SCEC Southern California Earthquake Center

Southern California Earthquake Center

1993 Report

prepared for the

SCEC Annual Meeting
December 10-12, 1993

The Resort at Squaw Creek
Squaw Valley, California

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Southern California Earthquake Center

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TABLE OF CONTENTS

1993 SCEC ANNUAL MEETING AGENDA

Friday, December 10

8:30 p.m. **Icebreaker**

Saturday, December 11

Session I: Plenary Session

8:00	Welcome and Introduction	Tom Henyey
8:10	Accomplishments, Proposal/Site Review Process	Tom Henyey
8:30	Statement from NSF	Jim Whitcomb
8:45	Statement from USGS	John Sims
9:00	Education and Outreach Developments	Tom Henyey
9:10	Engineering Applications Group Report	Geoff Martin
9:20	Infrastructure vs Science	Tom Henyey/Kei Aki
9:50	Task Discipline Matrix and Accomplishments	Kei Aki
10:20	Proposed Workshops	
10:45	Coffee Break	
11:15	**Discussion of Tasks**	**Discussion Leader**
	Phase II Report and Beyond	Dave Jackson
	Earthquake Scenarios/Geographic Foci	Kerry Sieh
	Fundamental Studies	Kei Aki
	Stress Regimes Proposal	Lynn Sykes/Chris Scholz/Gene Humphreys
	Intermediate Term Prediction	Bernard Minster
	Real Time Seismology	Egill Hauksson
	Post Earthquake Response	Ralph Archuleta

Note: We will break for lunch @ noon and resume this session at 1:00 p.m.

Saturday, December 11

Session II: Working Group Meetings

4:00 to 6:00 p.m.	Groups B & H:	Archuleta/Martin
	Group C:	Sieh
	Group D:	Clayton
6:00 to 8:00 p.m.	Group E:	Agnew
	Group F:	Hauksson
	Group G:	Knopoff
	Education and Outreach:	Henyey/McNally

Note: There will be an informal discussion of the Phase II Report after these sessions.

Sunday, December 12

Session II: Working Group Meetings (Continued)

9:00 to 11:00 a.m.	Group A:	Aki

Session III: Reports on Future Plans from Group Leaders

6:00 p.m. to 9:00 p.m.

Education and Outreach	Tom Henyey
Group G (Earthquake Physics)	Leon Knopoff
Group F (Regional Seismicity)	Egill Hauksson
Group E (Crustal Deformation)	Duncan Agnew
Group D (Subsurface Imaging)	Rob Clayton
Group C (Earthquake Geology)	Kerry Sieh
Group B (Strong Motion)	Steve Day
Group A (Master Model)	Kei Aki
Summary	Tom Henyey

End of SCEC Meeting

Note: SCEC Steering Committee will meet at conclusion of session

SCEC Annual Meeting-December 10-12, 1993

Participants	Institution
Curtis Abdouch	USC
Rachel Abercrombie	USC/UNR
Duncan Agnew	UC-San Diego
Kei Aki	USC
John Anderson	Nevada-Reno
Ralph Archuleta	UC-Santa Barbara
Glenn Biasi	Oregon
Jacobo Bielak	Carnegie-Mellon
Yehuda Bock	UC-San Diego
Kevin Bryan	San Diego State
Jim Buika	FEMA
James Chin	USC
Rob Clayton	Caltech
Allin Cornell	Stanford
Jim Davis	CDMG
Paul Davis	UCLA
Steve Day	San Diego State
Jishu Deng	
Jim Dolan	Caltech
Art Frankel	USGS-Denver
Eldon Gath	Leighton
Bob Ge	UCLA
Lisa Grant	Woodward-Clyde
Ruth Harris	USGS-Menlo Park
Egill Hauksson	Caltech
Tom Heaton	USGS-Pasadena
Tom Henyey	USC
Maria Herzberg	San Diego State
Kenji Hirabayashi	San Diego State
Yoshi Hisada	USC
Ken Hudnut	USGS-Pasadena
Gene Humphreys	Oregon
Dave Jackson	UCLA
Anshu Jin	USC
Laurie Johnson	
Luci Jones	USGS/Pasadena
Simon Katz	USC
Leon Knopoff	UCLA
Jeff Knott	UC-Riverside
Mark Legg	ACTA
Eric Lehmer	UC-Riverside
Yong-gang Li	USC
Anne Lilje	Caltech
Grant Lindley	UC-Santa Barbara
Scott Lindvall	Lindvall, Richter, Benuska
Mehrdad Mahdyiar	Leighton
Geoff Martin	USC
Jon Matti	USGS
Karen McNally	UC-Santa Cruz

John McRaney	USC
Bernard Minster	UC-San Diego
Jim Mori	USGS-Pasadena
Karl Mueller	Princeton
Craig Nicholson	UC-Santa Barbara
David Okaya	USC
Randy Palmer	Oregon
Steve Park	UC-Riverside
Mark Petersen	CDMG
Dan Ponti	USGS-Menlo Park
Maribeth Price	Princeton
Mike Reichle	CDMG
Jim Rice	Harvard
Tom Rockwell	San Diego State
Charlie Rubin	Central Washington
Dave Schwartz	USGS-Menlo Park
Jennifer Scott	Caltech
Craig Scrivner	Caltech
Nano Seeber	Lamont
Bruce Shaw	Lamont
Kerry Sieh	Caltech
Bob Simpson	USGS-Menlo Park
John Sims	USGS-Reston
Jamie Steidl	UC-Santa Barbara
Ross Stein	USGS-Menlo Park
Mark Stirling	Nevada-Reno
Denise Steiner	USC
John Suppe	Princeton
Lynn Sykes	Lamont
Mary Templeton	Cal State-Fullerton
Leon Teng	USC
Paul Thenhaus	USGS-Denver
Kim Thorup	San Diego State
Alexei Tumarkin	UC-Santa Barbara
Frank Vernon	UC-San Diego
John Waggoner	
Jim Whitcomb	NSF
Bob Yeats	Oregon State

Southern California Earthquake Center

Senior Research Investigators (1993)

Principal Investigator and Science Director: **Keiiti Aki**
Department of Geological Sciences
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Executive Director: **Thomas L. Henyey**
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Los Angeles, California 90089

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University of Southern California Department of Mechanical Engineering Los Angeles, California 90089	Marijan Dravinski
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California Institute of Technology Department of Civil Engineering Pasadena, California 91125	John Hall Ronald Scott
Columbia University Lamont-Doherty Earth Observatory Palisades, New York 10964	John Armbruster Leonardo Seeber Christopher Scholz Bruce Shaw Lynn Sykes
University of California Department of Earth and Space Sciences Los Angeles, California 90024	Paul Davis David Jackson

University of California Institute of Geophysics and Planetary Physics Los Angeles, California 90024	Yan Kagan Leon Knopoff
University of California Department of Civil Engineering Los Angeles, California 90024	Mladen Vucetic
University of California Scripps Institution of Oceanography LaJolla, California 92093	Duncan Agnew Yehuda Bock Bernard Minster Frank Vernon
University of California Department of Geological Sciences Santa Barbara, California 93106	Ralph Archuleta Craig Nicholson Sandra Seale Alexei Tumarkin
University of California Earth Sciences Board of Studies Santa Cruz, California 95064	Thorne Lay Karen McNally Steven Ward

Member Institutions	**Scientists**
University of California Department of Earth Sciences Riverside, California 90024	Stephen Park
University of Nevada Department of Geological Sciences Reno, Nevada 89557	John Anderson Steven Wesnousky
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Woods Hole Oceanographic Institute Department of Geology and Geophysics Woods Hole, Massachusetts 02543	Jian Lin
University of Oregon Department of Geological Sciences Eugene, Oregon 97403	Ray Weldon

Industry Participants	**Scientists**
ACTA, Inc. Torrance, California	Mark Legg
Leighton and Associates Diamond Bar, California	Eldon Gath Mehrdad Mahdyiar
Lindvall, Richter, Benuska, Associates, Inc. Pasadena, California	Scott Lindvall
S-Cubed, Inc. La Jolla, California	Keith McLaughlin

Southern California Earthquake Center

1993 DIRECTOR'S OVERVIEW

Keiiti Aki

Four and a half years ago, a workshop held at Lake Arrowhead, California was attended by scientists concerned with earthquake research in southern California. It was decided to establish a research center which focused on applying earth sciences to earthquake hazard reduction. The NSF Science and Technology Centers Program and the National Earthquake Hazards Reduction Program were potential sources of funding for the new center. Additional workshops and seminars followed the Lake Arrowhead meeting to promote interaction among researchers and develop proposals to NSF and the USGS. The proposals were successful; SCEC was born officially on February 1, 1991.

After two and three quarter years of activity, the structure and function of SCEC are taking shape. The center activities involve the development and maintenance of an infrastructure as well as scientific research, which is carried out by more than 50 PIs from 7 principal institutions and about a dozen participating institutions.

The center has developed a strategic plan based on the discipline-task matrix approach. 8 disciplinary groups constitute the center's working unit, and group leaders participate in the center's decision making. 6 major tasks have developed as a consensus through discussions at numerous meetings and workshops. The table of budget distribution in the matrix for the past 3 years shows the multi-disciplinary nature of the work at SCEC. We consider our consensus on task-disciplinary matrix approach as a major achievement of the center. The center mode of funding made this consensus possible.

The center mode of funding had several merits which were not clearly recognized by most of us in the beginning. The center

- Secures balanced support for the elements of the master model including: infrastructure, disciplinary group research, and dissemination of knowledge,

- Assembles a critical mix of disciplinary expertise,

- Fosters and helps resolve controversies within disciplinary groups,

- Fosters cooperation and interaction among the different disciplinary groups,
- Protects promising areas of research at rudimentary stages of development,
- Enables orderly transfer of knowledge from basic research to its applications,
- Helps produce scientific consensus documents needed by the public,
- Leverages considerable additional resources, and
- Provides a contact point for the user community.

Six tasks of the center developed as a consensus are as follows:

TASKS DEVELOPED AT SCEC

Task 1:	**Construct Maps of Probabilistic Seismic Hazard of Southern California**
Task 1A:	Construct a data base for characterizing earthquake sources in southern California.
Task 1B:	Construct a library of Green's functions for characterizing propagation-path effects in southern California.
Task 1C:	Construct a data base of meso-scale site amplification factors at various frequencies and basement accelerations for southern California.
Task 1D:	Develop the methodology for probabilistic seismic hazard analysis.
Task 2:	**Develop Plausible Earthquake Scenarios Emphasizing the Los Angeles Basin**
Task 3:	**Study Fundamental Relationships Among Fault Structures, Dynamics, and the Earthquake Recurrence Process**
Task 3A:	Detailed study of the 3-D fault zone structure for selected fault segments.
Task 3B:	Development of the "physical master model".
Task 3C:	Study of the regional stress field in southern California.

Task 4: **Develop and Test Intermediate-term Earthquake Prediction Methodology**

Task 5: **Support the Development of Real-time Earthquake Information**

Task 6: **Response to Future Earthquakes**

The details of the above tasks are described in the renewal proposal for 1994-1998 activities submitted to NSF in June, 1993, and explained to the site visit team in September, 1993. In essence, we are successfully completing a first-generation master model of earthquakes in southern California by integrating various disciplinary earth science data through the probabilistic seismic hazard analysis. In the next 5 years, we shall refine our hazard master model and put it on a firmer physical basis. As explained in detail in the Group A report in this volume, a comparison of the prediction by the first-generation SCEC model with the historic earthquake occurrence since 1850 lead to the following possibilities:

(1) A significant part of geodetic strain rate used for inferring the seismic moment rate may be released aseismically.

(2) The maximum possible magnitude for southern California may be much larger than the value assigned from geologic data on the basis of conventional segmentation model, as exemplified by the multi-segment faulting during the 1992 Landers earthquake.

(3) The historic seismicity in southern California might have been anomalously low as compared to the long-term seismicity inferred from geological and geodetic data.

The above issues are very fundamental to the science of earthquake hazard estimation, and fascinating subjects of focused studies at SCEC in the next few years.

- Year 1

	Group A	B	C	D	E	F	G	Sub-Total
Task 1	188	20	70	40	70			388
Task 2	16	103	80	70		35		304
Task 3	15	76	44	165	75	50	57	482
Task 4	11				10		143	174
Task 5						60		60
Sub-Total	230	199	194	275	165	145	200	1,408

- Year 2

	Group A	B	C	D	E	F	G	Sub-Total
Task 1	151		45		75			271
Task 2	60	40	282	80		40		502
Task 3	40	109	8	90	38	40	52	377
Task 4	23						72	95
Task 5						70		70
Sub-Total	274	149	335	170	113	150	124	1,315

- Year 3

	Group A	B	C	D	E	F	G	Sub-Total
Task 1	80		26		27			133
Task 2	65	142	118	52	69			446
Task 3	40	21	137	30	40	95	61	424
Task 4	114						34	148
Task 5						50		50
Sub-Total	299	163	281	82	136	145	95	1,201

SOUTHERN CALIFORNIA EARTHQUAKE CENTER (SCEC)
A NATIONAL SCIENCE FOUNDATION
SCIENCE AND TECHNOLOGY CENTER

■ Mission

The Southern California Earthquake Center's mission is to promote earthquake hazard reduction by defining when and where future damaging earthquakes are likely to occur in southern California, calculating the expected ground motions, and disseminating this information to the community at large.

