and the upper-crustal faulting will require detailed imaging of the SAF below 15 km. The depth influence of this fault beneath the LARSE I line is clear, because the root of the San Gabriel Mountains is centered on the SAF rather than the topographic high, and the Moho shows a 2-km step across the fault. To determine the rupture distribution during earthquakes will require dense, high-quality recordings of waveforms from both the broadband and strong-motion networks. The SCSN catalog itself is very useful for mapping seismic structures and determining the depth orientation of faults. Picks of the *P* and *S* phases have been essential data for tomographic studies of 3D structure, and a wider variety of phase picks can be expected from the new broadband 3-component data.

SCEC scientists have made good use of the portable broadband instruments of the PBIC, especially in aftershock studies following large earthquakes. Future uses and upgrades of this instrumentation will be coordinated with IRIS through its PASSCAL program and the USArray component of the EarthScope Project. The Seismology Committee will coordinate SCEC2 activities in active-source seismology with the USGS and IRIS, and it will explore the consolidation of PBIC with the PASSCAL Instrument Center at New Mexico Tech.

Geodesy. Geodetic measurements furnish important information for the study both of crustal dy-

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[33] The resources needed for operation of just the regional seismic and geodetic networks are comparable to the entire budget of this proposal; for example, over the six-year period from 1995 and 2001, the total investment in TriNet and SCIGN will be approximately $40 million.

[34] SCEDC, operated by Caltech, is the primary data center for the Southern California Seismic Network (SCSN/TriNet), which comprises over 300 real-time telemetered stations—100 with high-quality broadband sensors and strong-motion accelerometers—and 400 dial-up strong-motion stations. Data from the telemetered network are generally available within a few minutes of an earthquake. The primary archive consists of a master catalogue of events from 1930 to present (complete down to M1.8 in recent years), phase picks and triggered waveforms from 1980 to present, and continuous 20 sample/sec broadband records since October, 1999. SCEDC also archives (1) the survey-mode GPS observations made by various universities and government organizations in Southern California since 1985, and (2) the InSAR data sets compiled by the WInSAR consortium—activities that will interface to SCEC through the Geodesy Standing Committee.

[35] SMDB, maintained by UCSB, provides access through an on-line, relational data base to an extensive collection of strong-motion recordings—currently 1,796 records from 952 stations and 143 earthquakes. In addition to SMDB, UCSB maintains a web-accessible repository of over 84,000 seismograms from 1500 Southern California earthquakes for use as empirical Green's functions in seismological studies.

namics and of individual fault systems, as shown by the wide use of the SCEC Crustal Motion Map (CMM, Fig. 2.13). SCEC1 has supported the SCIGN continuous GPS network, including the activities of the Scripps Orbit and Permanent Array Center (SOPAC).[36] The focus within SCEC2 will be on making geodetic results available to a wider community, in keeping with the integrative goals of the new Center. In general, this will involve development of tools to work with data rather than operational support of geodetic facilities; as in the case of seismic networks, the primary funding of the geodetic networks will come from other sources. The Geodesy Committee will coordinate work in the following areas:

- GPS data interpretation. SCEC2 will update versions of the CMM and begin to provide, as a new product, a fault-slip model deduced from the CMM. SCIGN time-series and velocities will be made more accessible and interpretable to a wider range of users, as required for PBO.
- Deformation data interpretation. SCEC2 will develop improved codes to estimate strain from velocity or fault slip from surface deformation; e.g., for modeling earthquake ruptures and viscoelastic deformations.
- Strainmeter data processing and interpretation. SCEC2 will develop new methods of distributed access, interactive analysis, and interpretation of all types of strainmeters proposed for PBO.
- InSAR data. SCEC2 will make data products and analysis tools more widely available to, and usable by, a broader community. Some support for data purchases for the WInSAR archive may be necessary.
- GPS data collection. An important SCEC1 legacy is the archive of survey-mode GPS data for over 1200 locations in southern California. Reoccupying these sites with portable GPS instruments will give improved, more densely sampled velocities in many regions sparsely covered by SCIGN. SCEC2 will support modest efforts in survey-mode GPS to "harvest" these points, covering selected areas each year, and also to archive any such data collected by others, in order to improve the CMM.

Geology. The Geology Committee will replace WG-C as the coordinating body for field work in earthquake geology, and it will also oversee the gathering and synthesis of data from other sources, such as high-resolution seismic and well-log data collected by the petroleum industry and high-resolution digital elevation models. An early task will be to improve the data-gathering infrastructure for earthquake geology in Southern California. A line item in the proposed budget is designated for three geologic infrastructure activities:

- Data compilation and synthesis. Geologic data tend to be more diverse and require more complex semantics to place them in the appropriate scientific context than the instrumental time series of seismology and geodesy. Perhaps owing to this complexity, few resources have thus far been allocated to consolidate geological information into community data bases. In part because of SCEC1, geologic information on Southern California fault systems has mushroomed, and there is now a critical need for a substantial data-basing effort. SCEC2 will sponsor such an effort and coordinate it with the developing EAR initiative in "geoinformatics".
- Improved chronologies. High-precision chronologies are essential in extracting from geologic field observations, especially paleoseismic data, the information about fault-system kinematics, and rupture histories. The Geology Committee will develop a framework for integrating the efforts of field and laboratory scientists in the collection and dating of geologic samples, including standardized procedures for field documentation, sample treatment, and dating methodologies.
- Field equipment. Some infrastructural support will be expended annually for communal field equipment, such as shorings and a small backhoe for paleoseismic trenching.

Rock Mechanics. While the SCEC1 program has not explicitly involved rock mechanics, 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 (see §III.A.3). The Rock Mechanics Committee will largely rely on the established laboratories at SCEC2 participating institutions—USGS Menlo Park, Brown, Penn State, Columbia—for infrastructure, acting primarily to coordinate the on-going activities in these labs and fostering communication with the other major disciplines. Two examples illustrate the benefit that SCEC2 can achieve through disciplinary interaction between rock mechanics and seismology:

- Rock mechanics can hope to provide the *strength* drops that can accompany earthquake slip, while seismology provides information on *stress* drops. Determining how these changes are related one another may yield a better understanding of strong ground shaking.
- Restrengthening between earthquakes is predicted from laboratory friction studies and has been inferred from seismic observations on repeating earthquakes, but magnitudes do not appear to be the same. Coordinated studies are needed to resolve the discrepancy and understand fault strength.

[36] SOPAC, operated by UCSD, acts as a data archive and processing facility for SCIGN and other GPS activities in Southern California (http://lox.ucsd.edu). It provides near real-time and predicted GPS satellite orbits, the on-line GARNER data archive of the 200+ SCIGN and other continuously recording stations, and time series of daily ITRF station positions, as well as user software and software support.

Many other fruitful interactions can be envisaged. Laboratory studies suggest a correlation between unstable slip and localization of slip. Field studies of exhumed faults determine the degree of slip localization for testing laboratory inferences. Detailed field mapping of fault-surface geometry are important ingredients for dynamic-rupture modeling. Rock mechanics data suggest certain magnitudes for the size of geodetic motions immediately preceding and following earthquakes, but these magnitudes are dependent on the values of parameters in the description of the fault-zone rheology. Thus, geodetic observations can help constrain the parameter values in laboratory-based earthquake models and help lab workers learn how to scale their results to real faults. In turn, rock mechanics predictions can help geodesists design observations to detect earthquake-related signals close to the noise level.

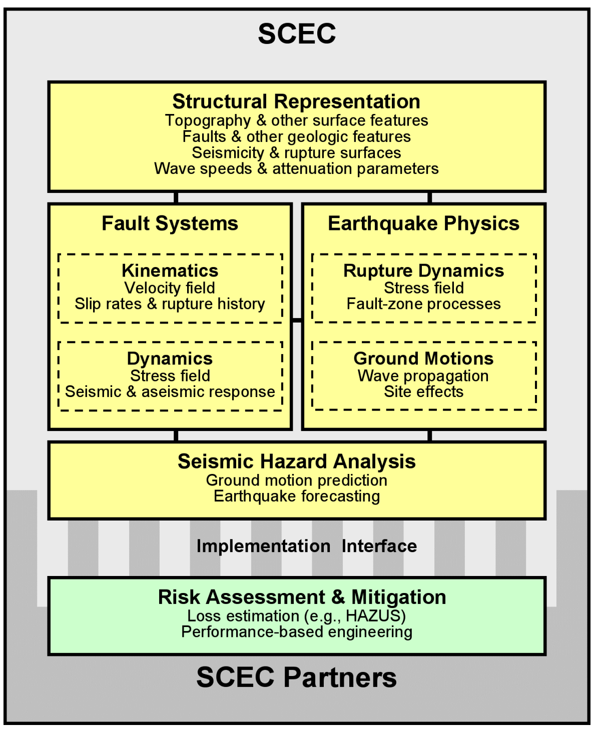

Figure 3.2. The four focus areas shown as yellow boxes will constitute the SCEC2 framework for integrating multidisciplinary research on the major science issues. Collaboration between SCEC and its partners in Risk Assessment & Mitigation, shown in green, will be managed through an Implementation Interface, designed to facilitate the transfer of science knowledge to earthquake engineering, risk analysis, and emergency management.