■ Cooperating Organizations

● Academic

- University of Southern California (managing institution)
- California Institute of Technology
- University of California, Los Angeles
- University of California, Santa Barbara
- University of California, San Diego
- University of California, Santa Cruz
- Columbia University

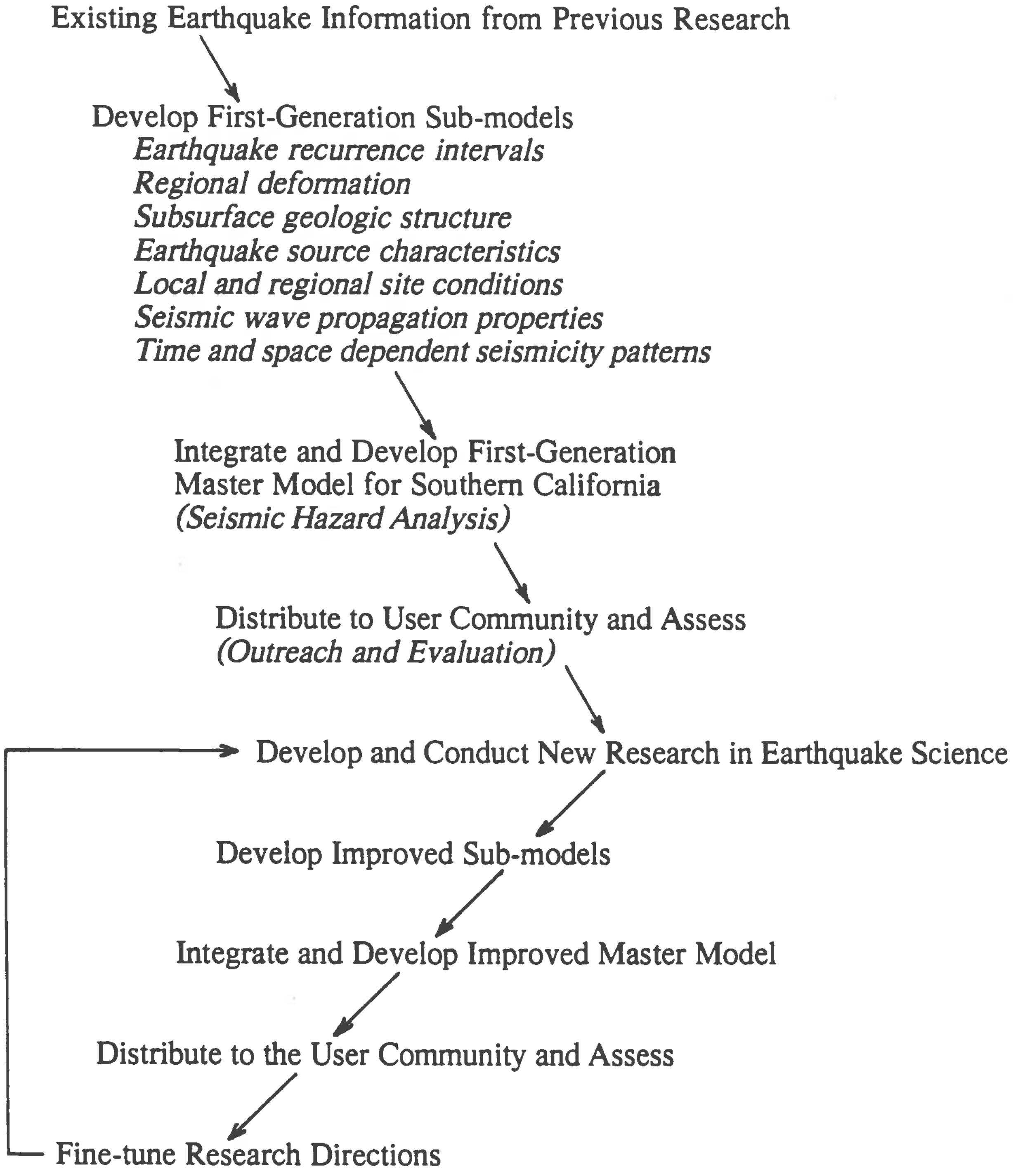
● Government

- United States Geological Survey
- California Division of Mines and Geology
- California Office of Emergency Services
- Federal Emergency Management Agency
- California Department of Transportation
- City of Los Angeles
- County of Los Angeles

■ Funding Sources (does not include institutional matching support)

• National Science Foundation (S&T Centers Program) --	$1.8 M/year
• U.S. Geological Survey (National Earthquake Hazards Reduction Program) -------------------------------	$1.1 M/year
• Federal Emergency Mangement Agency -----------------	$0.12 M/year
• California Department of Transportation ----------------	$0.25 M/year
• City of Los Angeles ---------------------------------------	$0.25 M/year
• County of Los Angeles ------------------------------------	$0.25 M/year
Total (F/Y 1993)	$3.77 M

■ Conceptual Flow Chart



Existing Earthquake Information from Previous Research

Develop First-Generation Sub-models
- *Earthquake recurrence intervals*
- *Regional deformation*
- *Subsurface geologic structure*
- *Earthquake source characteristics*
- *Local and regional site conditions*
- *Seismic wave propagation properties*
- *Time and space dependent seismicity patterns*

Integrate and Develop First-Generation
Master Model for Southern California
(Seismic Hazard Analysis)

Distribute to User Community and Assess
(Outreach and Evaluation)

Develop and Conduct New Research in Earthquake Science

Develop Improved Sub-models

Integrate and Develop Improved Master Model

Distribute to the User Community and Assess

Fine-tune Research Directions

■ Products

- Data Bases
- Probabilistic Earthquake Recurrence Estimates
- Maps of Strong Ground Motions
- Technical and Semi-technical Monographs
- Earthquake Science Curricula for Schools and Curricula
- Public Information Circulars
- Information and Training Workshops for Professionals

■ Users

- Emergency Preparedness Officials
- Regional Planning Agencies
- State and Local Governments
- Public Schools (K-12)
- Geotechnical Engineers
- Media
- General Public

■ New Technologies

- Global Postitioning Satellites (US)
- High-Fidelity Seismometers (European)
- Digital Data Acquisition Systems (US)
- Analog and Digital Communications (US)
- High-Speed Micro- and Mini-Computers (US)
- Laser-Disk Mass-Storage Devices (US)
- Geographical Information Systems (US)

Report on the 3rd meeting of the Advisory Council to the Southern California Earthquake Center

October 8-9, 1992,

University of Southern California.

The 3rd meeting of the SCEC Advisory Council was held in conjunction with the SCEC Annual Meeting. Members present were J. Davis, J. Dieterich, I.M. Idriss, D. Mileti, W. Petak, B. Romanowicz (Chair) and J. Rundle.

The Advisory Council is impressed by the Center's progress in organising its internal planning activities, as evidenced by the improved focus expressed by the group leaders in their annual report presentations. Furthermore, the "matrix" system introduced by the Center's Scientific Director, Professor K. Aki, has had a very favorable effect in fostering communication and cooperation across disciplines and should be recognized as a key element of strategic planning, although such a plan does not yet exist in writing.

The Advisory Council still thinks that it would be helpful for the Center to have a Strategic/Science Plan in written form for the reasons outlined in our previous two reports, namely:

1) to serve as the reference document to be used when approaching other agencies/foundations for complementary funding

2) to clarify the goals, priorities and choices of the Center for the benefit of both the Center community and the rest of the seismological community.

3) to serve as reference in the event that future budget cuts make it necessary to enforce priorities.

If such a document were made available to the Advisory Council prior to the next meeting, Council members would be ready to provide timely input to the SCEC Board, if needed, in working out details towards its final version.

The principal unexpected element of change since the last Advisory Council meeting was introduced by the occurrence of the June 28, 1992 Landers earthquake. The Center's management and participants should be commended for responding promptly and enthusiastically to the largest earthquake to occur in Southern California since 1952. Particularly notable are the comprehensive nature of the field campaign, the rapidity with which it was organised, and the tenacity of Center participants in following through with a continuing observational program. It is worth noting on the other hand that, had the Center not existed, the response to this earthquake would have most certainly been more disorderly, less timely and less efficient.

An issue which has arisen as a consequence of the Landers earthquake is that of the appropriate balance between the original Master Model objectives and the activities associated with this earthquake, or any future large earthquakes that might occur during the Center's existence. The Council suggests that careful thought be given to how much of the Center's finite resources can be devoted to study the Landers event, given the need to achieve the original Center objectives in a timely manner and in the light of the findings of the Phase I report, when it becomes available. For instance, if these findings lead to a modification of the prevailing thinking about seismic risk in Southern California, the narrow focus on the Los Angeles basin, discussed at the last meeting, needs to be justified on a scientific basis, given the stress transfer mechanism that may operate between fault segments. In the same manner, the scientific rationale for working on areas not strictly included in the L.A. Basin must be clearly explained.

There is a natural role for the Center to play in formulating follow up planning after the Phase I report. The Center could for example help in identifying areas where more intensive monitoring would be useful, and could propose recommendations to the funding agencies for additional support, as required.

In spite of notable efforts by Center participants in the past six months, the one issue which still needs to be addressed is that of the Outreach Program.

Current activities that engage physical scientists, engineers and other center members in outreach activities should be celebrated and continued as a means to interest and engage people in such activities. Nevertheless, the Center should decide who is its primary target for outreach, professional communities or the public, and formulate a strategic plan accordingly. This plan should be informed by those with seasoned experience *and* contemporary knowledge from the communication sciences as one is not adequate without the other. Also, feedback from users must be designed into the process that produces the Master Model.

Highest current priority should be placed in organising education and outreach activities with other organisation and individuals regarding earthquake risk changes following the Landers earthquake, and obtaining an associate director for education and outreach *after* decisions about the outreach program's purpose and form are decided.

The Advisory Council welcomes current efforts and encourages further ones for cooperation with other agencies for putting out their products (maps etc..) and presenting them in a consistent way to the public, by making use of existing distribution networks.

Finally, the Advisory Council would like to continue to meet twice a year, and tentatively plans the next meeting to occur in conjunction with one of the monthly Center Workshops in April or May 1993.

Report on the
4th meeting of the Advisory Council
to the Southern California Earthquake Center
April 29-30, 1993
University of Southern California

The Advisory Council met at USC on April 29-30, 1993, in conjunction with the SCEC April monthly seminar, devoted to presentations by coordinators of chapters of the Landers Phase II report. Council members present were J. Davis, J. Dieterich, P. Flores, I.M. Idriss, T. Jordan, W. Petak, B. Romanowicz (Chair), J. Rundle* and R. Smith.

The Council congratulates the Center and its leaders, Professors Kei Aki and Tom Henyey, for the scientific momentum it has achieved, as first results of its activities are becoming apparent. Particularly, the Council wishes to stress the outstanding accomplishment of bringing together members of the scientific community to jointly work towards the Center goals. This mode of operation is unique and will serve as a valuable example of the kind of interactions between scientists that might be successful in the future in the seismological community.

The Council also commends the Center for responding to earlier recommendations and putting together a Strategic Plan as well as making sizable progress in developing an Outreach Plan.

The Strategic Plan, which is in fact both a Strategic and a Science Plan, reflects the level of maturity now attained in the Center's definition of its goals and in its vision of how all the pieces come together in the "Big Picture". The efforts deployed towards defining an Outreach Program, on the other hand, have helped identify directions and priorities as well as the means necessary to implement the Program. The Council is very impressed by the progress in this area and recognizes that this Program is now "on track".

The Council offers the following recommendations concerning the Strategic Plan:

1) In the mission statement, the "coordination of scientific research" component is missing. This aspect of the Center's mission is underplayed in the current statement, but will be a key component in the evaluation process of the main funding agencies.

2) The current section on Infrastructure reads more like a financial report, while an actual discussion of priorities is missing. The Council feels strongly that the Strategic Plan should address the question of balance between infrastructure

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*Not present April 30, 1993.

and research funding and the relationship between the two. It should briefly explain the rationale behind the relative allocation of funds to each component until now and also for the future. For example, it should indicate whether and why the funding level for trenching and GPS is expected to go up or down, and likewise for the Data Center and seismological instrumentation. Among specific examples, the GIS is clearly a key element for the ultimate presentation of results and products, yet no plan exists defining the priorities in the development of applications of this capability.

The Council wishes to stress that while the Center is still investing heavily in equipment - perhaps rightly so - its science budget is at a minimum critical value. It should now plan its strategy for the infrastructure/research priorities in the event of future budget cuts. It should also, more generally, plan the evolution of the infrastructure/research budgets and be concerned with achieving a balance between the quantity of data produced and collected and the realistically feasible high level analysis of these data.

3) The Council notes that the Visitors Program budget seems to be decreasing with time and stresses that this Program is very important in order to bring in new ideas to the Center and export the Center 's achievements. This program should be sustained and could now be used more effectively by seeking out specific expertise not currently present in the Center's pool of scientists.

Concerning the Outreach Program, the Council recognizes the value of the effort and time devoted to education at the K-6 level and particularly at the college level, with the opportunity for bringing a component of diversity to the Center.

However, the Council feels that the Outreach Program should be driven primarily by Center products, a point that has been stressed in the oral presentations during this meeting. Also, the staff of three presently identified as needed for this Program should not, for practical and budgetary reasons, be implemented in one single step. The first priority should go to filling the position requiring technical background.

The Council also recommends that the Center not neglect an important component of Outreach, which is that within the scientific community. This can be achieved, for example, by distributing a periodic report on the activities and achievements of the Center, publishing articles in EOS and organising a special session at the next Fall American Geophysical Union meeting.

MEMORANDUM TO THE MEMBERS OF THE NATIONAL SCIENCE BOARD

SUBJECT: Southern California Earthquake Center, University of Southern California
($16,250,000; 60 months)

There is transmitted herewith for the review and approval of the National Science Board a proposed award for renewal of support for the Science and Technology Center at the University of Southern California at a level not to exceed $16,250,000 for a period of 60 months, under the direction of Prof. Keiiti Aki. After approval by the NSB at its August 16, 1990 meeting (NSB-90-116), this Center was established on February 1, 1991. NSF support for this Center in Fiscal Years 1991 through 1993 has totaled $5,023,880. In addition, support from non-NSF sources during this period totaled $5,819,000. The recommended FY 1994 award for the first year of renewed support is $2,850,000, which includes a $1,070,000 (60%) increase beyond the FY 1993 award. The recommended award represents 3.2% of the Earth Sciences Division's FY 1994 budget request.

PROJECT DESCRIPTION

The University of Southern California, in collaboration with the California Institute of Technology, the University of California at Los Angeles, the University of California at Santa Barbara, the University of California at Santa Cruz, the University of California at San Diego, Columbia University and the U. S. Geological Survey (USGS) form the core institutions of the Southern California Earthquake Center (SCEC), an NSF Science and Technology Center. Also, eleven other institutes and four private corporations are research participants in the SCEC, and relevant state and local government agencies have established ties with the Center.

Goals and Objectives

The basic goal of the SCEC is to mitigate injury and the loss of life and reduce property and other damage from earthquakes in southern California. It intends to do this through the application of research findings from the various disciplines in earthquake-related science. The SCEC will develop a prototype probabilistic seismic hazard model (master model) for southern California. Center scientists use the master model to focus the research and provide a framework through which planning, engineering, and construction code revision can be facilitated by users outside the Center.

Research

The initial choice of southern California for an earthquake center was based in part on its being an ideal natural laboratory because of high seismicity and population density. This choice was confirmed by the occurrence of the 1992 M=7.4 Landers earthquake, the largest event in the coterminous U.S. in 40 years. Without the SCEC coordination of field studies, research and outreach on this earthquake would have been significantly reduced. The results have led to a reevaluation of the paradigm on fault segmentation and characteristic earthquakes, a foundation of most earlier earthquake-hazard site-evaluation techniques. Also, geodetic field parties showed strong evidence for viscoelastic response of the crust to the large distortion of the Landers event.

Two significant research results were directly interpretable in terms of seismic hazard. First, much of the early SCEC effort has gone towards gathering Global Positioning System (GPS) data from the many divergent GPS projects in southern California, and integrating that data into a uniform and remotely accessible data base. The result was a detailed strain velocity map for southern California that was generally thought unattainable at this early stage. The second was an integrated multi-disciplinary research focus of the SCEC leading to the discovery of blind-thrust faults that underlie most of the Los Angeles basin. Efforts are now underway to evaluate these results within the framework of the master model.

The SCEC adopted a matrix approach to prioritizing research by dividing into eight disciplinary research groups and focusing their efforts towards six tasks. The current tasks are to 1) construct maps of probabilistic seismic hazard for southern California; 2) develop plausible future earthquake scenarios emphasizing the Los Angeles basin; 3) study the fundamental relationships among 3-D fault zone structures, fault dynamics and the earthquake recurrence process emphasizing the Landers earthquake sequence; 4) develop and test intermediate-term earthquake prediction methodology; 5) Support the development of real-time earthquake information; and 6) coordinate, carry out, and support post-earthquake studies of major earthquakes in southern California as they occur.

Education

Graduate education was a major component of the SCEC. Most of the funding for salaries went to graduate students (total of 45 in FY 1993) and post-doctoral researchers (total of 16 in FY 1993). Undergraduate students (10 in FY 1993) participated in SCEC research projects. Monthly, topic-specific seminars were well-attended by students who not only participated in the interactive forum but made presentations. SCEC reached out to K-12 and the general public with exhibits at the Los Angeles County Museum of Science and Industry, and with an earthquake hotline and newsletter in collaboration with other state and federal agencies. An innovative series of radio segments, developed in collaboration with a local radio personality, explained geological and seismological results to the public, including the newly discovered Los Angeles basin faults.

Knowledge Transfer

Two widely-anticipated reports on future seismic hazards in southern California after the Landers event were intended for government agencies and the general population. Phase I, "Implications of the 1992 Landers Earthquake Sequence" published in November 1992, deals with near-term changes in estimated seismic hazard as a result of the earthquake. Phase II, "Future Seismic Hazards in Southern California", is near completion and deals with the longer-term reevaluation of seismic hazard in light of new knowledge and techniques. Phase II breaks new ground in integrating seismicity, geodetic, and geologic research results into a combined estimate of probabilistic seismic hazard. This is, in fact, the first-generation master model. Both reports were done in close cooperation with the National and California Earthquake Prediction Evaluation Councils. The SCEC has been recognized by officials and the public as an authoritative source of information about earthquakes.

The SCEC had a good record of dissemination of research results in the scientific literature and at regular workshops and seminars. Scientists in the extensive visitor program transferred knowledge both to and from the visitors' home institutions. SCEC is developing a Geographic Information System (GIS) data base with hazard maps, fault information, soil types, and other data that is accessible to planners, engineers and scientists.

Management

A team management structure involving Prof. Keiiti Aki as Science Director and Prof. Thomas Henyey as Executive Director effectively utilized their talents and spread the heavy management load. Discipline group leaders were leaders in their fields and contributed directly to defining the goals and products of the SCEC. The Advisory Committee met twice each year and had a strong interest in the operations and scientific goals of the Center. SCEC management has been highly responsive to recommendations and concerns of the Advisory Committee and past site visit teams. In particular, resource allocation has become more focused through use of the matrix approach at the recommendation of the advisory groups.

Institutional and Other Support

The core institutions continued to be strong supporters of SCEC with significant funding in addition to salary support and space. The USGS has been a major funding partner of the SCEC ($1,200,000 in FY 1993) as well as a scientific partner in supporting USGS personnel and operations as part of the Center. USGS observers were part of the Site Visit Team. Additional support was received for engineering applications from the California Department of Transportation, and the County and the City of Los Angeles (total of $750,000 in FY 1993), for outreach from the Federal Emergency Management Agency ($125,000 in FY 1993), and for knowledge transfer from the Pacific Gas and Electric Company ($10,000 in FY 1993).

SUMMARY OF REVIEW

Mail Review

Six mail reviewers representing a broad spectrum of experience were used. A response to the reviews was prepared by SCEC prior to the site visit. The mail reviewers rated this proposal highly. Universally cited strengths were the high intrinsic merit of the proposal with its relevance to an important societal problem, the high quality of participants, the high quality of Center management who used the goals to focus the science and the NSF support to leverage other funding, and the importance of the four data centers for seismic, strong motion, GIS, and GPS data. Other strengths mentioned were the effective response to the Landers earthquake; the high percentage of funding for students, post-docs, and visiting scientists; and the outreach/technology transfer resulting from the Phase I and Phase II reports. One reviewer felt that this was the best proposal he has ever read and that the SCEC had contributed a new vitality to the earthquake science and engineering community.

However, while some outreach was considered strong, two mail reviewers expressed concern that other parts of the outreach program were not fully operational. Undergraduate and K-12 programs were still in the planning stage, and the Assistant Director for Outreach position was not yet filled. The SCEC management recognized this situation and the Site Visit Team was satisfied with their plans and increased emphasis to be placed on these components of outreach. Other mail review questions involving the transformation of science results into user products were answered by the Phase I and II reports, the expanded engineering effort and GIS development plans. Questions related to the physics behind the master model pose some of the biggest challenges to the Center and an increased focusing of the physics group towards center goals was outlined to the satisfaction of the Site Visit Team.

Site Visit

The site review occurred on September 1-2, 1993. Five mail reviewers formed the Site Visit Team. Seven other visitors at the site visit included an NSB observer, two NSF observers, and four USGS observers. The first afternoon of the site visit was devoted to a visit to the Caltech seismic data center, the UCLA GPS data center, and an "urban geology" field trip to trenching sites across the newly discovered faults in Hollywood and Beverly Hills. The next one and one-half days were devoted to the formal review and a poster session with students and post-doctoral researchers.

The USGS observers wrote an independent review from the USGS viewpoint as both supporting agency and participant in the Center. In their view, the establishment of SCEC has resulted in far more interaction among investigators and institutions with State and local governments, industry, the engineering community and the public. Areas that required additional attention were similar to those outlined in mail reviews and the Site Visit Team report, and the USGS was satisfied with SCEC plans in these areas. The USGS was pleased with the progress of the Center and anticipated supporting the Center at or above past levels of support. They urged the NSF to support the Center at or near the requested level of funding.

The Site Visit Team felt that the SCEC has brought a visible and essential focus to the problem of earthquake hazards in southern California. Construction of the master model has given the intended focus to both the science and technology transfer. The high quality of researchers and management has proven effective by fostering cooperation between disciplinary groups which attack the same scientific problem from different, complementary directions. The four data centers developed by SCEC for seismic, strong motion, GIS, and GPS data have become important resources for the general scientific community and would not have existed otherwise. The team encouraged an increased emphasis on undergraduate and K-12 education as planned by SCEC.

The Site Visit Team concluded that the SCEC is viewed at the national, state, and local levels as an important asset. The management and leadership has been highly effective and responsive to outside advisory groups. Core institution and outside support other than NSF, especially the USGS support, has been strong. The Team unanimously recommended that the SCEC be awarded full support as requested with no significant reservations.

Review Analysis

Evaluated on the basis of mail reviews and the site visit reports, the SCEC has done an excellent job of focusing the major southern California institutions and diverse disciplines on the problem of earthquake hazard in southern California. These were groups that, while good in their own right prior to the SCEC, were not interacting at this level. The four major data centers, seismic at Caltech, GPS at UCLA, GIS at Riverside, and strong motion at UC Santa Barbara, have been recognized by the general scientific community as a powerful new asset. Significant scientific advances have already been made in the two and one-half years of operations. Examples included the Landers earthquake response and findings, the detailed strain velocity map of southern California, and the integration of geologic, seismicity, and geodetic data into a probabilistic hazard evaluation - the first-generation master model.

Outreach had both strengths and weaknesses. Graduate student, post-doctoral researcher, and visitor support were very strong. Public information was effective with a museum exhibit, radio spots, and participation in an earthquake hot line and newsletters. Communication and products relating to other responsible government agencies were very strong. Undergraduate support was moderate with ten students but already had examples of attracting women into science graduate work under SCEC support. However, a planned K-12 program, a significant undergraduate program, and an Assistant Director for Outreach position were not yet implemented. The SCEC recognized these needs and the Site Visit Team was satisfied with plans to move forward with these components.

Reviewers agreed that the management and leadership of the SCEC were excellent and responsive to site visit teams and their Advisory Committee. A strong case was made for a budget increase that will be used to enhance infrastructure, the outreach program, and geographical coverage of the master model. This increase will bring SCEC funding to the original Board authorization level. In the opinion of reviewers, site visitors and our major partner, the USGS, the SCEC is starting to fulfill its potential to achieve major scientific advancement on earthquake hazard in southern California. It is likely that these results could be applied to metropolitan areas at risk elsewhere in the Nation and the world.

RECOMMENDATION

I recommend that the Board approve this project in accordance with the following resolution:

> RESOLVED, that the National Science Board approves the making by the Director at his discretion of a grant, contract or other arrangement to the University of Southern California for "The Southern California Earthquake Center" in an amount not to exceed $16,250,000 under the direction of Prof. Keiiti Aki for 60 months.

Neal Lane
Director

ABSTRACT

SOUTHERN CALIFORNIA EARTHQUAKE CENTER - UNIVERSITY OF SOUTHERN CALIFORNIA

The University of Southern California, in collaboration with the California Institute of Technology, the University of California at Los Angeles, the University of California at San Diego, the University of California at Santa Barbara, the University of California at Santa Cruz, Columbia University and the U.S. Geological Survey form the core of the Southern California Earthquake Center, an NSF Science and Technology Center. Other academic institutes and private corporations participate in research projects. The goal of the center is to mitigate injury and the loss of life and reduce property and other damage from earthquakes in southern California. It does this through the application of research findings from the various disciplines in earthquake-related science and engineering. The center scientists are developing a prototype probabilistic seismic hazard model, the master model, for southern California which focuses the research and provides a framework through which planning, engineering, and construction code revision is facilitated by users both inside and outside the center. Topical workshops and monthly symposia are used to move the center's research forward and develop the master model. They bring together scientists from core and participating institutions, the U.S. Geological Survey, and the user community. They have also become highly effective intellectual training grounds for graduate students and post-doctoral fellows. Earthquake hazard mitigation is also done through public information and education programs and the training of teachers and students. The center is led by Professor Keiiti Aki as Science Director and Professor Thomas Henyey as Executive Director.