2. Focus Areas for Interdisciplinary Research

Science at the system level necessarily involves collaboration and synthesis across many disciplines, as the recent progress on another major geoscience problem—global climate change—illustrates so well. Interdisciplinary, system-level earthquake science is clearly an arena where SCEC2 can play a special role. SCEC2 interdisciplinary research will be organized into four main focus areas: (1) *unified structural representation*, (2) *fault systems*, including both kinematics and dynamics, (3) *earthquake physics*, including rupture dynamics, wave propagation, and site effects, and (4) *seismic hazard analysis*. These foci furnish an appropriate framework for the integration of the SCEC research on the major science topics discussed in §III.A. In addition, the SCEC2 framework will incorporate a fifth area, *risk assessment and mitigation*, that will be the subject for collaborative activities between SCEC scientists and partners from other communities—earthquake engineering, risk analysis, and emergency management. This partnership will be managed through an *implementation interface*, described in §III.B.4, designed to foster two-way communication and knowledge transfer between the different communities. The relationships among the focus areas are diagrammed in Fig. 3.2.

Unified Structural Representation. The long-term goal is to develop a unified structural model of Southern California that properly represents the major active faults and their relationship to other geologic structures, and embeds these structures in an accurate 3D representation of the seismic velocities and attenuation parameters. A unified representation will foster the integration of seismologic, geologic, and geodetic constraints on earthquake sources, as well as provide common reference models for fault kinematic and dynamic studies, strong ground motion predictions, and seismic hazards assessments. Activities in this focus area will therefore contribute to all of the major science goals discussed in §III.A.

SCEC1 efforts in structural representation are currently separated into two independent activities: (a) improvement of the 3D Community Velocity Model (CVM), under WG-D, and (b) development of a Community Fault Model (CFM), under WG-C. The CVM (Fig. 2.14) has been a focal point in SCEC1 for diverse data collection, analysis, and interpretation efforts, and it has formed the standard for benchmarking different wavefield simulation techniques and comparative modeling of specific ground-motion data sets (e.g., from the 1994 Northridge earthquake). The model currently represents only seismic wave speeds in the Greater

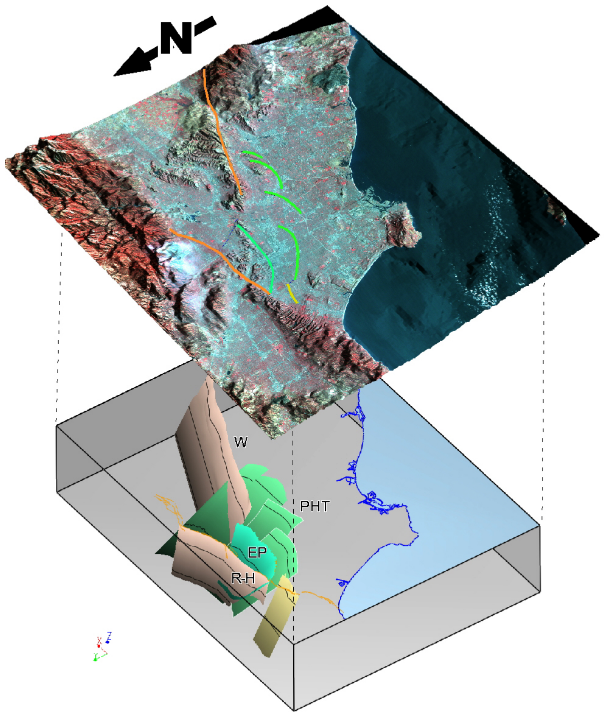

Figure 3.3. 3D perspective of active strike-slip and blind-thrust faults in the northern Los Angeles basin, which illustrates the work towards a Community Fault Model that will be continued in SCEC2. Fault surfaces were defined using surface traces, fault-plane reflections, wells, and relocated seismicity. The top surface of the models is composed of a Landsat TM image draped on regional topography and bathymetry. R-H: Raymond and Hollywood faults; PHT: Puente Hills thrust; W: Whittier fault; EP: Elysian Park thrust. (Courtesy of J. Shaw.)

Los Angeles region. Initial tasks will be (a) to extend it to offshore regions and other parts of Southern California, and (b) to include attenuation factors, rock densities, and stochastic parameterizations of sub-grid heterogeneities.

Collaboration on a digital, 3D CFM for Southern California has really just begun (Figs. 3.2). An important element of CFM design will be an explicit linkage to a data base containing the geologic and geophysical data that are used in building the model (Fig. 3.3). Vast amounts of these data are available as products of USGS and SCEC1 programs and from extensive hydrocarbon exploration and production in the coastal sedimentary basins.[37] Even with these substantial data resources, the geometry and earthquake potential of many faults remain in question. These uncertainties are particularly obvious for blind thrust and reverse faults inferred from kinematic models of hanging-wall folding.[38] Different investigators often ascribe different geometries and slip rates to these faults,[39] with profound consequences for seismic hazards assessments. The CFM will incorporate such differences in expert opinion by offering alternative fault geometries and properties for the most contentious structures.[40]

Although the separation of the CVM and CFM will be maintained through the next series of releases, actions needed to merge the two approaches into a Unified Structural Representation (USR) will receive immediate priority in SCEC2. In addition to fault surfaces and wave-propagation parameters, the USR will include surface topography, bathymetry, surficial geology and properties, and subsurface geologic horizons. The multiple uses of the USR in the other focus areas of Fig. 3.2 require that this community model (a) be topologically consistent in all four space-time dimensions (i.e., kinematically feasible), (b) retain geological understanding through object identification and appropriate descriptive semantics, and (c) be parameterized to allow the extraction of structural representations at less than full resolution (e.g., for low-frequency wavefield simulations). The considerable experience accumulated by the petroleum industry over the last decade has shown that the construction of faithful and flexible structural representations is a *very* difficult task, requiring significant resources and substantial reliance on advanced IT tools. Hence, the USR problem will be one of the central issues for the SCEC/IT partnership, described in §III.B.3.

Fault Systems. Attaining a comprehensive understanding of the Southern California fault system will be among the most difficult challenges faced by SCEC2. The Center will therefore adopt several approaches to system-level modeling for forward calculation, data inversion, and (eventually) data assimilation. The first will focus on *fault-system kinematics*, which will construct block-motion models consistent with observed geologic

[37] Surface fault traces, trench logs, precisely located seismicity, seismic reflection data, and fault penetrations in wells offer the most direct means of defining the subsurface position and geometry of active faults, while trench logs, geodesy, marine terrace data, and geomorphic observations provide constraints on their kinematics.

[38] J. Shaw & J. Suppe, *J. Geophys. Res.* **101**, 8623-8642, 1996; L. Seeber & C. C. Sorlien, *Geol. Soc. Am. Bull.* **112**, 1067-1079, 2000.

[39] T. L. Davis, J. Namson & R. F. Yerkes, *J. Geophys. Res.* **94**, 9644-9664, 1989; C. L. Schneider, C. Hummon, R. S. Yeats & G. L. Huftile, *Tectonics* **15**, 341-355, 1996.

[40] This methodology for handling uncertainties is consistent with, and will tied directly into, the RELM approach for developing and evaluating a range of seismic hazard models. It will also guide subsequent research efforts to resolve differences in interpretation.

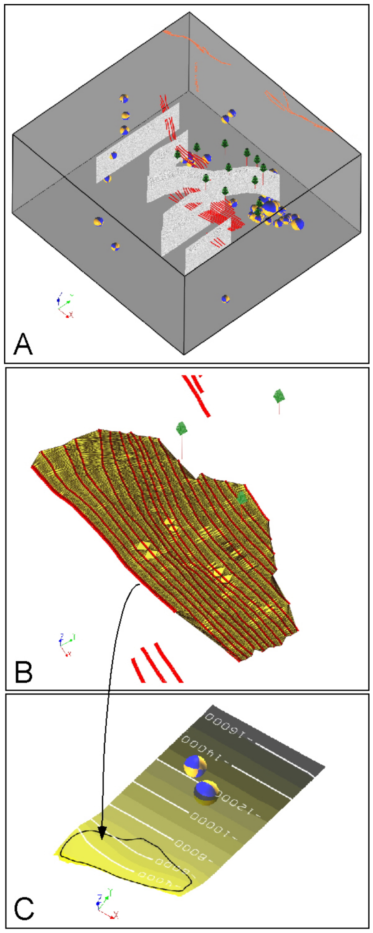

Figure 3.4. Method of constructing fault surfaces using multiple data sets. **A**: Surface fault traces, seismic reflection profiles, wells, earthquake hypocenters, and focal mechanisms, are merged in a 3D modeling environment. **B**: Fault surface is interpolated from control points, in this example from a structure contour map of fault-plane reflections. C: Fault surface is extrapolated to depth based on the geometry of the shallow segment and deep seismicity. (Courtesy of J. Shaw.)

slip rates and geodetic velocities using realistic block geometries derived from the USR. An example of existing software that can be adapted for this purpose is MIT's Blocks.3 code, which models the secular velocity field as the difference between block motions and a coseismic slip deficit associated with the lack of large earthquakes.[41] This approach will be useful for reconciling geologic and geodetic data and for resolving kinematical controversies, such as the "escape from LA" problem[42] and thick-skin vs. thin-skin tectonics, and it will undoubtedly result in the identification of gaps in the existing set of data, which in turn will guide the direction of focused geologic and paleoseismic studies within SCEC2. The second approach will be based on *dynamical earthquake simulation*, in which fault driving stress is balanced against fault frictional resistance using a 2D, quasistatic approximation. This approach has been employed by S. Ward to create synthetic catalogs of large earthquakes on the SAF system,[43] and yields simulated earthquake catalogs useful for comparisons with paleoseismic data (Fig. 3.5).