NSF/USGS SITE VISIT OF THE SCEC
August 31 - September 2, 1993

Site Visit Panel

Dr. Charles A. Langston, Department of Geosciences, Pennsylvania State University

Dr. Carl Kisslinger, Department of Geology, University of Colorado

Dr. John L. Aho, General Engineering Manager, CH2M Hill, Anchorage, Alaska

Dr. Robert S. Crosson, Geophysics Program, University of Washington

Dr. Francis T. Wu, Dept. of Geological Sciences, SUNY at Binghamton

Additional Mail Reviewer

Dr. Susan Beck, Department of Geosciences, University of Arizona

National Science Board Observer

Dr. Warren J. Baker - President, California Polytechnic State University

NSF Observers

Dr. James H. Whitcomb - NSF Coordinator for the SCEC, Program Director, Geophysics

Dr. Nathaniel G. Pitts - Director, Office of Science and Technology Infrastructure

USGS Observers

Dr. Randall G. Updike - USGS Coordinator for the SCEC, Acting Coordinator for NEHRP

Dr. Robert L. Wesson - Office Head, USGS Office of Earthquakes, Volcanos and Engineering

Dr. Wayne R. Thatcher - Geophysicist, Menlo Park Office

Dr. John Simms - USGS Office of Earthquakes, Volcanos and Engineering

SITE VISIT REPORT

Southern California Earthquake Center

University of Southern California

September 2, 1993

OVERVIEW

Southern California is an area of high population density that is also an area that is undergoing active geological deformation. Destructive earthquakes have occurred many times in the past and will continue to occur in the future, putting the population at risk. The Southern California Earthquake Center (SCEC) is a major effort of the geological, geophysical and engineering community to mitigate the disastrous effects of earthquakes. This is being done by coordinated scientific research to construct what is termed as the "Master Model" for earthquake hazards in southern California and through outreach efforts. As such, the SCEC is an unusual NSF Science and Technology Center in that its primary goal is to provide scientific products and guidance to government and emergency management organizations in the area. While SCEC goals are directed towards societal benefit, the existence of the center is also providing exceptional direction to seminal geological and geophysical research in one of the most tectonically active areas of the world.

Evaluation of earthquake hazards is a difficult scientific problem requiring extensive information on location of potential active faults, their history of movement, the physical conditions of the crust and the nature of seismic wave propagation from ground rupture to points on the surface of the earth. The SCEC is following an integrated research program where scientific results from geology, geodesy and seismology are being used to deduce the tectonic framework and dynamics of southern California. The center approach to this problem is proving to be effective by fostering cooperation between disciplinary groups which attack the same scientific problem from different, complementary directions. An example of this synergy occurred in response to the 1992 Landers, California, earthquake where participants in the SCEC mounted an effective field effort to study the faulting process. They made several significant discoveries which will result in a new paradigm for evaluating earthquake potential from mapped fault structures.

The SCEC has matured over the past 2 1/2 years under the able guidance of the Scientific Director, Keiti Aki, and Executive Director, Thomas Henyey. In addition to well-focused scientific programs concerned with producing usable products of the master model, programs in Outreach and Education are beginning to be implemented which will transmit scientific results to the public and public institutions, fulfilling the original intent of mitigating earthquake hazards in southern California. The SCEC management has shown itself to be very responsive to comments and suggestions made by its Advisory Council and by past site visit teams. The site visit team is enthusiastic about the progress of SCEC and expects it to successfully fulfill its mission in the future.

INTRINSIC MERIT OF THE STC RESEARCH

The SCEC has brought a spectacular and essential focus to the problem of earthquake hazards in southern California. It has fostered scientific communication between research groups from previously competitive institutions resulting in a very effective and collegial collaboration. The SCEC has become a model for interdisciplinary research in the earth sciences.

It is clearly having a synergistic effect in bringing high quality results from geology, geodesy and seismology to bear on the earthquake problem. Activities and research results which demonstrate this include:

- Coordinated field studies of the 1992 Landers earthquake
- Phase I report communicating the significance of the Landers event to the public
- Phase II report reevaluating earthquake hazard of southern California in light of updated data and techniques
- Results which question the standard earthquake paradigm on fault segmentation and characteristic earthquakes
- Strong evidence, from geodesy, of the viscoelastic response of the crust to large earthquake motions
- Detailed strain velocity map for southern California
- Geologic evidence for major, blind thrust faults in the Los Angeles basin.

Construction of the master model is providing a framework for scientific understanding of earthquakes and is generating products that are useful for hazards mitigation. Indeed, this scientific effort promises to be a remarkable opportunity for significant advances in probabilistic seismic hazard analysis. Major research participants are leaders in their respective fields and are producing significant results as well as building the SCEC's reputation as a world-class scientific organization.

Research is generally well-focused and effective in meeting center goals. The center also supports, at modest levels, high risk/high potential research. The site visit team encourages the management to continue its current process of evaluation of research results to ensure that such research is directed towards center goals.

The SCEC has developed facilities which have become important resources for the general scientific community and which would not have existed otherwise. These include:

- The SCEC data center located at Caltech which has unified the USGS/Caltech Southern California Network and Caltech TERRAscope broadband array
- A strong motion data center at UC Santa Barbara making strong motion data generally available to the scientific and engineering community.
- The UCLA GPS data center
- The UC Riverside GIS data center

Research plans have matured through a strategic planning process and include six different tasks that address scientific needs of the master model and new, important thrusts in developing real-time earthquake information and a response plan for future large earthquakes. The center has also included an important component of earthquake engineering through a project funded by Caltrans, the County of Los Angeles and City of Los Angeles. The site visit team encourages the continued interaction between the strong-ground-motion and engineering groups of the center. One of the initial contributions of the engineering group is digitization of the USC strong motion data.

The SCEC has been very effective in meeting its initial goals. Future scientific plans are aggressive and appropriate. Evidence of the center's success is an effort in northern California by area institutions to form a similar organization. Indeed, the site visit team encourages the management of SCEC to take a leadership role in working with this group and others since it has much to offer to the earth sciences community in the area of data collection, data management and public outreach. The SCEC is clearly a value-added enterprise which has brought together major research universities and the U.S. Geological Survey into a cohesive whole benefiting both earthquake science in southern California and the earthquake community at large.

EDUCATIONAL AND TRAINING COMPONENT, INCLUDING OUTREACH

The outreach program is viewed as a key element of the Center operation by the Center management and the Advisory Council. It consists of three main tasks: (1) provision of information to the government agencies for earthquake preparedness, (2) establishment of a linkage to the engineering community so that relevant products are effectively used, and (3) education of students at all levels in an effort to disseminate earthquake knowledge and improve science education. A strategic plan for outreach product application and dissemination has been made. It described the products, the potential users, the dissemination plans and time table.

Liaison with the relevant State agencies and local governments was established during the first two years of operation of the Center, and a Memorandum of Understanding between SCEC and California Governor's Office of Emergency Services was signed in May of this year, specifying the working relationship between the Center and the State agency. The phase II report, or the first generation master model, is nearing completion and it is due to released. This document has broad social implication and SCEC is taking steps to ensure that it will reach the potential users.

The liaison with the engineering community was initiated when the SCEC Engineering Application Group came into existence in April 1992. In addition to performing earthquake engineering research and providing relevant input to the building of the master model, the group will be an important interface to the geotechnical and structural engineers who are potential users of the SCEC products.

With respect to education, a group of 45 bright and enthusiastic graduate students are now working on earthquake research under the aegis of SCEC; their contribution to the research productivity of the Center is evident. Ten undergraduate students have participated in Center activities and some became graduate students as a result. Although the number of undergraduate students involved is small, the trend of student involvement in Center activities is very encouraging. In addition, a significant number of post-doctoral researchers and senior visitors, from US as well as foreign universities and research organizations, have worked at SCEC institutions.

Significant efforts have been made to develop materials for public information. They include educational "spots" on the radio, exhibits in southern California science museums, public newsletters, etc. The museum exhibits are viewed by the site visit team to be quite effective.

Due to funding shortages in the first two years, a conscious decision was made not to implement the K-12 earthquake education program. For the same reason, no special emphasis was put on the Center's involvement with the undergraduate education. The urgency of these programs however, is now widely acknowledged. A SCEC Student Summer Internship Program for Undergraduate Students is being planned; it is scheduled to take place next summer. A comprehensive program has been proposed for grades K-6, grades 7-12 and undergraduate students.

In summary, the Site Visit Committee is satisfied by the progress SCEC has made in the broad area of outreach, and it is encouraged that grades K-12 and undergraduate education will now become a high priority program.

LINKAGES TO OTHER SECTORS (Academic, Federal, State and Local Governments, National Laboratories, Industry) AND KNOWLEDGE TRANSFER

The active participation of all seven of the core institutions in the research and educational programs of SCEC is the strongest link to the academic sector. The site visit team was pleased to learn that SCEC is viewed as an asset by the administrators of the core institutions with whom they met. An additional 11 institutions (eight from outside of California) are participants in the SCEC program. SCEC has demonstrated that it is an effective mechanism for coordinating research and promoting the exchange of ideas among productive university researchers. The program of visiting scientists provides a further link to the national and international scientific communities.

The SCEC data centers are a national asset. They are important not only for their content, but also for their potential to serve as a model for data center operation in the academic setting. The data centers serve as a natural link between SCEC and the community of data users.

SCEC is viewed at the national, state, and local levels as an important asset. The primary tie at the national level is with the USGS. The close everyday collaboration of working scientists is beneficial to all parties. SCEC research and outreach programs contribute strongly to the goals of the National Earthquake Hazards Reduction Program, in which NSF, the USGS, FEMA, and NIST are participating agencies. In particular, the USGS has come to depend on SCEC as a partner in carrying out its earthquake-related mission in southern California.

The financial support of SCEC efforts by FEMA is an indicator that that agency values the Center. Interactions should increase as the SCEC program in outreach matures.

The products coming from SCEC are sensitive because of their societal impact. For that reason, the review of those products by the National and California Earthquake Prediction Review Councils (NEPEC and CEPEC) is prudent. This interaction also provides an additional link to the external communities.

SCEC efforts in engineering applications are supported by the California Division of Transportation, the City of Los Angeles, and the County of Los Angeles as mentioned above. SCEC has also established good working relations with the California Office of Emergency Services (OES) and the California Division of Mines and Geology.

The primary relation to the private industrial sector is through the participation of four companies as investigators. SCEC products will impact several industries, including construction, banking and insurance. It is desirable that the Center establish links with these industries. Progress in this direction appears imminent, because ties are being established with a number of organizations related to engineering applications which were described during the site visit.

In the area of knowledge transfer, SCEC is recognized in California, and especially in the Los Angeles area, as an authoritative source of information about earthquakes. The Phase I report on the immediate implications of the Landers earthquake was reviewed and approved by NEPEC and CEPEC. It was distributed through the OES. The response to the Phase II report will be a good test of the effectiveness of the SCEC approach to knowledge transfer. The record of SCEC scientists in publication of their research results in the scientific literature is very good. The regular workshops and seminars are also effective in communicating within the scientific community.

Much remains to be done in communications with the professional community and with the general public. The implementation of the current plans for the outreach component of the program will overcome this deficiency.

MANAGEMENT AND LEADERSHIP

The management team of Aki and Henyey is viewed by the site visit team to be capable and effective in SCEC's operation. Their talents are highly complementary and provide an exceptional resource for SCEC. The visiting team found abundant evidence of the confidence placed in the management team by the member institutions. The collaborative focusing of effort on earthquake hazards in southern California by the diverse core and participating institutions is a major success of SCEC, and is a highly visible indicator of the effectiveness of management. Cooperation between the USGS and the university community has been improved by the creation of SCEC. SCEC is in a unique position to play a leadership role in a number of aspects of earthquake science and technology, and the management team appears to be prepared to exploit this position. Infrastructure development such as the regional data centers, GPS network, rapid deployment instrumentation, and outreach programs could not have happened in a coordinated fashion without the SCEC leadership. A tribute to the SCEC leadership is the enthusiasm for SCEC objectives and programs among the investigators and students.

Based on evidence from the reports of the SCEC Advisory Council, past site visit reports, and other data provided to the site visit team, the SCEC management has been highly responsive to recommendations and concerns of advisory groups. Although the educational component of the outreach program has been viewed as needing strengthening, the management team has responded vigorously with a plan that the site visit team found to be both detailed and effective.

Under the SCEC leadership a highly effective matrix approach has been developed to manage both tasks and products of SCEC. The matrix approach is utilized effectively for both operation and funding decisions. Discipline group leaders are recognized leaders in their fields, and the groups have contributed directly to defining the goals and products of SCEC. The site visit team supports the Center's decision to continue with this management mode.

INSTITUTIONAL AND OTHER SECTOR SUPPORT

The SCEC continues to be strongly supported by the core institutions. Discussions with officials from each of the universities confirmed their satisfaction with the SCEC's progress. They also acknowledged the synergism resulting from the institutions' interaction.

The USGS is a major financial supporter of SCEC. In addition, FEMA provides support for outreach activities. Caltrans, the County of Los Angeles and the City of Los Angeles are continuing their substantial financial support to the SCEC engineering group through funding of an engineering applications project.

Strong ties continue between SCEC, state, county and city organizations. A memorandum of understanding has recently been signed between the SCEC and the California Governor's Office of Emergency Services. This association is expected to enhance continuing efforts in the area of earthquake response planning and preparedness. Strong support to the SCEC is also being offered by the California Division on Mines and Geology through the State Geologist. He has an active interest in the progress of the SCEC and has noted that his organization can offer access to their data base and can assist in post-earthquake clearinghouse activities when necessary.

The SCEC directors have indicated that they are interested in leveraging the Center's project experience to actively seek funding from private enterprise in the future.

BUDGET ANALYSIS

The SCEC continues to serve as an essential focal point for earthquake studies in southern California. It has been extremely effective in leveraging its direct support against member institutional support and support of individual scientists and consultants.

In the past, budget cuts have resulted in the need to compromise infrastructure, particularly the educational outreach program, and science programs. The Center has a continuing need to expand its education and outreach component, enhance their facilities through equipment acquisition, and extend its data acquisition and master model development to a larger part of southern California. The Center's response to the Lander's earthquake is an example of an activity that put an unexpected and severe strain on the SCEC's budget. Response to future earthquakes will do the same.

The site review committee is pleased with the science that has been accomplished to date given the budget constraints. The SCEC management team has done a remarkable job in meeting the Center goals given these constraints. The site visit team is also favorably impressed that a large portion of the budget goes for the support of students.

The funding request is appropriate when compared to the Center's strategic plan. It is extremely important that the SCEC be funded at the requested level. A reduced funding level could have a detrimental affect on current SCEC programs, cause some scientists to reconsider their participation in the Center's programs and delay the start of other necessary project activities.

RECOMMENDATION

The site review team unanimously recommends that the SCEC be awarded full support as requested with no significant reservations.

SITE VISIT REPORT

SOUTHERN CALIFORNIA EARTHQUAKE CENTER

SIGNATURE PAGE

SEPTEMBER 2, 1993

Dr. John L. Aho, CH2M Hill

Robert S Crosson Prof. Robert S. Crosson, University of Washington

Carl Kisslinger Prof. Carl Kisslinger, University of Colorado

Charles A. Langston Prof. Charles A. Langston, Pennsylvania State University

Francis T. Wu Prof. Francis T. Wu, SUNY at Binghamton

NSF STAFF

James H. Whitcomb Dr. James H. Whitcomb, Program Director for Geophysics

U.S. GEOLOGICAL SURVEY SITE VISIT OBSERVER TEAM

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USGS Coordinator for the SCEC, Acting Coordinator for NEHRP

Dr. Wayne R. Thatcher
Geophysicist, Menlo Park Office

Dr. John Simms
Deputy for External Research Program

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA 22092

In Reply Refer To:
Mail Stop 905

September 22, 1993

Dr. James F. Hays
Division Director, Earth Sciences Division
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

Dear Jim:

It is my pleasure to convey to you the following report and recommendations of the U.S. Geological Survey (USGS) relative to the Southern California Earthquake Center (SCEC, or the 'Center'), which is, as you know, a science and technology center jointly funded by the National Science Foundation (NSF) and the USGS. We understand that the NSF is now considering a proposal from SCEC for a 5 year extension of the initial 5-year award (fiscal years (FY) 1991–1995). As part of the consideration of that proposal, a site review was carried out by the NSF and the USGS on September 1–2, 1993. Our recommendations are based on that site review, the submitted proposal, written reviews provided to us by the NSF, and our own experience with SCEC since its founding in 1991.

The USGS has participated in SCEC in two ways. First, we have joined with NSF in funding the university participation in the Center. This funding has been at the levels of $1.88 million in FY 1991, $1.15 million in FY 1992, and is $1.25 million in FY 1993. Our intention is to fund SCEC at the level of $1.2 million for FY 1994. In addition to the direct support of the Center, each year the USGS has also awarded external research grants to non-USGS investigators for work in southern California. For example, in FY 1993 the USGS is providing $3.26 million for external grants for southern California work.

The second way in which we participate in SCEC is through the direct participation of the USGS employees, particularly through our Pasadena Field Office. The USGS directly funds the salaries and support for our employees and have, in fact, increased that support since the establishment of SCEC. The USGS

SEP 24 1993

currently provides $3.76 million in salaries, research support, and network operations for internal USGS activities in southern California.

THE NEED FOR THE CENTER

Prior to the establishment of SCEC, both the NSF and USGS supported research by individual investigators at various institutions in southern California through our respective parts of the National Earthquake Hazards Reduction Program (NEHRP). Although this research was of generally very high quality, the USGS had a number of concerns. First, we perceived a lack of integration and focus when viewing the investigations as a whole. Second, we perceived that the interconnection between the academic researchers in the region on the one hand, and government officials and the public on the other hand, were not as strong as was desirable. Third, we were concerned that data from major capital investments and operational costs, such as the largely USGSfunded Southern California Seismic Network, were not adequately shared among researchers at the various institutions. Finally, we were concerned that the sum of resources available for earthquake research in this critical region from both the NSF and USGS was not adequate to the needs.

We believe that the establishment of the Center has produced remarkable progress in addressing each of these concerns while contributing significantly to the advancement of knowledge of earthquake hazards in southern California. The Center has become the focal point for virtually all the earth science researchers working on earthquake problems in southern California, allowing for a more comprehensive integration of efforts and results than had heretofore been realized.

The establishment of SCEC has also resulted in far more interaction among investigators and institutions with State and local governments, industry, and the public. In addition, the engineering community has now begun to directly interface with the Center, which can provide both significant user input as well as a means of effecting hazards reduction in southern California. These new linkages have provided for more efficient access and sharing of data collected by the Southern California Seismic Network and other specialized monitoring arrays.

FINDINGS

Successes and Strengths

We have recognized a number of successes and strengths of the Center that deserve special emphasis. First, the Center has provided a highly effective organizational umbrella under which to plan cooperative activities, to provide a forum for discussing results and outstanding unresolved issues, and to transmit research products to users for hazard mitigation. The establishment of the Center has stimulated the initiation of new scientific programs, such as the Global Positioning Satellite (GPS) surveys to map earthquake-related movements of the crust across southern California and the intensive geological and geophysical studies of the complex active faulting within the Los Angeles Basin.

Notable scientific findings made in the short life of the center include: identification of active faulting at the foot of the Hollywood Hills and Santa Monica Mountains; utilization of the results of the GPS surveys to generate maps of southern California crustal deformation rates and velocities; determination of enhanced earthquake potential on faults of the San Andreas fault system adjacent to the rupture of the 1992 M7.4 Landers earthquake; and imaging the subsurface geologic structures beneath the region to model the current tectonic regime.

As SCEC has matured, the collaborative relationship among the member universities and the USGS has been enhanced. The USGS has for several years worked with Caltech to operate the Southern California Seismic Network. Now the scientists at a number of universities have fast and easy access to the data collected and processed in Pasadena. In addition, the USGS is benefiting from the Center in being able to conduct cooperative GPS surveys, collaborate in the compilation of geologic GIS data bases, have an effective partnership to respond to damaging earthquakes (such as the Landers earthquake), interact with a broader assemblage of research scientists and engineers, more efficiently reach consensus on critical public policy issues, and work creatively on outreach efforts.

For the past 15 years, the USGS has supported research by individual investigators working on earthquake hazards problems in southern California as part of the USGS external research grants program. The USGS intends to continue that program. The establishment of SCEC has significantly improved the effectiveness of ongoing individual research grants for earthquake research in southern California from the NSF and USGS through improved access to data, through expanded communication among researchers owing to the leadership provided by SCEC, and through the high level of excitement in the research community stimulated by the Center.

From its inception, SCEC has had as its underlying goal—to integrate the research findings from the various earthquake-related scientific disciplines into the development of a probabilistic seismic hazard model, or Master Model, for southern California. The Landers/Big Bear earthquakes added an impetus to that goal, resulting in the Phase I (1-year time frame implications for the local region) and Phase II (30-year time frame for the southern California region). It is unlikely that the breadth of data could have been efficiently collected, the rigorous analyses conducted, and the most important consensus reached in published form without the existence of SCEC.

We believe that, ultimately, effective public actions to reduce the risk from earthquakes will be motivated by the clear and persuasive communication of the emerging scientific understanding of earthquakes and the hazards that they present. This is particularly true in southern California, the most populous region in the United States subject to a high level of earthquake hazard. The establishment of SCEC presents a superb opportunity for the earth scientists to achieve this communication; the Phase I and Phase II reports present tangible evidence that the Center is taking the responsibility to communicate in a timely and responsible manner. SCEC has made substantial advances in developing the needed communication skills and linkages, and the USGS looks forward to working closely with SCEC to make further progress in this area.

Areas Requiring Additional Attention

We believe that outreach activities are critical to the success of the Center. An important aspect of outreach is education. Because there are so many different options for educational outreach, we feel that the Center needs to identify a few key topical areas where it feels it can make substantial contributions, e.g. undergraduate education, summer intern programs, secondary schools, and adult education. Future work can build on these successes, focusing on broader issues. The involvement of minorities and women in these educational opportunities needs to be emphasized.

Communication of research findings to the user community is another aspect of outreach that requires continual attention. The research community must be fully engaged with the users to insure that the appropriate work is being conducted and that the results of that work are translated into usable formats. We recognize that the present engineering effort would probably not have occurred without the presence of SCEC, and we are encouraged by the movement toward better integration of science and engineering in the Center. We look forward to seeing increased involvement of engineers in the main body of SCEC research activities, particularly in the area of strong ground motion research and its application to design and code issues.

We are concerned that the integration of research in earthquake physics into the formulation of the Master Model has progressed slowly. The current work is focused on conventional concepts of strike-slip and thrust fault mechanics, as well as pattern recognition studies. The studies have used modeling which does not necessarily accurately characterize the tectonics in the region. Although the currently supported work is interesting, we hope that the scope of supported research will be broadened to include a wider array of approaches that will address the complex Los Angeles basin tectonics.

Southern California Earthquake Center

5-Year Plan from 1993 NSF Proposal

General Statement

The Southern California Earthquake Center has emerged as a focal point for new earthquake research in southern California. Although the center is strongly mission-oriented, it continues to nurture the important elements of basic science. These include: 1) interaction and controversy, 2) curiosity and creativity, and 3) following promising new avenues of research. These elements evoke a dynamic scientific environment in which the research directions of the center are under constant review. Our workshops, annual meetings, and project-funding process serve to define the specific directions and mix of disciplinary research on a year-to-year basis. Thus, in this section we discuss, generally, the plans of the center over the next five years.

We can say with conviction that the long-term goals of the center will continue as originally conceived --

- To develop a socially useful prototype probabilistic seismic hazard model (master model) for southern California by promoting research in the various earthquake-related scientific disciplines (geologic, geophysical, geodetic, seismological, geotechnical), and integrating the findings of this research through structured interaction among the center's scientists, and
- To communicate the essence of the master model to a targeted community of users, including emergency preparedness officials, policy makers, practicing engineers, and the general public.

These goals have been cast in the context of six primary tasks in our strategic plan as noted earlier. In this section we develop the essence of the strategic plan over the next five years -- specifically the disciplinary research and integration needed to address these tasks. At this time, we do not anticipate adding additional assignments to the center over the next five years. Instead, our strategy will be to constantly update the output from the six tasks, in response to new data and ideas. As work progresses on these tasks, various products will result -- these are the center's milestones and can be identified in the discussion below. Because of the need for communication with our user communities, we recognize two levels of products -- scientific products and outreach or user products. Scientific products result when certain lines of research reach intermediate or final stages of completion, and then may be used in one or more of the following ways:

- As input to more advanced scientific research along similar or expanded lines,
- In combination with other scientific results to develop more complex or higher level scientific products, or
- As the basis for an outreach or user product.

An outreach or user product is one identified by the center's education and outreach component as ripe for transmittal to the center's user community -- e.g., earthquake engineers, emergency preparedness officials, schoolchildren, the general public, etc. As such, future planning for the center includes establishing mechanisms for identifying and developing user products from among the scientific products. This process and the resulting products are the responsibility of the center's education and outreach staff and its

Tasks 1 to 5 Over the Next Five Years

In the following sections we describe our five-year plans for addressing the six tasks. Included in this discussion are the inputs from the various working groups, and the scientific products or milestones. Table 2 indicates how we do the budgeting for the various scientific tasks (note that neither the expenditures for Task 6 -- post earthquake studies -- nor for infrastructure are shown). Each disciplinary group has responsibilities under one or more tasks. The three panels from top to bottom are for years 1, 2, and 3, respectively. We expect to continue budgeting in this way, and expect that the proportions will be about the same for year-4. Final decisions on the relative mix are made during our annual review and budgeting process which begins with an annual meeting in the fall and is completed with a final decision by the Science Director in January. Our fiscal year begins the first of February.

Task 1 Construct Maps of Probabilistic Seismic Hazard for Southern California

With the publication of the Phase II report scheduled for release in fall, 1993, we will have completed the first-generation master model for southern California. Through our work on the Phase I and Phase II reports, the center gained experience in generating public policy documents regarding earthquake hazards. If another earthquake comparable to Landers occurs in southern California in the next five years, we plan to produce documents similar to the Phase I and Phase II reports. Our scientific response plan to such an earthquake is described later. Here we assume that there will be no such event in the next five years.

In the next five years, we shall improve and update the data bases to be used for constructing the second-generation master model at the end of the period. For this purpose, we define four subtasks:

- Task 1A: Construct a data base for characterizing earthquake sources in southern California.
- Task 1B: Construct a library of Green's functions for characterizing propagation-path effects in southern California.
- Task 1C: Construct a data base of meso-scale site amplification factors at various frequencies and basement accelerations for southern California.
- Task 1D: Develop the methodology for probabilistic seismic hazard analysis.