The third approach is through full *3D fault-system simulators* that attempt to model the details of time-dependent stress transfer and must therefore consider the full range of elastic, poroelastic, and viscoelastic effects, as well as the rate and state dependence of fault friction. Examples include the Virtual California simulation environment being erected by the GEM group, which is employs the fast-multipole method,[44] as well as a variety of finite-element codes, such as GAEA, ABAQUS, FEMLAB and TECTON.[45]

The short-term objectives of this focus group will be to (a) compile integrated data sets for comparisons with fault-system simulations, (b) conduct comparative benchmarks of existing software packages using standardized simulation problems, (c) identify codes for further development into user-friendly community models, and (d) expand these codes to include more realistic geometries and physics. Related activities will be work by GEM and other groups on methods for identifying seismicity patterns[46] and data-assimilation methods.

Earthquake Physics. Earthquake rupture entails nonlinear and geometrically complex processes near the fault surface, generating stress waves which evolve into linear anelastic waves at some distance from the fault. In strong earthquakes, the wavefield may be intense enough to induce further nonlinear response in weak, low-impedance surface strata. All three phenomena—rupture processes, anelastic wave propagation, and near-surface soil/rock nonlinearity—are coupled and therefore constitute a set of issues for a single focus area, here called Earthquake Physics. The long-term goals and short-term objectives of the Earthquake Physics focus group have been detailed in §III.A.4 & 5. The discussion here centers on the requirements for numerical simulation, where some differences must be recognized in the SCEC2 community-modeling framework.

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41 B. J. Meade, B. H. Hager & R. E. Reilinger, *Bull. Seismol. Soc. Am.* submitted, 2000.

42 C. Walls, T. Rockwell, K. Mueller, Y. Bock, S. Williams, J. Pfanner, J Dolan, & P. Feng, *Nature* **394**, 356-360, 1998.

43 S. N. Ward, *J. Geophys. Res.* **101**, 22,393-22,418, 1996; *Bull. Seismol. Soc. Am.* **87**, 1422-1441, 1997; *Bull. Seismol. Soc. Am.* **90**, 370-386, 2000.

44 R. Giering and T. Kaminski, *ACM Trans. Math. Software* **23**, 437-474, 1997.

45 E. H. Hearn and E. D. Humphreys, *J. Geophys. Res.* **103**, 27,033-27,049, 1998 (for GAEA); H. J. Melosh & A. Raefsky, *Bull. Seismol. Soc. Am.* **71**, 1391-1400, 1981 (for TECTON).

46 E.g., J. B. Rundle, W. Klein, K.F. Tiampo & S. Gross, in *Geocomplexity and the Physics of Earthquakes*, ed. J. B. Rundle, D. L. Turcotte and W. Klein, American Geophysical Union Monograph 120, Washington, DC, 127-146, 2000.

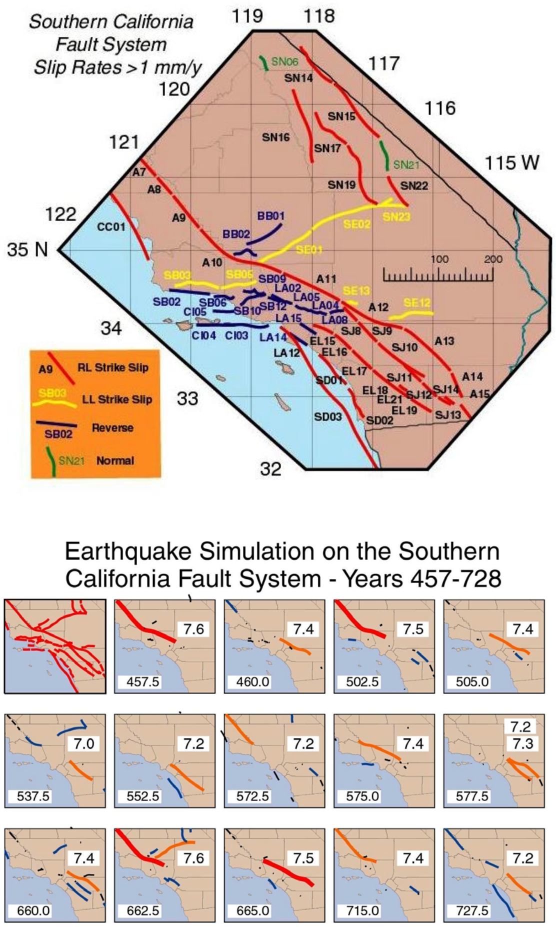

Figure 3.5. Top. Faults included in Ward's (1996) prototype "earthquake simulator" for Southern California. Colors indicate faulting style.
Bottom. Sample earthquake series from this earthquake simulator. Panels show M>6 earthquakes expected on the southern California fault system (upper left) over a 270-year interval. Line color corresponds to different magnitudes. The numbers at the lower left of each panel indicates time in years, and the frames update on the occurrence of an M>7 event. Physically-based simulations like these serve as useful platforms for hazard analysis and data assimilation. (Courtesy of S. Ward.)

Numerical modeling methods for 3D anelastic wave propagation are now fairly mature. Several efficient, capable codes are in regular use within the SCEC community. Codes based on the fourth-order staggered velocity-stress formulation, for example, have proven efficient and flexible.[47] Moreover, a systematic testing program to assess and validate existing anelastic codes has been conducted as part of a SCEC1/PEER collaboration.[48] SCEC2 is therefore in an excellent position to construct a Community Wave-Propagation Model that combines key elements of existing codes appropriate to regional-scale ground motion simulation.[49]

Rupture modeling involves nonlinear processes and geometrical complexities on various length scales, and there is no consensus methodology optimal for all aspects of this problem. An appropriate simulation framework will allow for individual user-supplied rupture modules embedded in, and coupled to, the community wave propagation model. With appropriate links to the community URS for Southern California, this approach furnishes a natural framework for comparison of synthetic waveforms with recorded seismic data, as well as for predictive simulations of strong ground motion for future earthquake scenarios. The numerical implementation of the rupture-model/propagation-model link poses a challenging technical problem at the boundary between seismology and computational sciences.[50]

A specific target will be the development of a module for coupling rupture dynamics and wave

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[47] R.W. Graves, *Bull. Seism. Soc. Am.* **86**, 1091-1106, 1996.

[48] Part of this effort has been funded under PEER's "Program of Applied Earthquake Engineering of Lifeline Systems" with industry (PG&E) and state (Caltrans) support.

[49] Features include parallelism (K. B. Olsen, R. Madariaga, & R. J. Archuleta, *Science* **278**, 834-838, 1997; H. Bao et al, *Comput. Meth. Appl. Mech. Eng.* **152,** 85-102,1998), realistic anelastic losses (S. M. Day, *Bull. Seism. Soc. Am. 88*, 1051-1062, 1998; S. M. Day & C. R. Bradley, *Bull. Seism. Soc. Am*, submitted, 2000), discontinuous gridding (multiple structured grids coupled at simple interfaces, S. Aoi & H. Fujiwara, *Bull. Seism. Soc.* **89**, 918-930, 1999), unstructured meshing (Bao et al, *op. cit.*), memory optimization (Graves, *op. cit.*), surface topography, propagating kinematic earthquake sources, an interface to optional rupture dynamics modules, and links to the USR, with options for user-defined model modifications.

[50] Existing 3D rupture-dynamics codes are based on boundary integral element (BIE) (E. Fukuyama & R. Madariaga, *Bull. Seism. Soc.* **85**, 614-628, 1995), finite-difference (FD) (S. M. Day, *Bull. Seis. Soc. Am.* **72**, 1881-1902, 1982; Olsen et al., *op. cit.*), and finite-element (FE) (D. D. Oglesby, R. J. Archuleta, & S. B. Nielsen, *Science* **280**, 1055-1059, 1998) numerical methods. These implementations cover a wide range of capabilities, including rate-dependent friction laws (e.g., Olsen et al., *op. cit.*; N. Lapusta, J. R. Rice &Y. Ben-Zion, *J. Geophys. Res.* **105**, 23,765-23,789, 2000), segmented fault planes (R. A. Harris & S. M. Day, *Geophys. Res. Lett.* **26**, 2089-2092, 1999), intersecting faults (H. Magistrale & S. M. Day, *Geophys. Res. Lett.* **26**, 2093-2096, 1999), and bent faults (Oglesby et al., *op. cit.*).

propagation during large thrust earthquakes, such as those which have been postulated for the Sierra Madre fault bounding the L.A. basin. This module will be based upon existing FE codes, but it will also incorporate existing techniques from other codes, such as rate-dependent friction, fault segmentation, and intersecting faults. The FE approach will give this module the geometrical flexibility to address the thrust-earthquake problem. The module will also provide a prototype for testing and demonstrating the rupture-model/propagation-model interface.

An important initial objective for the Earthquake Physics focus group will be to undertake the systematic validation of existing rupture-dynamics codes using a set of reference earthquakes as a basis for comparison. Some specific tasks related to this proposed work are listed as short-term objectives in §III.A.4 & 5.

Soil response to strong shaking is a complex, nonlinear phenomenon that has long been investigated in laboratory experiments and in the field following large earthquakes.[51] Numerical codes that can account for soil nonlinearity are numerous, ranging from equivalent linear models to several-cyclic nonlinear models that also incorporate pore-pressure generation,[52] but computational approaches continue to evolve. The situation is analogous to rupture-dynamics calculations, in that there is no single consensus methodology suitable for all situations. The SCEC community modeling framework must therefore accommodate a range of soil-modeling methodologies by developing a consistent interface for coupling ground-motion calculations to nonlinear codes. This will be relatively straightforward for 1D nonlinear models, in which user-selectable sets of soil models can be made available through a convenient interface. The objective is to encourage the ground-motion simulation community (primarily seismologists) to become more familiar with nonlinear soil models (which have been developed primarily within the engineering community) and to make effective use of them in research and seismic hazard products.