Task 1A As described previously, our master model will integrate the paleoseismic and neotectonic data on potential earthquake faults, the historical and seismological data on past earthquakes, and the geodetic data on regional strain accumulation. During the next five years, we shall improve the precision, reliability and regional coverage of these data sets. Group A will be responsible for this task, with assistance from Groups C, E, and F for the geologic, geodetic and seismological data, respectively. This subtask will also address the issue of appropriate seismic source zones, and improve upon the zones used in the Phase II report as needed. It will be done in consultation with the earthquake engineering community. The first such workshop is scheduled for September, 1993.

Task 1B This task represents an innovative approach toward characterizing the propagation-path effects on ground motion. Ideally, we would like to have a library of empirical Green's functions for every arbitrary source point and arbitrary recording site in southern California. Since this is unrealistic, we will use the 3-D structure assembled by Group D to interpolate between the large number of seismograms of small earthquakes (empirical Green's functions for actual source-receiver pairs) stored at the SCEC data center to obtain the Green's function for the desired source-to-receiver propagation path. For interpolation we will use wave theory based on the known 3-D structure. In the case of P-waves, for example, we may apply the so-called phase-screen method recently introduced in elastic-wave seismology to the 3-D velocity structure of the crust and upper mantle under southern California. For S-waves, we may not be able to construct a library of wave-forms because we still don't have a well-established 3-D S-wave velocity structure. In this case, we may have to be satisfied with a library of the envelope of spectral amplitudes, which will be sufficient for earthquake engineering purposes. With respect to the coda part of the empirical Green's function, we already do have a library of site amplification factors covering southern California in the form of a GIS-based map as noted earlier.

In the first year of the 5-year period, we shall develop the methodology for constructing the library of “empirical” Green’s functions as well as for the interpolation procedures based on the known 3-D structure. A workshop will be organized in the first year to debate and reach agreement on methodology and procedures. In the second year, we plan to develop the algorithm and computer program, based on the workshop’s outcome. Development of the library of Green’s functions will be continued in the third and fourth years to develop as complete a data base as possible for constructing the second-generation master model in the fifth year.

Task 1C This task continues a SCEC project to construct maps of site amplification factors for southern California. We have already completed maps for the weak-motion amplification factors at 1.5, 3, 6, and 12 Hz using coda waves recorded at the southern California Seismic Network, together with empirical relations between surface geology and site amplification factor. We will modify these maps to be applicable to strong motion by accounting for non-linear soil response. At the same time, we shall verify these maps against empirical results for past and future earthquakes. The mesh-size of the map will be meso-scale, about 5 km, to serve as a regional reference for practicing seismic hazard analysts. These maps will be constantly improved for their accuracy, reliability and areal coverage in the next five years.

In addition to the above maps for frequencies higher than 1 Hz, we shall continue to study the site response at long-periods up to 10 seconds. For this purpose, we already have microseismic data obtained at 148 sites in the LA basin, as well as earthquake data at the broadband TERRAscope stations. We shall expand the database to cover a broader region of southern California in the next five years.

Task 1D Integrating three different data sets in our Phase II report (geologic, geodetic and seismological) is a new way of estimating probabilistic seismic hazard. We need to improve the method for better communication of earth science information to our user communities.

We also need to incorporate the physics of the earthquake processes to gain more confidence in our hazard estimation. We plan to develop a “physical” master model for earthquakes in southern California in the next 5 years as described later (see Task 3A). A marriage of the “hazard” and “physical” master models will provide the foundation for constructing the second-generation master model in the 5th year. Task 1D will develop the method for incorporating the physics of earthquake processes in the seismic hazard analysis.

Task 2 Develop Plausible Earthquake Scenarios Emphasizing the Los Angeles Basin

This task represents SCEC's regional focus on multidisciplinary research toward plausible earthquake scenarios. These scenarios will start with earthquake source characterization using geologic, geodetic and seismological observations, and will predict strong ground motion, taking into account the propagation-path and local site effects in more detail than in Task 1. In some cases, individual earthquake scenarios will be developed for probable earthquakes affecting large populations.

Several groups will contribute to this task through data collection, interpretation and/or modeling. Group B (ground motion) will contribute by: 1) extracting site amplification characteristics from weak and strong motion data, 2) reevaluating existing strong motion relationships by various methods, and 3) developing deterministic and stochastic methods for ground motion simulation, including the discrete wave number, Gaussian beam-boundary element, and finite difference methods. This group will also study the earthquake rupture process from near-source observations in cooperation with Group F (seismicity and source process).

Group C (earthquake geology) will continue collecting basic data on potential earthquake faults, including: 1) the style of fault (strike-slip or dip slip; normal or thrust), 2) characteristic slip, 3) segmentation properties, 4) slip rate, and 4) dates of past earthquakes. Over the next two years the group will finish up their work on the Elysian Park - Santa Monica Mountains fold and thrust belt which includes a number of major buried thrusts as well as structures which cut the surface, including the Coyote Pass, MacArthur Park, Hollywood, Santa Monica, and Malibu faults. We also propose to explore ancient ponded swamp deposits in the west Los Angeles area (La Cienega) as a possible source of dates on buried thrust events. In the subsequent three years, work will shift northward to the Verdugo Mountains/Sierra Madre frontal fault system of the San Gabriel Mountains, and westward to the Santa Susana/San Cuyatano fold and thrust belt of the Ventura basin. To date, studies of the Santa Monica Mountains uplift have focused on structures along the southern flank of the range; in the future added emphasis will be placed on the range as a whole (Santa Monica fold and thrust belt), and relationships to the more northerly Sierra Madre and Santa Susana fold and thrust belts. These studies will address important questions of fault segmentation and multiple fault rupture within the Transverse Ranges. Group C will also assemble a detailed fault and Quaternary geologic map of the Los Angeles basin. The map will both emphasize slip rates, dates of previous earthquakes, and styles of faulting, including blind thrusts, and distinguish between various types of surficial materials for characterizing site effects.

Group D (subsurface imaging and tectonics), in cooperation with the USGS (Menlo Park), is just beginning a ~200 km long regional crustal structure profile extending from Barstow to Santa Catalina Island and crossing the eastern San Gabriel Mountains and Los Angeles basin. The first data will be acquired in Fall, 1993 using shots fired into a 100+ km land seismic receiver array. A second phase of data collection will occur in Fall, 1994 when the Lamont-Doherty seismic research vessel R/V Ewing will be used to fire a ~10, 000 cu. in. tuned air gun array into a 200 km seismic line consisting of onland and ocean bottom seismometers. Reprocessed industry data (raw Texaco data already in hand) will be used to fill gaps along the profile in the Los Angeles basin proper.

The objectives of the project are to: 1) define the velocity structure along the profile, 2) image possible low-angle structures beneath the Transverse Ranges and Los Angeles basin, 3) define the shape of the Los Angeles basin, and 4) look for evidence of crustal discontinuities across the major fault systems including the Newport-Inglewood, Sierra Madre, and San Andreas faults. A NW-SE line perpendicular to this profile -- along the long axis of the Los Angeles basin -- is tentatively planned for the future, depending on results from the 1993-94 survey. In addition to providing information on velocities and the 3-D structure of faults beneath the Los Angeles basin and Transverse Ranges, the results of this survey will be used to improve our estimates of propagation-path effects in these regions.

Group D is also working with Group C to explore the integration of paleoseismicity-neotectonics and shallow high-resolution seismic reflection work to characterize active faults. An initial workshop is scheduled for August to: 1) review past work of this type by USGS/SCEC/UCR on the Palos Verdes and Elsinore faults in southern California, 2) review similar work by the USGS in other parts of the U.S., 3) explore future needs in southern California, and 4) review the methodology. If the workshop results in positive recommendations, the center will consider more extensive use of high-resolution Mini-Sosie (or equivalent) surveys to map the upper parts of faults in conjunction with the paleoseismic and neotectonic work.

Group E (crustal deformation) will improve the resolution and accuracy of the crustal strain maps of the Los Angeles and Ventura basins over the next 5 years, and develop a detailed model relating observed strain to buried fault slip. This will allow geologic and geodetic data to be compared meaningfully, and provide slip rate estimates on faults inaccessible to paleoseismic investigation.

Group F will continue deterministic and statistical studies of the temporal, spatial, size, and focal mechanism distribution of earthquakes. It will implement the new 3-D velocity model of southern California to analyze seismicity. This group plans to analyze the new broadband TERRAscope data together with strong motion data to further our understanding of faulting, state of stress in the fault zones, slip heterogeneity, and fault friction. This group also plans to synthesize a new regional seismotectonic model consistent with the spatial and temporal patterns of historic earthquakes . The model will also facilitate interpretation of geodetic and geologic data relevant to seismic source characterization.

SCEC has chosen southern California as the natural laboratory in which to apply the multidisciplinary approaches described above. This region is most appropriate since the product of population density times earthquake hazard -- i.e., earthquake risk -- is higher than anywhere else in the U.S. However, limited resources have required the center to develop a sharper focus, so priority in the first two and one half years has been given to the Los Angeles basin. We expect to spend the next five years completing our data collection efforts here, developing a set of earthquake scenarios, and completing a seismic hazard analysis of the region.

We wish, however, to extend our focused research beyond the Los Angeles basin as time and resources permit, initially toward the San Bernardino area to the east and the Ventura area to the west, and eventually to the entire Transverse Ranges structural province. Regions to the east include the eastern San Gabriel Valley, the San Bernardino Valley, and the Riverside area. Important faults are the eastern Sierra Madre, northern San Jacinto, and the San Bernardino Mountains segment of the San Andreas. The Landers earthquake increased the stress toward failure on both the San Andreas and San Jacinto fault segments, and WGCEP 88 reported relatively high probabilities of a major earthquake on these segments in the next 30 years.

To the northwest is the Ventura basin and a number of major active east-west trending structures including the Santa Susana, San Cayatano, Oak Ridge, and Santa Ynez faults. Geologic and geodetic data suggest that convergence across the Ventura basin may be as large as 10 mm/yr. Based on the Landers earthquake as well as comparisons of the Transverse Ranges with similar structures in other parts of the world, the probability of more than one of these faults breaking in a M7 to M8 earthquake cannot be discounted. In fact, such a rupture could propagate eastward onto similar east-west trending structures along the northern flank of the Los Angeles basin discussed earlier. While these events may be rare with recurrence intervals on the order of thousands of years, they would be devastating.

The center will develop a set of seismic hazard scenarios for the Los Angeles basin, starting with a M7.5 on the Santa Monica-Malibu fault. This scenario will have its first exposure at the SSA/EERI annual meeting in Pasadena next year (1994). Next, we will develop several scenarios for the San Andreas fault, involving rupture of different combinations of the Mojave, San Bernardino Mountains, and Coachella Valley segments. These scenarios will be extended to include all of southern California. We will also consider M6.5-7.5 projections for the Palos Verdes and Whittier faults which pose major hazards to the coastal plains of southern Los Angeles and Orange counties.

Task 3 Study Fundamental Relationships Among Fault Structures, Dynamics, and the Earthquake Recurrence Process

This task is at the heart of developing our master model. Through it we gain a deeper understanding of the seismogenic structures and the earthquake processes in southern California, which, in turn, will give us greater confidence in the information we deliver to the general public and other users. An example of this task is studying the fault segmentation which occurred in the Landers rupture. SCEC attacked the problem using various observations including: surface geology, trenching, GPS measurements, seismic source inversion, foreshock and aftershock locations and focal mechanisms, tomographic imaging, and properties of seismic guided waves trapped in the fault zone. Important controversies are being raised by these different approaches with regard to how fault segments connect at depth, such as in the gaps between the Emerson and Johnson Valley faults, and across the Pinto Mountain fault. Resolving these controversies -- so fundamental to the interrelationship between fault zone structure and the rupture process during failure -- will improve our understanding of the earthquake process.

If another Landers earthquake occurs during the next 5 years, we will again perform detailed multi-disciplinary studies of the fault zone structure. In the absence of such an event, we shall adopt three targets for task 3:

- Task 3A: Detailed study of the 3-D fault zone structure for selected fault segments.
- Task 3B: Development of the "physical master model".
- Task 3C: Study of the regional stress field in southern California.

Task 3A This task continues the multidisciplinary study of 3-D fault zone structure initiated on fault segments that slipped during the Landers earthquake. It is fundamental to characterizing the 3-D geometry and physical properties of fault zones needed for constructing a physical master model. For example, the width of the fault zone in the Landers rupture was estimated to be about 200 m based on observations of seismic trapped modes. This thickness is consistent with the value of the source-controlled f_{max} (10 Hz) that gave good agreement between observed and predicted strong ground motions generated by the same earthquake. If this fault zone thickness reflects the size of the break-down zone (or cohesive zone in fracture-mechanics terminology), it may be related to the critical weakening displacement that controls various aspects of the failure process including precursory slip.

Numerous observations of earthquake phenomena suggest the existence of characteristic scale lengths shorter than the commonly accepted thickness of the brittle upper crust (10-15 km). For example, the commonly observed short rise time (shorter than that expected from a smooth crack over the brittle zone thickness) for major earthquakes in California has been attributed to distributed heterogeneities or to the healing process with a short characteristic time (or length). Other examples include: 1) the departure of the scaling law of seismic source spectra at magnitudes smaller than a certain threshold, 2) the strong correlation between the temporal change in code Q^{-1} and the fraction of the number of earthquakes within a certain magnitude range, 3) a kink in the magnitude-frequency relation, 4) small faults crossing a major fault as revealed by detailed mapping of fault plane solutions, and 5) the existence of critical threshold magnitudes for precursory seismicity bursts.