Seismic Hazard Analysis. This focus group will be the continuation of the RELM Working Group (§III.A.6). RELM's activities to develop and test a range of seismic hazard models will bridge between SCEC1 and SCEC2. The community models and their links to standardized data bases, as described above, will be fundamental to the success of RELM. The challenge will be to construct data bases and models that can represent uncertainties and accommodate a wide variety of potential uses, while still encouraging and incorporating creative science.[53]

PSHA and waveform modeling are complementary approaches to seismic hazard analysis. For example, the composite PSHA hazard estimate can be disaggregated to find the most menacing scenarios for a given site, and ground motion simulations can be carried out to generate time histories for those events. The notion of full waveform modeling of scenario earthquakes is not new to SHA, of course—vigorous efforts have been ongoing both inside and outside of SCEC1—but the time is right for a greater level of interdisciplinary research, including collaboration with earthquake engineers, to develop an methodology appropriate for performance-based engineering and risk-management applications. An immediate objective is a web-based "clickable" hazard map that provides on-demand time histories for any location from a large inventory of scenario earthquakes.[54] Long-term work is needed on how to use waveform modeling to characterize the probability distributions of ground-motion time histories (or parameters derived from those time histories) in a way that properly accounts for both aleatoric and epistimic uncertainties. Constructing appropriate probability distributions will require multiple runs for many potential sources and geologic structures and thus will place great demands on the resources for numerical simulation and the analysis of simulation output.

3. Information Technology Partnership

The goal of the SCEC2/IT partnership is to develop an advanced IT infrastructure for system-level earthquake science in Southern California. SCEC2 capabilities in data analysis, community modeling, and knowledge transfer will depend heavily on IT improvements, including computational algorithms for exploiting massively parallel

51 H. B. Seed & I. M. Idriss. *Bull. Seism. Soc. Am.* **60**, 125-136, 1970; M. Zeghal & A.-W. Elgamar. *Journal of Geotechnical Engineering* **120**, 996-1017, 1994; E. H. Field, P. A. Johnson, I. A. Beresnev & Y. H. Zeng, *Nature* **390**, 599-602, 1997; J. Aguirre & K. Irikura. *Bull. Seism. Soc. Am.* **87**, 1244-1258, 1997.

52 K. Arulanandan & R. F. Scott. *Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, 2 Vols, Balkema, Rotterdam,Netherlands, 1993.

53 A good example of "out-of-the-box" thinking is J. Brune's controversial idea that precariously balanced rocks can be used as indicators of prehistoric strong motions in Southern California (J. N. Brune, *Bull. Seismol. Soc. Am.* **86**, 43-54, 1996). SCEC1 sponsored some of Brune's initial fieldwork and theoretical investigations of what may turn out to be a unique source of information about seismic hazards.

54 P. Spudich, presented at *ATC-35 Ground Motion Initiative Workshop*, Rancho Bernardino, CA, July 30-31, 1997. A demonstration version for the Los Angeles region has recently been developed by K. Olsen and his colleagues at UCSB (http://www.crustal.ucsb.edu/scec/websims/la/).

computers and other "big iron", access to distributed computing and collaborative environments, advanced methods for code development and sharing, software libraries, distributed visualization tools, and data-management capabilities. These capabilities have been the focus of substantial IT research outside the Earth-science community, and this partnership will take advantage of this research. The partnership currently comprises SCEC2, the USGS, USC's Information Sciences Institute (ISI), the San Diego Supercomputer Center (SDSC), the Incorporated Institutions for Research in Seismology (IRIS), and the Generalized Earthquake Models (GEM) project.[55]

Community Models. SCEC2 will play a major role in the development and implementation of community models. *In this context, "community models" are on-line, documented, maintained resources that can function as virtual collaboratories for knowledge quantification and synthesis, hypothesis formulation and testing, data conciliation and assimilation, and prediction.* Over the next five years, community models will be constructed in all of the focus areas diagrammed in Fig. 3.1. To meet this challenge, SCEC2 will have to erect new organizational mechanisms to develop, verify, and maintain the requisite software components and make them available to a heterogeneous, widely distributed group of users. Some of the routine applications by these users (e.g., high-frequency wavefield simulations for scenario earthquakes) will be terascale computations requiring substantial resources from the national computational grid. ISI's expertise in grid-based computing and SDSC's expertise in knowledge-based representation, as well as the considerable computational resources of both organizations, will aid in community-model implementation.

Unified Structural Representation and "LA3D". The development, distribution, and maintenance of the USR and supporting data bases will be a leading activity of the SCEC2/IT partnership. In the first year of funding, the Center will erect a prototype Community Fault Model (CFM), dubbed "LA3D", which will represent the well-constrained active faults in the Greater Los Angeles area (Fig. 3.3). This set of faults (Category 1 LAB) has been agreed upon by a SCEC1 working group and represents the main earthquake sources that threaten metropolitan Los Angeles. IT development in this initial USR effort will focus on two key elements: (1) a CAD-based modeling engine to register and integrate three-dimensional data, interpolate fault surfaces, and generate topologically consistent models; and (2) a web-based relational data-base manager and visualization toolkit to provide access to the models and the supporting data. SCEC2 core institutions with expertise in structural representation (e.g., Harvard, UCSB, USGS Menlo Park) currently employ a variety of 3D visualization and modeling tools, including the powerful Gocad software package.[56]

In the second year, the CFM will be broadened to incorporate more poorly defined faults in the Los Angeles Basin (Category 2 LAB), as well as offshore and coastal faults that threaten the population centers of San Diego, Ventura, and Santa Barbara, and the CVM will be integrated with this CFM into a first-version USR. SCEC2 and its IT partners[57] will continue to evaluate Gocad and other similar applications (e.g. EarthVision) for use in model construction, implementing one or more modeling engines that can successfully (a) integrate surface and subsurface data in a GIS/CAD-based system with precise geographic registration, (b) manage complex structural topologies, (c) provide an object-oriented environment, allowing multiple attributes to be assigned to each feature, and (d) produce simple ASCII-based output of geologic structures for use in other community-modeling applications. Web-based data manipulation and visualization tools will be implemented that allow users to access and contribute to the data bases. These efforts will require significant human and computational resources, including high-bandwidth connectivity among core institutions supporting the USR.

USGS Collaboration. While SCEC2 will coordinate essentially all of its activities with the USGS (a Joint Planning Committee is being set up for this purpose; see §IV.E), the goal of an expanded IT infrastructure offers some exceptional opportunities for joint research. An obvious example is the SCEC/USGS collaboration in RELM to erect a webportal for providing users with access to advanced methodologies in seismic hazard analysis. Another is the capability needed to respond to a big earthquake—when "all hell breaks loose." The USGS Pasadena Office has been very active in developing real-time software capabilities for rapid earthquake response, such as the USGS/TriNet

[55] The structure and activities of these organizations can be found at their home websites: ISI (http://www.isi.edu), SDSC (http://www.sdsc.edu), IRIS (http://www.iris.org), and GEM (http://geodynamics.jpl.nasa.gov/gem).

[56] J. L. Mallet, *Computer Aided Design* **24**, 178-191, 1992.

[57] An attempt will be made to involve major petroleum and petroleum-service companies in the SCEC2/IT partnership, because they hold much of the current expertise in methodologies for constructing unified structural representations.

ShakeMap,[58] and will be the lead organization in this aspect of model development. In future extensions of these capabilities, a subset of community models—source imagers, wavefield simulators, damage estimators—would be automatically and rapidly coupled to assimilate data as they are acquired in real time, create new products and predictions, and distribute the output to multidisciplinary teams scattered across Southern California. These teams would then jointly visualize, manipulate, and modify the products and communicate the results to non-specialists, such as engineers, emergency managers, government officials, and the media.[59] All of these operations will have to be done under potentially stressful conditions using distributed, multiply-connected computational systems that are robust to major regional disruptions in power, communications, and transportation.

In addition to its role in leading the real-time, operational aspects of an IT partnership, the USGS will ensure that the results of the IT effort are exported to other regions of earthquake risk outside of Southern California, as well as to other foci of USGS research. In particular, the development of robust, flexible, web-based models for 3D structural representation, as proposed here, could benefit many programs within the USGS. SCEC2 will therefore work with the three USGS offices participating as core institutions to seek augmented USGS support for the IT partnership.

IRIS Collaboration. The development of a USR for Southern California provides a strong basis for SCEC2/IRIS cooperation in the USArray component of the EarthScope project. SCEC2 will take the lead developing the USR methodology and applying it to the earthquake problem in Southern California, while IRIS will ensure that the methodology can be transported to other regions and applied to other Earth-science problems, which include requirements for the representation of cratonic structures, orogenic belts, and active volcanic provinces absent in Southern California. SCEC2 and IRIS will also collaborate on methods for assimilating wavefield observations into updated 3D structural models. Better methodologies for solving the structural inverse problem on a regional scale will contribute substantially to the success of USArray. Examples of desirable IT infrastructure in this area include (a) search engines that build data sets from existing waveform libraries according to model-based attributes, and (b) distributed interactive visualization tools to allow scientists at different locations to view simultaneously the contents of the massive remote sets produced by computer simulations. The IRIS Data Management Center in Seattle, Washington, which has been leading U.S. seismological efforts in data archiving and distribution, will be able to contribute considerable IT expertise to this collaboration.

GEM Collaboration. The expansion of SCEC2 activities in the numerical modeling of fault-system dynamics will be done in collaboration with the GEM group. The goal of GEM is to evolve new approaches for understanding earthquake dynamics, leading to system-level forecasting and prediction of space-time patterns in seismicity and deformation through the use of large-scale computational simulations of earthquake physics as well as state-of-the-art IT. SCEC2 and GEM will work together to (a) develop numerical frameworks, standards, interoperability, and conventions, (b) utilize the latest thinking in object-oriented computational approaches, web-based computing and object-broker software, and visualization and analysis software, and (c) establish community models of fault-system dynamics that will be useful to a wide range of scientists. In addition to cooperation on these general issues of earthquake modeling, SCEC2 will support GEM efforts on the analysis of space-time patterns of Southern California earthquakes.

Proposal Submission to the NSF/ITR Program. Resources to nucleate the SCEC2 IT effort are built into the budget proposed in §V, including an "IT architect" to oversee the development of the software standards for the community models (e.g., data structures and model interfaces), as well as research support for the GEM group. However, the proposed funding is inadequate to fully support the type of collaboration among SCEC2, ISI, SDSC, USGS, and IRIS envisaged here. Therefore, a preproposal will be submitted to the NSF/ITR Program under program solicitation NSF00-126 on December 4, 2000, that outlines plans for the major involvement of these organizations, particularly ISI and SDSC, through an ITR "large project". (Large projects are defined as those with total 5-year budgets of $5-15 million.) If the preproposal is successful, a full proposal will be submitted to the ITR Program on April 23, 2001.

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[58] D. Wald, V. Quitoriano, T. Heaton, H. Kanamori, C. W. Scrivner & C. B. Worden, *Earthquake Spectra* **15**, 537-556, 1999; http://www.trinet.org/shake.

[59] In earthquake-disaster situations, the USGS has the operational responsibility for coordinating these tasks with FEMA and California Office of Emergency Services. SCEC's role will be to work with the USGS in the development of new earthquake-science capabilities, including operationally qualified community models and the associated IT infrastructure, and to provide scientific organization and expertise that can be called on by the operational agencies during earthquake emergencies.

4. Communication, Education and Outreach Program

SCEC has always viewed the transfer of its research results to other communities as an essential component of its mission. The SCEC1 Outreach program has established itself among SCEC's external communities as a valuable resource for Southern California, both for its products and for the expertise its Outreach staff has developed in coordinating effective dialogue and cooperative projects among multiple communities. Still, the efforts in this direction must evolve to match the transition from SCEC1 to SCEC2. The SCEC1 Outreach Program will therefore become the SCEC2 Communication, Education and Outreach (CEO) program. More than a just name change, CEO will be a strategically designed, outcome-oriented program with two significant enhancements: (a) a closer collaboration with the USGS outreach program in Southern California, and (b) a restructuring of the knowledge-transfer activities through an "implementation interface" with SCEC2 partners in earthquake engineering and risk management (Fig. 3.1). The collaboration with the USGS will include shared CEO planning, training programs, web pages and materials. A primary objective of the joint effort will be to facilitate the interaction of scientists directly with the users of earthquake information. Taken together, the three programmatic elements—the Implementation Interface, Education, and Outreach—will comprise a set of coordinated projects between SCEC2 and the USGS that will contribute to the utilization and understanding of earthquake knowledge for many practical purposes: better engineering design, more accurate risk assessment, improved K-12 and university-level education in Earth sciences, and greater public awareness of earthquake risk and risk mitigation. Stated more bluntly, the goals of CEO are to save lives, reduce loss, and improve scientific literacy.

Implementation Interface. The results of SCEC2 research will include findings and products that are useful to the earthquake-engineering and risk-management communities. Implementation of SCEC2 research results into earthquake engineering research and practice will be done in partnership with the Consortium of (formerly California) Universities for Earthquake Engineering (CUREE), the Network for Earthquake Engineering Simulation (NEES), and the Pacific Earthquake Engineering Research Center (PEER). The SCEC2 focus areas most relevant to the earthquake-engineering research community include Earthquake Physics, Seismic Hazard Analysis, and Risk Assessment & Mitigation.

CUREE (http://www.curee.org) is involved in topical studies of immediate importance to earthquake engineering practice, such as the recently completed SAC Steel Program, the ongoing CUREE-Caltech Wood Frame Project, and the proposed CUREE Near Fault Seismic Risk Project. SCEC1 has had a long and fruitful collaboration with CUREE, and is currently managing the education and outreach element for the Wood Frame project. In the project plan for the Near Fault Seismic Risk Project, SCEC2 scientists and CUREE engineers will be organized into teams that address in an interdisciplinary way the broad range of technical issues related to the seismic risk from near-fault ground motions.

The vision of NSF's NEES program is to improve the seismic design of buildings, bridges, utilities and other infrastructure.[60] SCEC1 is currently interacting with NEES through the NEESgrid System Integration Project, whose goal is to design and develop an implementation plan. A consortium will be selected to manage NEES in the latter part of 2001, and will become SCEC2's primary interface with NEES. SCEC2 will provide seismic hazard information, primarily in the form of ground-motion time histories, for use as input into the various NEES testing facilities and software. SCEC2 may benefit from NEES's use of advanced IT to facilitate the communication of data, experiments, models and ideas among investigators throughout the U.S.

The focus of the PEER Program (http://peer.berkeley.edu/) is on performance-based earthquake engineering.[61] PEER has organized five thrust areas: Socio-Economic Assessment, Hazard Assessment, Global Methodology, Demand Assessment, and Capacity Assessment. The Hazard Assessment thrust area is primarily focused on ground motions and ground deformation, and it is in urgent need of earthquake science support, which SCEC2 will provide. Many of the other thrust areas require ground-motion inputs. The performance-based earthquake engineering focus of PEER, and its focus on the tectonically active

[60] NEES will provide real-time remote access to a complete set of testing and experimental facilities, making them widely available to earthquake engineers. The online network, or "collaboratory," will furnish researchers across the country with telepresence capabilities and shared-use access to advanced equipment, data bases and computer modeling and simulation tools (http://www.eng.nsf.gov/nees/).

[61] The goal of performance-based earthquake engineering is to develop methods for seismic design that are based on predicting the behavior of structures under various levels of potential ground motion. Performance-based earthquake engineering involves a set of global processes that include the establishment of performance objectives, conceptual design, and engineering and socio-economic evaluation.

western United States, furnishes an important earthquake engineering context for SCEC2 science. Further context is provided by specific PEER field laboratories, which include older existing concrete buildings, newer concrete bridges, and the Port of Los Angeles, and by the Program of Applied Earthquake Engineering Research for Lifeline Systems. SCEC2 products may be useful to many of these studies.

The Risk Assessment & Mitigation focus area will provide Earth-science and hazard-characterization inputs to risk-assessment and performance-based earthquake engineering modules, including revisions to modules that already exist (e.g. HAZUS and FEMA 273 respectively), as well as new modules being developed by earthquake-engineering research organizations and providers of public hazard estimates, such as CDMG and the USGS. To facilitate the implementation of these hazard and risk assessment methodologies, SCEC2 will work with FEMA, the USGS, CDMG, and OES to develop forums for interacting with potential users, such as the Southern California HAZUS User Group (see the Outreach section below). In addition to earthquake engineers, agency specialists, and SCEC2 scientists, the Risk Assessment & Mitigation focus group will comprise experts in decision analysis and information comprehension, social scientists, and economists.

The Implementation Interface is designed to help SCEC2 plan its research program by communicating the goals of the various earthquake-engineering and risk-management research programs, and identifying SCEC2 research products that are potentially useful to these programs. The Implementation Interface will also identify products and findings from the SCEC2 research program that are useful to organizations outside of SCEC2. These products and findings will be identified in a separate section of SCEC2 annual reports. Some of these products and findings may need further testing and development for practical application, which could occur within the research programs of the earthquake-engineering research organizations.

Education. SCEC2 and its expanding network of education partners are committed to fostering K-12 and college-level education in Earth science. The primary transition objective in this area is to make more effective use of (a) the intrinsic interest of the Southern California students in their natural environment, including the "teachable moments" when earthquakes happen, and (b) the scientific and educational expertise available from SCEC2 core and participating institutions. Projects will be concentrated in four main areas.

Educational experiences. SCEC2 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. A new credit-bearing field program in earthquake science, based on MIT's mid-year (January) course in Southern California, will be offered to undergraduates from SCEC2 institutions. The Center's growing inventory of field-trip guides for the Los Angeles region, written by and for earthquake professionals, will be adapted for high-school and college class excursions. It will continue to offer scientist-mentored summer internships to undergraduates, and it will seek to expand the number of interns through funding from the NSF *Research Experiences for Undergraduates* program. It will work with its partners to create novel educational facilities such as the Riverside County Youth Museum's *ShakeZone* exhibit and the *Wallace Creek Interpretive Trail* (Box 2.9).

Curricula Development and Review. SCEC2 will assist in the development of K-12 earthquake curricula in accordance with California's Earthquake Loss Reduction Plan and the National Science Education Standards. 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. At the college level, the focus will be on general-education earthquake courses offered at SCEC2 schools.