Task 3A will investigate all these intriguing observations over the next 5 years with a focus on selected fault segments. The task will involve: 1) seismic tomographic imaging using local earthquake data, 2) collection and analysis of seismic trapped mode data, 3) determining scaling laws of seismic source spectra for small local earthquakes, and 4) detailed mapping of focal mechanism solutions to delineate subfaults. In the first two years, we shall continue to work on the Landers rupture using the wealth of data already in place at the data center. We shall then shift our focus to the San Bernardino Mountains segment of the San Andreas fault in the third year, to the San Bernardino Valley segment of the San Jacinto fault in the fourth year, and finally to the Mojave segment of the San Andreas fault in the fifth year.

Task 3B As described in the section on achievements, we believe that with the completion of the Phase II report, we will have integrated research findings from geology, geodesy and seismology in the form of a first-generation prototype probabilistic seismic hazard model. In this first-generation master model of seismic hazard, integrating the various earthquake-related science disciplines was made in the end product. In this sense, we may call it the "hazard master model". In Task 3B we would like to develop a "physical master model" which would provide a physical basis for our "hazard master model". That is, we would like to explain all observations relevant to earthquakes in southern California in terms of the physical properties and conditions in the earth's crust, and thus gain confidence in predicting future seismic hazards in southern California.

We feel that the building blocks needed to construct the physical master model have accumulated during the first two and one half years of SCEC. For example, the subsurface imaging group feels that the first-generation P-wave tomographic image of the crust and upper mantle for southern California has been completed, and the next step is to construct kinematic and dynamic tectonic models using the finite element method. The choice of elements can be made compatible with the seismic source zones used for hazard estimation in the Phase II report and described earlier in the section on achievements.

In addition to the 3-D seismic velocity structure and distribution of hypocenters, we now have an extensive data base of fault plane solutions. A 3-D display of the different types of source mechanisms reveals striking patterns of fault zone structures and stresses operating in various parts of southern California. The stress redistribution by fault slip and the resultant change in the Coulomb failure criterion is another tool for understanding space and time dependent seismicity. The new velocity field for southern California determined from the dense GPS network naturally calls for more elaborate tectonic and stress modeling than attempted earlier.

All these developments suggest that it is time to construct a "physical master model" for southern California. However, as described in the section on achievements, the earthquake physics group found the following considerations essential in developing a useful model for seismicity simulation:

- The model must be at least 2-D to allow for interaction among faults.
- The choice of constitutive laws for fault instabilities is fundamental.
- Faulting does not take place on smooth singular surfaces.
- Quasistatic simulation misses important elements of dynamic rupture.
- End barriers which define the maximum earthquake of a given model cannot remain forever undeformed.
- The significance of the loading boundary condition needs to be considered.

Considering all the items enumerated above appears impossible in the foreseeable future. To develop a strategy for approaching this seemingly impossible task, we will organize a workshop in the first year of the 5-year period to discuss the various elements of the physical master model.

We must first clearly define the crust and upper mantle system under southern California. We introduced 58 seismic source zones for the hazard master model. Our starting point for the physical master model may be to focus on some of these source zones. If a source zone contains a fault, we need to define the constitutive law for fault instabilities. The source zone may be inhomogeneous and the fault plane may be irregular. We also need to define how the loading is applied to the system. Unstructured finite elements may provide the necessary adaptivity and multiscale resolution needed to deal with such a problem. The non-linearity of the constitutive relations and inhomogeneities rule out the integral equation and other dimension-reduction methods. Irregularity, multiscale behavior, and complex geometry rule out structured finite difference and spectral methods. Thus, we are led to unstructured finite element methods for our physical master model development.

The workshop will consider the choice of the finite element mesh, constitutive laws, fault geometry, inhomogeneities, and loading mechanism, as well as the computation methods. We need to survey the available finite element software using supercomputers or super minicomputers. We may seek expert assistance in this area (some SCEC visitors are involved in developing computational methods for unstructured finite elements using parallel computing systems).

The second year will be devoted to developing algorithms and computer programs. In the third year, the algorithms will be applied to a pilot area involving a small number of seismic source zones, and in the fourth year to a broader area. The output of the computer simulation will be crustal deformation, stress and seismicity, which can be compared with seismological and geodetic observations. Such comparisons may offer a physical basis for some of the empirical relations used in constructing the hazard master model. This marriage between the hazard and physical master models is planned for the end of the 5th year when we construct the second-generation master model.

Task 3C The time is ripe for SCEC to make a major effort over the next five years in understanding both the state of stress and changes in the stress field (and fluid pressures in fault zones) in southern California. This effort would greatly contribute to the master model and is timely in light of : 1) computed changes in stress along the southern San Andreas and northern San Jacinto faults resulting from the Landers earthquake sequence, 2) findings that bends in master faults like the southern San Andreas drastically affect the state of stress in nearby areas, 3) the success of computations of changes in the Coulomb failure stress in understanding rates of occurrence of both small and moderate size earthquakes before and after large quakes, 4) the developing consensus that fluid pressures and the state of effective normal stress is different within major fault zones from that in surrounding areas, and 5) the use of thousands of focal mechanisms in mapping small faults, styles of faulting, and temporal variations in maximum compressive stress on a fine scale.

We plan to develop a model of southern California that includes all major active faults. Boundary stresses can be constrained by GPS measurements, VLBI, and other goedetic data, and residual stress determined by simulating movement on the faults constrained by geological slip rates and the record of large earthquakes both from paleoseismic and historic data. The model would then be updated by the adding data from microearthquake focal mechanisms, borehole breakouts and other stress indicators, GPS and other geodetic measurements, ongoing paleoseismic investigations, and future seismicity data. Thus the model will serve as a vehicle for synthesizing and interpreting many kinds of data being gathered by SCEC.

Finally, most physical models of changes in the earth imply precursory effects to large earthquakes (on time scales of months to about a decade) which are likely to have tensor properties. Thus far, however, most work on changes in seismicity have examined changes in scalar functions like the number of earthquakes, release of seismic moment, or various "traits" in the temporal and spatial patterns of seismicity. The response to tensor forcing functions such as changes in stress are likely to involve seismic quiescence in some places and enhanced activity in others.

This task represents a segment of the physical master model (Task 3B) which is amenable to practical application, and thus clearly cuts across Tasks 2 and 4 as well.

Task 4 Develop and Test Intermediate-term Earthquake Prediction Methodology

An important capacity of a center is the ability to protect promising areas of research at rudimentary stages of development. In the case of SCEC, an obvious example is research on intermediate-term prediction. The rationale for considering intermediate-term prediction is that the stakes are extremely high. That is, if reliable earthquake predictions could be made over the intermediate-term (weeks to years), their impact on society would be tremendous. As noted by an eminent social scientist, earth scientists tend to avoid working on this subject fearing its impact on society. There is a need to put this risky endeavor under the umbrella of the center. Since this task will take a long time due to the intrinsic slowness of geologic processes, its focus will remain the same for the next five years.

We propose to continue testing two algorithms, namely the M8 algorithm for identifying the so-called TIP (time of increased probability) for the next five year period, and a monthly prediction of the maximum magnitude using the method of Artificial Neural Networks (ANN).

We intend to increase the data base beyond the catalog of earthquakes to include the waveform data of the Southern California Seismic Network now readily available from the SCEC data center. For example, the space-time variation of coda Q^{-1} (which showed a strong precursory anomaly before both the Loma Prieta and Landers earthquake) can be routinely included in the ANN analysis. Also, the planned growth of the permanent GPS array in southern California with more concentration along major faults will produce data on strain accumulation which can be included.

We continue to seek the physical basis for some of the phenomenological precursors by seismicity simulation. For example, some theoretical studies predict that pressure changes from the Landers earthquake will induce fluid flow, which may stimulate earthquakes on the San Andreas over the next few years. Group E proposes installing a continuous strain meter along the San Bernardino Mountains segment of the San Andreas fault to detect such effects and monitor anomalous strain on the fault. Also, the center will continue to support the strain monitoring at Pinon Flat. At SCEC, we have both strong believers in precursory phenomena who are enthusiastic about this task, and objective critics who try to eliminate wishful thinking from the enthusiast's interpretation of data. Thus, SCEC offers an ideal atmosphere for the healthy development of precursor studies.

Task 5 Support the Development of Real-time Earthquake Information

The rapid synthesis and dissemination of all available seismological information following a major earthquake is receiving increasing attention in California. Lifeline operators and emergency preparedness personnel are interested in a rapid assessment of regional ground shaking, and knowing where damage is likely to be the greatest. The media and general public are interested in rapid and precise determinations of mainshock and aftershock magnitudes and locations. Scientists need to know where to mobilize for post-earthquake investigations, and what the nature and extent of the rupture is. SCEC can assist in developing real-time seismology through both its basic research and outreach functions.

In addition to magnitude and location, most important information desired immediately after a major earthquake is essentially contained in the master model -- namely, predicted ground motions from that particular event. As our data bases on source, path and site effects grow, the master model and our predictions of ground motions improve. This information can be rapidly disseminated using microwave and microcomputer technologies, as is currently being done with the CUBE (Caltech/USGS Broadcast of Earthquakes) system in southern California. In addition, part of the real-time response will be post-mainshock deployments of both transportable network stations and/or portable recorders and broadband sensors from the SCEC Portable Instrument Center.

With its outreach activity, SCEC is in an excellent position to assist in communicating real-time seismological information to the emergency preparedness community and general public. Since it will be many years before such real-time systems are foolproof, SCEC can assist in training users of these systems, and providing the interface for answering questions and keeping user software up to date.

Perhaps the most provocative concerns about real-time seismology relate to its use as an early warning system. Although we feel that this goal is ultimately attainable and worthwhile for a number of applications, SCEC does not plan at this time to make it a part of its next 5-year program.

Task 6 -- Response to Future Earthquakes

The Landers earthquake clearly demonstrated the significance of major earthquakes in southern California to SCEC's mission. Post-earthquake studies of such events by the center are important for two fundamental reasons:

- They accelerate the development and application of the master model, and
- They raise new issues, highlight others, and generally add to our knowledge of the physics of earthquake processes.

In general, post-earthquake studies of future events will involve various observations. Among the most important to the center's mission are the recording of aftershocks, determining coseismic and post-seismic deformation, geologic mapping of the primary rupture, and determination of the mainshock source parameters.

Many earthquakes occur on complex structures in areas with sparse seismic network control. Thus, the recording of aftershocks will rely on combining permanent network stations with deployments of portable instruments. Aftershocks can be used to provide the following information about an earthquake:

- Geometry and extent of primary and secondary rupture surfaces
- Distribution of post-earthquake stresses in the neighborhood of the rupture using first motions and shear wave splitting
- Local and regional crustal structure
- Ground motion response for various site conditions and calibration of numerical models
- Aftershock migration patterns
- Fault zone structure using fault zone trapped modes and refracted phases

Geodetic (e.g., GPS) mapping of the deformation field not only provides an independent characterization of the source, but also removes the coseismic strain (and any post-seismic relaxation) from the secular velocity field in southern California. Geologic mapping of the rupture provides data on important issues including the characteristic earthquake, fault segmentation, source parameters, relationships of maximum slip and rupture length to earthquake moment, and relationships to older seismogenic structures.

SCEC must carry out post-earthquake investigations in an efficient, timely, and coordinated manner. As such, the center has begun assembling a post-earthquake response plan -- beginning with aftershock recordings. In cooperation with IRIS, SCEC is currently developing a Rapid Array Mobilization Program (RAMP) for deploying SCEC and PASSCAL portable seismic recorders immediately following a major earthquake in southern California. Geodetic and geologic components will be added later. We anticipate completing the post-earthquake response plan by early 1994 (the end of our third year).

The plan will include responses to several specific earthquake scenarios in southern California including:

- A M=6+ event directly on the San Andreas fault somewhere in southern California
- A M=7.8 event on the San Andreas which ruptures the Coachella Valley and San Bernardino Mountains segments
- A M=8+ on the San Andreas which ruptures the Mojave, San Bernardino Mountains, and Coachella Valley segments
- A M=7+ in the Los Angeles basin on the Sierra Madre or Santa Monica/Malibu fault system.

Pre-planned, post-earthquake response policies and procedures are necessary for several reasons:

- Guidelines need to be in place to determine when SCEC will commit resources to a particular earthquake (generally dependent on magnitude and location),
- There is not time for careful strategic and logistical planning to optimize the post-earthquake science following a major earthquake,
- Earthquakes are surprise occurrences which significantly disrupt ongoing activities and budgets, and which usually require a major re-programming of resources,
- SCEC is an amalgamation of scientists and institutions with shared and limited resources, and
- It is useful to have an inventory of available instrumental and human resources.

When completed, our response plan will serve as a template for similar groups of scientists in other parts of the country.