Educational Resources. SCEC2 will augment and continue the distribution of educational resources developed SCEC1, including one of the best on-line collections of earthquake education information, tools, and resources. It will build on its involvement in the Electronic Encyclopedia of Earthquakes (E^3) pilot project (Box 2.9), and it will promote Earth-science degree programs through an on-line reference guide for students and counselors about undergraduate and graduate degree opportunities at SCEC2 institutions.

Professional Development for Educators. SCEC2 will offer workshops 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. Most of these workshops will held at the SCEC2 Training Center at USC, which will be located in the new 11,000-sq.ft. SCEC2 facility constructed by USC as part of the North Science Hall renovation.

Outreach. The Center will continue to serve the public of Southern California through a wide array of outreach activities. The transition objectives in this area are (a) to work more closely with the USGS in all aspects of public outreach, (b) to expand general access to earthquake information via the Internet and public media, and (c) to foster a greater public understanding of earthquake risk through quantitative risk-assessment tools, such as HAZUS.

Southern California HAZUS Users Group (SoCalHUG). SCEC2 will coordinate the development and activities of this new group with FEMA, the USGS, and OES. SoCalHUG will be modeled on the existing San Francisco Bay Area HAZUS User's Group (BAHUG). It will bring together current and potential HAZUS users from industry, government, universities, and other organizations to (a) train GIS professionals in HAZUS earthquake loss estimation software, (b) improve earthquake databases and inventories, and (c) develop and exercise emergency management protocol. Training will be conducted at the new SCEC2 Training Center at USC, as well as the California State University Fullerton Earth Science Department GIS laboratory and the Ventura Community College GIS facility. These locations would each serve a distinct region of Southern California.

Non-Technical Products and Programs. SCEC2 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 on-line via the INSTANeT News Service (http://www.scec.org/instanet). Partnerships with media organizations will be developed to produce effective, accurate materials and messages in the form of press releases, information sheets, on-line resources, an updated version of *Putting Down Roots in Earthquake Country*, and televised awareness programs. SCEC2 and USGS scientists will conduct general-audience seminars in local communities that will provide current earthquake information.

Technical Products and Programs. SCEC2 will continue to publish and distribute technical information for design professionals, the business community, planning and safety officials, and policy makers. Priorities will include increased promotion of published research, broader distribution of annual and technical reports, the development of community-specific summaries highlighting relevant research, and workshops will be based on the scientific results of SCEC2. All workshops will result in a SCEC2 product (document, CD-ROM, software, etc.), and to improve workshop attendance and effectiveness, SCEC2 will establish a Continuing Education Unit (CEU) program.

Partnerships. SCEC2 will participate in the Earthquake Information Providers (EqIP) group (www.eqnet.org) and the California Post Earthquake Technical Clearinghouse. It will maintain its extensive database of SCEC partners and information recipients, which now comprises over 7500 people and organizations, and will use this network to communicate earthquake information.

IV. Management Plan

The management of SCEC2 will build on the successful structure of SCEC1. However, this structure will be substantially modified to meet the transition objectives (§I.B) and to execute as effectively as possible the new science plan (§III). The University of Southern California (USC) will continue as the managing institution, with T. Jordan, the Principal Investigator on this proposal, as the new Center Director. The management plan, outlined here, will be codified in a new set of by-laws, which will be adopted upon the transition from SCEC1 to SCEC2, tentatively planned for January, 2002.

A. Institutional Membership, Board of Directors, and Executive Committee

SCEC2, like the current Center, will be an institutionally-based organization governed by a Board of Directors. The structure of SCEC2 will recognize both *core institutions*, which are research organizations with a major, sustained commitment to SCEC2 objectives, and a much larger number of *participating institutions*, which are self-nominating through the involvement of individual scientists or groups in SCEC2 activities. The 14 core and 26 participating institutions that were enrolled as of the proposal submission date (December 1, 2000) are listed in Tables 1.1 and 1.2, respectively. This listing may change, however, because SCEC2 will be an *open consortium*, available to any individuals and institutions seeking to collaborate on the science of earthquakes in Southern California.

Each core institution will appoint one member to the Board. In addition, the Board will elect two nominees 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 SCEC2; it will meet at least once 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. Provisions will be made in the by-laws to allow the Board to conduct other business by electronic mail. The Center Director will act as Chair of the Board and the representative of the managing institution (USC). Based on the institutional membership listed in Table 1.1, the Board will comprise 16 voting members. Non-voting members will include the Deputy Director, the Vice-Director for Administration (serving as Executive Secretary), the Vice-Director for Communication, Education, and Outreach, the Chair of the Advisory Council, and the Chair of the Planning Committee.

The Executive Committee will handle the day-to-day decision-making responsibilities through regular meetings and electronic mail. It will have five voting members, the Center Director, who will act as Chair, and four Board members elected for two-year terms by the Board, as well as two non-voting members, the Deputy Director and the Vice-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.

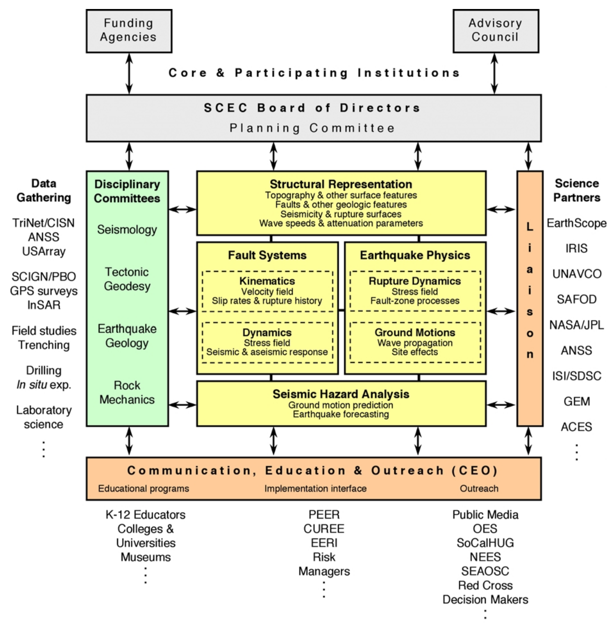

Figure 4.1. The SCEC2 matrix of activities. Disciplinary committees (green box) will coordinate data-gathering activities and infrastructure. Focus groups (yellow boxes) will organize project-oriented interdisciplinary research. Interfaces to SCEC partners (orange boxes) will include scientific liaison, managed by the Deputy Director, and the Communication, Education, and Outreach Program, managed by the CEO Vice-Director. Scientific planning will be the responsibility of the Planning Committee, which will prepare annual budgets for the Board of Directors (gray box).

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 science plan, based on proposals or work plans submitted to the Center, and overseeing the plan's 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 from the Center.

The Deputy Director will serve as (non-voting) Vice-Chair of the Board of Directors. He/she 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 SCEC2 science partners and (c) oversight of the CEO Program. T. Henyey of USC, the current SCEC1 Director, will act as the Deputy Director for SCEC2.

The Vice-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 SCEC1 Director for Administration, will act as the SCEC2 Vice-Director for Administration.

C. Advisory Council

The Center will establish an external Advisory Council to serve as an experienced advisory body to the Board of Directors. The Advisory Council 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 and risk management), formal and informal education, and public outreach. The Council will report to the Board through its Chair, who will serve as a non-voting member of the Board. 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. 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.

D. Management of Center Activities—a Matrix Approach

SCEC2 will function as a matrix of activities with relationships approximated by the diagram in Fig. 4.1. Standing disciplinary committees in Seismology, Geodesy, Geology, and Rock Mechanics (§III.B.1) will coordinate the principal data-gathering activities (e.g., seismic and geodetic networks, geologic field studies, laboratory work) and the disciplinary infrastructure, which will include the SCEC2 data centers and centralized data processing (e.g., SCEDC, SMDB, SOPAC), as well as communal field equipment and experiments. The chairs of the disciplinary committees will be responsible for annual reports and will submit budget recommendations to the Planning Committee.

Interdisciplinary research will be organized in terms of the focus areas described in §III.B.2—Structural Representation, Fault Systems, Earthquake Physics, and Seismic Hazard

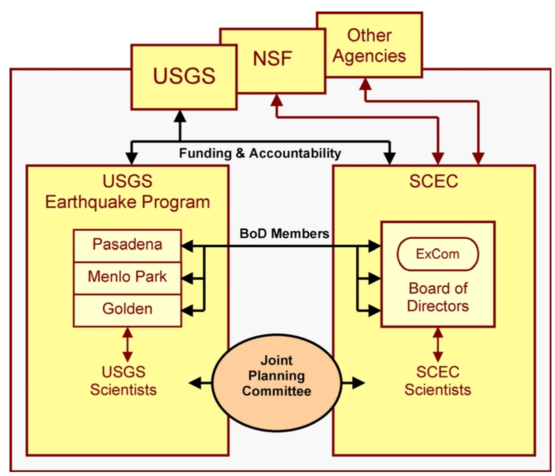

Figure 3.2. Diagram showing (in black) the three mechanisms for coordinating SCEC2 and USGS activities: USGS funding and SCEC2 accountability, USGS memberships on the SCEC2 Board of Directors, and the Joint Planning Committee. The JPC will coordinate research programs at the working level by developing an joint science plan.

Analysis. These four 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 SCEC2 Community Models. 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 SCEC2 Information Technology Architect. The IT Architect will report to the Center Director and will coordinate the SCEC2/IT Partnership (§III.B.3) and other technical liaison activities.

Knowledge transfer, education, and public outreach will be managed by a Vice-Director for CEO, who will supervise a staff of CEO specialists. The Vice-Director will act as liaison with SCEC2 partners in earthquake engineering and risk management and will facilitate the activities of the Risk Assessment & Mitigation focus group. Two-way knowledge transfer between SCEC2 and its partners will be actively managed through the Implementation Interface (§III.B.4), which will be facilitated by a contract with P. Somerville at URS, a SCEC2 participating institution involved in earthquake research and engineering implementation.

Annual and long-term budget planning will be the responsibility of the SCEC2 Planning Committee. The Planning Committee will be chaired by the Deputy Director and comprise representatives from each of the disciplinary committees and focus groups; the CEO Vice-Director and the IT Architect will serve as non-voting members. The annual budget cycle will begin with the articulation of the research plan, coordinated through a Joint Planning Committee with the USGS (see below) and approved by the Executive Committee. This research plan will form the basis for the solicitation and evaluation of "miniproposals" from SCEC2 participants. From these proposals, the Planning Committee will prepare a preliminary science budget for the Executive Committee. The Executive Committee will combine this recommendation with requests from the CEO Vice-Director and the IT Architect and submit a coordinated Center budget to the Board of Directors. The annual budget approved by the Board and signed by the Center Director will then be submitted to the sponsoring agencies for final approval and funding.

E. SCEC2/USGS Joint Planning Committee

A major objective of the SCEC Transition is to align the Center's activities more closely with those of the USGS. A strong collaboration in basic and applied research, knowledge transfer, education, and outreach will be maintained by the three separate mechanisms diagrammed in Fig. 4.2: (a) the accountability required by USGS funding of SCEC2 activities, (b) memberships on the Board of Directors by the three USGS offices now enrolled as SCEC2 core institutions, and (c) by a SCEC2/USGS Joint Planning Committee (JPC). The JPC will be a combination of the SCEC2 Planning Committee described above and a parallel structure to be set up by the USGS. The purpose of the JPC will be to coordinate research programs at the working level through the development of an annual joint science plan. The joint science plan will be the basis for the SCEC2 budget process, as described above, and will be fed into the internal USGS budget process through channels determined by USGS management.

V. Budget Justification

This proposal for the continuation of the Southern California Earthquake Center (SCEC2) is being submitted jointly to the NSF and the USGS. The NSF funding request is $3M in Year 1 and $16.665M over 5 years. The USGS funding request is $1.5M in Year 1 and $8.335M over 5 years. The combined budget for NSF/USGS funding is listed tables that follow this section. The breakdown of the budget requests for NSF and the USGS for the entire 5 years is also included. The following discussion applies to Year 1 only.

A. Budget Overview

SCEC2 requests $3M in FY02 from the NSF Earth Sciences Division and $1.5M from the USGS NEHRP. With 5% annual increases, the total NSF request for 5 years is $16,665,000 ($3.15M in FY03, $3.32M in FY04, $3.5M in FY05, and $3.695M in FY06). The total request for the USGS is $8,335,000 ($1.575M in FY03, $1.66M in FY04, $1.75M in FY05, and $1.85M in FY06). Therefore, the total request over 5 years is $25M. NSF/USGS funding of SCEC2 will trigger $5.5M in university cost sharing ($1.1M/yr) over the 5 year period. NSF/USGS funding at this level also will greatly enhance the Center's efforts to acquire additional resources from other federal agencies, the State of California, private foundations, and industry. To address the research proposed here, SCEC2 has assembled a team comprising many of the top earthquake scientists in the U.S.; participants are listed in the table entitled *SCEC2 Institutions* in the Supporting Documents section of this proposal.

B. Infrastructure Budget

While separate requests are being made to NSF and the USGS, the funding from each agency will be combined for the purposes of building a SCEC2 program each year. Over its lifetime, the Center expects to spend roughly 50% of its base funding on project science and post-earthquake investigations, and 50% on infrastructure and integrative activities including facilities, management, seminars, workshops, outreach, IT infrastructure, and a post-doctoral fellows/visitors program. If both requests are funded, SCEC2 will have $4.5M to support this core research program in Year 1. This NSF/USGS funding will allow the Center to maintain much of the SCEC1 infrastructure now in place in Southern California.

In Year 1, the Center will allocate the $800K of USGS funds for science and $700K for infrastructure. The latter is budgeted as outlined in Table 5.1: $100K for management, $50K for science workshops, $150K for our Communication, Education, and Outreach (CEO) program, $100K for supporting geodesy infrastructure (mainly the SCIGN array), $100K for seismology infrastructure (mainly the maintenance of the Southern California Earthquake Data Center), $100K for new geology infrastructure (new shores, a backhoe, and database compilation), and $100K for IT infrastructure.

In Year 1, $1550K of the NSF budget will be allocated to infrastructure. A Center administration budget of $100K will provide two months of support each for the Center Director and Deputy Director, who have major, Centerwide leadership responsibilities, as well as other administrative costs. A Vice-Director for Administration will be supported at 75% time. Center administrative office staff support will be paid from the USC cost-sharing funds. SCEC2 will host an annual meeting for Center participants and conduct focused science workshops, for which $150K is budgeted. Center workshops will be widely advertised and open to all scientists from both the public and private sector. Support will provided for graduate and undergraduate student and post-doc participation in the workshops. A Centerwide post-doctoral fellows/visitors program will conduct annual competitions to attract young scientists into Center research; this program will be budgeted at $150K, which will be matched by the institutions hosting the post-doctoral fellows. $100K will be budgeted to support geodesy infrastructure (mainly the SCIGN array), $150K for seismology infrastructure (mainly the maintenance of the SCEDC and the Strong Motion Data Base), $100K for new geology infrastructure (new shores, a backhoe, and database compilation), and $350K for IT Infrastructure.

SCEC2 will continue the Center's excellent and nationally recognized outreach program, which will be retitled Communication, Education, and Outreach (CEO) and coordinated with the USGS outreach program in Southern California. The program will be staffed by a CEO Vice-Director and one CEO Specialist supported by the Center's base budget of $450K ($300K from NSF, $150K from USGS). Supplemental funding is expected from other sources (for example, SCEC1 Outreach has received $800K from FEMA for the past 8 years and more than $100K from sources such as the media and City of Los Angeles). Undergraduate summer internships, partnerships with high-achieving school districts, and research-related educational modules will be a key part of the SCEC2 educational program. A $50K CEO sub-

Table 5.1. SCEC2 Year 1 Funding Request by Agency and Activity

Activity	USGS Infrastructure	NSF Infrastructure	Combined Infrastructure
Management (Director's Stipends, Management)	100	250	350
Workshops/Meetings	50	150	200
Post-Doctoral Program (cost-shared with core institutions)	0	150	150
Seismology Infrastructure (Data Center, SMBD)	100	150	250
Geodesy Infrastructure (SCIGN)	100	100	200
Geology Infrastructure (Shores, Backhoe, Database)	100	100	200
Education and Outreach	150	300	450
Computer Modeling (IT Infrastructure)	100	350	450
Subtotal	700	1,550	2,250
	Science	**Science**	**Science**
Structural Representation	150	300	450
Fault Systems/Kinematics	100	225	325
Fault Systems/Dynamics	100	225	325
Earthquake Physics/Rupture Dynamics	150	225	375
Earthquake Physics/Ground Motions	150	225	375
Seismic Hazard Analysis	150	250	400
Subtotal	800	1,450	2,250
Total Request ($3.0M from NSF; $1.5M from USGS)	1,500	3,000	4,500

contract to URS Corporation will support work by Paul Somerville on the Implementation Interface.

C. Science Program Budget

SCEC2 will spend $1.45M of NSF funds and $800K of USGS funds—half of the total budget—on the science programs outlined in the proposal. Most of these funds will support project-oriented, interdisciplinary research, which will be organized into the four focus groups described in §III.B.2: Structural Representation, Fault Systems (Kinematics & Dynamics), Earthquake Physics (Rupture Dynamics & Ground Motions), and Seismic Hazard Analysis. Table 5.1 indicates an approximate split of the research budget among these focus areas, although these amounts will surely change as research results warrant; over time, resources will be directed toward areas showing the most promise. Science grants will average $40-50K/yr, which translates into support for about 50 projects per year from the core program. Science funding will be allocated in two ways: smaller grants to support individual scientists working in the Center environment, and larger grants to support scientists and scientific teams collecting integrating, and modeling data for major Center projects.

While there will be many senior scientists involved in the Center, the base science funding will be primarily targeted for young faculty, post-doctoral fellows, and graduate and undergraduate students. Some funds are budgeted within each academic institution to support participation by undergraduates. Priority will be given to students from underrepresented groups to encourage their early involvement in science activities.

The major research effort will be undertaken by scientists from the core institutions, and the USC and subcontracted institutional budgets have been structured accordingly. However, as noted in the management section, the Center Director and Board will make final decisions on funding levels for research projects. Thus, total funding per institution may vary substantially from those projected here. Should this proposal be approved, SCEC2 will establish its Board of Directors as outlined in §IV.A and prepare a science plan for Year 1 funding. Following final selection of research projects for Year 1 by the Center Director, in consultation with the Board, a budget plan will be submitted to both NSF and USGS for approval. USC will waive overhead on subcontracts issued to other participating institutions—a significant cost share.

D. SCEC2 Cost Sharing

The cost sharing being provided by academic institutions and the USGS for SCEC2 is truly impressive. The core academic institutions of SCEC2 have committed $5.5M to the support of the Center in hard funding ($710K/yr; $1.1M/yr accounting for overhead). The amount of direct cost sharing per core institution is shown in the supporting documents section on institutions/personnel. The cost-sharing funds at each institution will be spent on SCEC2 research at their institutional discretion and not be controlled by the SCEC2 Director or Board. Institutional representatives will provide a report to the Center Director and funding agencies on how the cost-sharing commitment was expended each year. Indications of how these funds will be expended can be seen in the cost-sharing commitment letters in the Supporting Documents section.

In addition to direct cost sharing, each core institution is providing release time for its faculty to work on Center activities and providing the necessary space and facilities to conduct Center research. The academic release time salary support and salary support of USGS collaborators from Pasadena, Menlo Park, and Golden will each be more than $1M annually. Additional matching support for the Center can be seen in the cost sharing letters from the deans at the core institutions.

A major cost sharing commitment has been made by University of Southern California, which will provide 11,000 square feet of renovated space in North Science Hall for SCEC2 activities. Triggered by the needs of SCEC2, the university is planning to spend $32M over the next 2-3 years to completely remodel North Science Hall and upgrade the building's infrastructure (including seismic retrofitting). SCEC2 will be allocated 25% of the space in this building, which translates to an additional commitment by USC of $8M. The North Science space will house a media center, conference room, a training center, advanced computing facilities, laboratories, office space for visitors, and the administrative headquarters of SCEC2.

In summary, total cost sharing will be more than $23M: $5.5M in academic institution hard funding, at least $5M in academic institution faculty release time, at least $5M in USGS collaborator salaries, and $8M in facilities renovation at USC.

E. Other Funding Sources

Over 150 Ph.D.-level scientists have already enrolled in SCEC2 (see Supporting Documents), so it will be impossible to fund all eligible participants from this base-funding request. As in SCEC1, many scientists will participate although their primary funding comes from other sources. The ambitious science plan presented in this proposal and the high enrollment by earthquake scientists in this plan argue strongly for expanding the resources for SCEC2 beyond the current request. The Center management will therefore work with the USGS, NSF, and other agencies to increase the SCEC2 funding base.

The Center is already working with the City and County of Los Angeles and other state agencies to acquire California State support (similar to the state's support for PEER). These funds will enhance the basic research and CEO programs outlined in the proposal. Funding can also be anticipated from other sources in California during the life of the Center, primarily from the California Department of Transportation and the utility industry. Most of this ancillary work will be applied research, and, except for a management fee, all funds will go to science programs. This research is more likely to be undertaken by senior Center scientists and will furnish important practical input to such areas as critical facilities and highway retrofit and construction. The Center also plans to seek additional funds from private foundations for Center activities.

VI. SCEC2 Facilities

Office and Research Facilities

The University of Southern California is committed to providing 11,000 square feet of space in North Science Hall for future SCEC activities. This space will media center, conference room, a training center, advanced computing facilities, laboratories, office space for visitors, and the administrative center of SCEC2. Triggered by the needs of SCEC2, the university is planning to spend $32M over the next 2 years to remodel North Science Hall and bring the building's infrastructure into the 21st century. This renovation will begin as Phase 1 from May-September, 2000 with Phase 2 being completed from May-September, 2001. The cost of preparing this space for SCEC2 is $8M. When completed, SCEC2 will have a state-of-the-art research and administrative facility located less than 5 km south of the main Los Angeles government/business district.

Infrastructure Facilities

The scientists in the SCEC2 will share a number experimental facilities. While the facilities will be housed at various institutions, data will be available to all researchers in the Center and the broader scientific community on the web. It will be the policy of SCEC2 to make data available to academic and government scientists without cost. Should commercial firms begin to access the data for profit-making enterprises, a user-fee system may be developed. The SCEC2 shared facilities are described below:

Seismology Infrastructure

SCEDC Operations in SCEC2. The purpose of the SCEDC is to archive, and make available to a general audience, information and data related to earthquakes and earthquake studies in Southern California. The primary source for this data archive is the new TriNet system which operates over 300 seismic stations, and has access to 400 dial-up strong motion sites. The SCEDC also archives waveforms from recent seismic surveys, e.g. LARSE, approximately 500 scenes recorded by SAR, and the raw and RINEX data files from GPS campaign-mode surveys.

The primary types of datasets available for scientific users of the SCEDC are:

1. The Southern California event and phase catalog from 1932 to the present (~400,000 events/4,000,000 picks).
2. Seismogram segments for all triggered events (over 20 million seismograms from short period, strong motion and broadband sensors).
3. Continuous waveform recording of all 20 sample-per-second or lower broadband channels (in place since October of 1999).
4. Specially compiled waveform data sets for significant events (e.g. 1 hour and 24 hour snap shots of the entire array for the Hector Mine Earthquake).
5. SAR images (500 scenes).
6. LARSE I and II datasets.
7. SCEC 3D Velocity model (Version 2.2).
8. Campaign GPS data.

The seismic waveform data is available to scientific users through various WWW interfaces, e.g. the IRIS BREQ-FAST program for seed-formatted files, or through a "seismic-transfer-program" for a variety of user formats, such as SAC. Scientific users may also maintain individual accounts on the Data Center computers in order facilitate special data requests.

The initial earthquake parameters and the triggered waveform data are generally available within a few minutes of the occurrence of a local earthquake. The continuous waveform data is available for user retrieval 15 minutes after each completed hour.

The SCEDC facilities consist of a 5 Tbyte optical-disk based mass-storage system and a suite of computers which run the Oracle and waveform archive databases, web server software, and user interfaces. The Data Center is staffed by a full-time manager, a three-quarter time data archivist, and a part-time user-interface programmer. In addition, the SCEDC shares a full-time Oracle database specialist with TriNet.

Strong Motion Data Base. SCEC2 will continue to support the maintenance and operation of the SCEC Strong Motion DataBase (SMDB) housed at UC-Santa Barbara for at least 3 years. The SMBD is a relational database containing parametric information for 5,559 accelerograms, 121 earthquakes, and 654 strong motion stations—all of the data recorded within the state of California. Users can query the database directly from the World Wide Web (http://smdb.crustal.ucsb.edu/) and download the strong motion data from an on-site FTP server, or, whenever possible, from outside FTP sites, such as the U.S. Geological Survey and the California Strong Motion Instrumentation Program sites. It is the only relational database for strong motion that is web-based.

Some of the parametric information in the database include peak ground acceleration, hypocentral distance, closest distance to the fault, response spectral amplitudes, instrument trigger times, earthquake locations, magnitudes, station locations, site geology, and references to original data sources.

Six methods for accessing the data have been developed and can be found on the home page. Station and event summaries allow the user to view summaries of all of the data which are available for a particular station or earthquake. Users can also query the database through two HTML forms pages, a basic search page and a custom search page. An interactive Java map applet has also been written that allows the user to easily search for earthquakes and stations in particular locations. Finally, for those users familiar with the database query language, SQL, a search page is available that allows the user to input a SQL query directly.

SMDB has plans to expand the database to include all US strong motion data with the possibility of making it a national strong motion database. The basic SMDB structure will allow for this expansion as well as it becoming a worldwide database. As the SMDB moves to being a national database, funding will likely come from other sources.

The database is currently being served on a Sun Ultra 10 computer with a 300 MHz UltraSPARC processor, 17 GB of disk space, and 640 MB of RAM. The database software is the latest version of Oracle8 and includes the Oracle Web Application Server. A dedicated ethernet line is connected to a single port on a 10Base-T ethernet switch that is connected directly to the UCSB campus FDDI backbone.

Geodesy Infrastructure

SCEC2 will provide partial support for maintaining the existing Global Positioning System network in southern California (SCIGN). SCIGN is being built and maintained by JPL, the USGS, USC, and the University of California at San Diego. Most of the SCEC support will go to the Scripps Orbit and Permanent Array Center (SOPAC) at the University of California, San Diego, the main data archive. It is the current policy of SCIGN to have Rinex data from all stations available on-line as soon as they can be physically moved from the site to the archive, i.e. within a few hours. The only restriction attached to the data is that users acknowledge the source of the data and its funders. Daily coordinate, periodic velocity solutions, and plots of resulting positions or position differences are also available promptly to the scientific community. SCEC2 support will include salary support for computer engineers to maintain the data archive, storage media, and computer usage.

Geology Infrastructure

Hardware for Field Investigations. An ongoing headache for geologists opening, maintaining, and closing trenches for paleoseismology studies is the cost of backhoe rental to open and close trenches, and shoring rental to keep the trenches from collapsing. These two items can be 25% of a typical budget for a project that involves trenching. We plan to buy a backhoe and train a technician at one of the universities (most likely San Diego State) to operate the equipment so that we can reduce this cost significantly in the future. We also plan to buy shores for use in trenching projects to reduce the cost of rental.

GIS Center for Archiving Geologic Data Bases. Rapid and reliable access to and use of digital map databases will be important to the proper functioning of the California Earthquake Research Center. From the rapid construction of maps of surface faulting, seismicity and geodetic measurements in the aftermath of a large, destructive earthquake, to the creation of maps of stress evolution from paleoseismic and geodetic data, SCEC2 scientists will have an abundant need for GIS (Geographic Information System) and image-processing software. Our education and outreach functions will also require development of the capability to provide maps to a wide variety of users in government, industry, and the public-at-large.

A facility is envisaged that includes the hardware, software, databases and supporting technical staff necessary to support a wide variety of SCEC2 activities.

Computer Facilities

Computer facilities are widely available at all academic institutions. SCEC2 scientists will have access to these facilities for this research. As an example, USC scientists have access to a Linux cluster, Sun 3000 and 4000 servers, several Ultra workstations, PC's, and laptops.