1993-1998 Proposed SCEC Budgets (in K$)

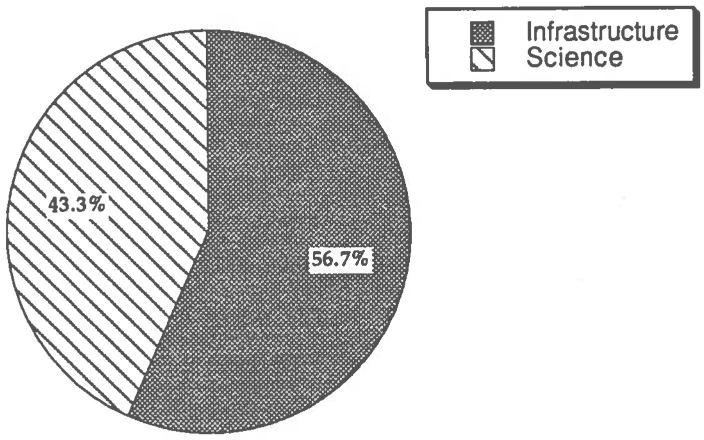
Infrastructure

	1993	1994	1995	1996	1997	1998
Management:	222	250	265	280	300	320
Workshops/Meetings:	60	105	110	120	120	130
Visitors Program:	110	250	300	330	300	300
Data Center Support:	181	200	220	240	260	280
Data Center Equipment:	0	200	0	0	0	0
Strong Motion Data Base and Empirical Green's Function Library:	35	75	80	85	90	90
Broad Band Recorders:						
Equipment:	125	120	135	120	100	70
Support:	77	90	100	110	120	130
GPS Acquisition:						
Data Analysis Support:	310	210	220	230	240	250
Permanent GPS Stations:	0	80	200	200	160	160
Borehole Strainmeters	0	135	135	10	10	10
GIS:	105	105	110	115	120	135
Earthquake Geology GIS	95	100	105	110	110	110
Education and Outreach:	90	300	320	340	360	380
Facilities:						
Pinon Flat:	20	25	25	30	30	30
TERRAscope:	60	65	65	70	70	75
Subtotal Infrastructure:	1,490	2,310	2,390	2,390	2,390	2,470
Landers Data Archival Fund	289	0	0	0	0	0
LARSE Experiment	0	130	0	0	0	0

Science

		1993	1994	1995	1996	1997	1998
Group A	Master Model	299	340	390	430	490	550
Group B	Ground Motion Prediction	163	210	260	310	350	370
Group C	Earthquake Geology	281	350	390	400	400	400
Group D	Subsurface Imaging and Tectonics	82	190	210	240	280	300
Group E	Crustal Deformation	136	190	200	210	220	230
Group F	Seismicity and Source Processes	145	200	240	280	320	330
Group G	Physics of Earthquakes	95	130	170	190	200	200
Subtotal Science		1,201	1,610	1,860	2,060	2,260	2,380
Total Budget		2,980	4,050	4,250	4,450	4,650	4,850
NSF Funding		1,780	2,850	3,050	3,250	3,450	3,650
USGS Funding		1,200	1,200	1,200	1,200	1,200	1,200
Total NSF/USGS Funding		2,980	4,050	4,250	4,450	4,650	4,850

SCEC Total Expenditures, 1991 - 1993



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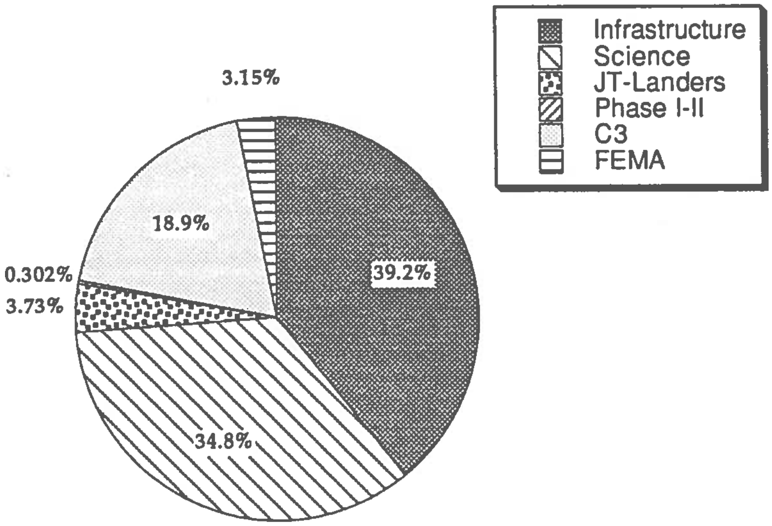

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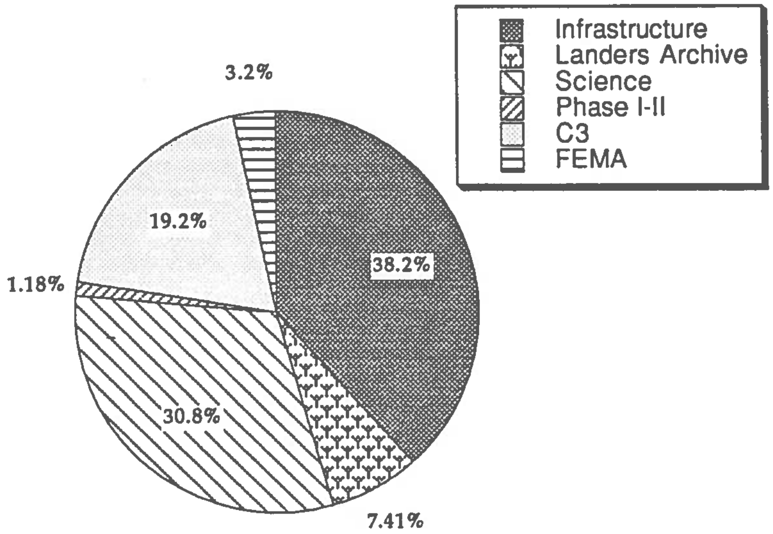
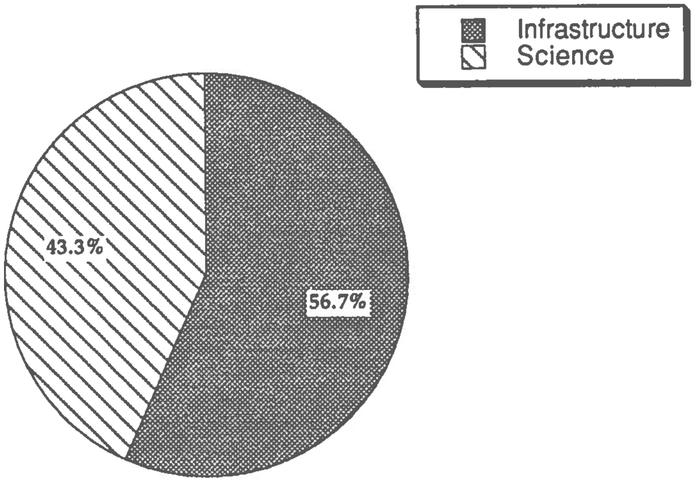


1993

NSF/USGS Expenditures, 1991 - 1993



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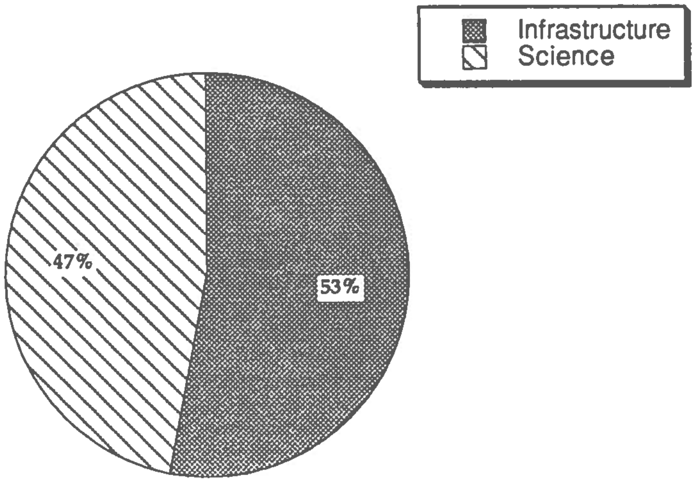

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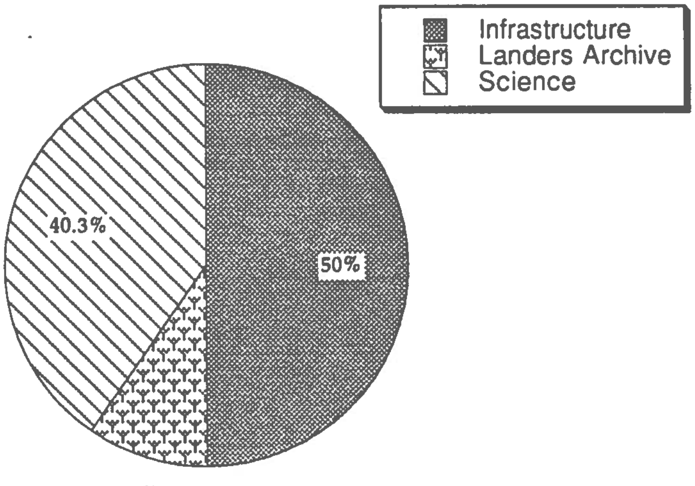
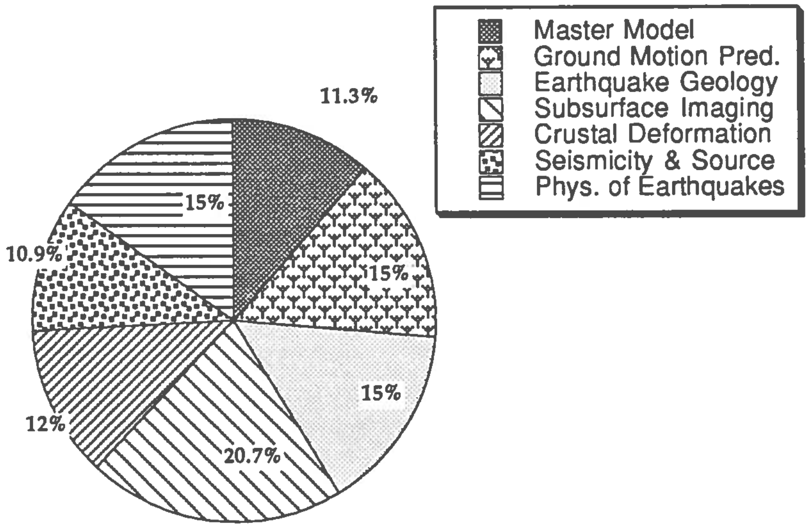


1993

SCEC Science Expenditures, 1991 - 1993



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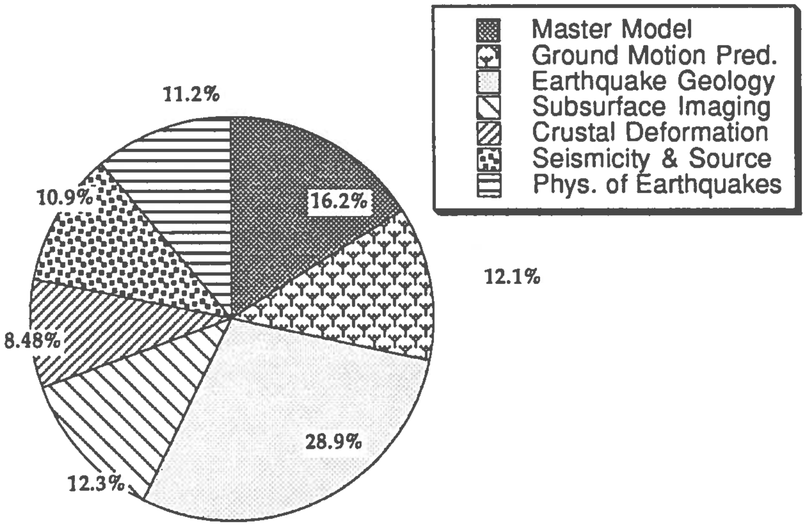

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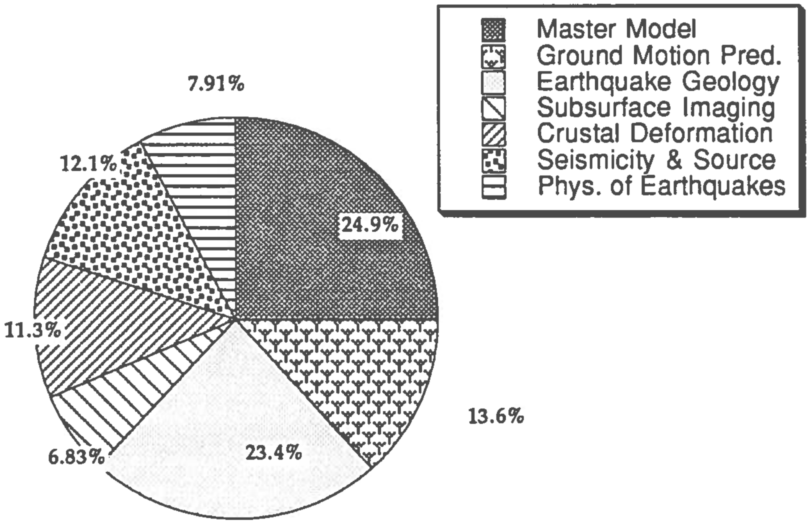

1993

1993 SCEC INFRASTRUCTURE

SCEC ORGANIZATION - 1993

Management

Science Director:	Keiiti Aki University of Southern California
Executive Director:	Thomas Henyey University of Southern California
Assistant Director for Engineering Applications:	Geoffrey Martin University of Southern California
Assistant Director for Administration:	John McRaney University of Southern California
Assistant Director for Education:	Curtis D. Abdouch University of Southern California
Assistant Director for Outreach:	To Be Named
Academic Coordinator for Education and Outreach:	Karen McNally University of California, Santa Cruz

Board of Directors

Chair:	Keiiti Aki University of Southern California
Vice-Chair:	Bernard Minster University of California, San Diego
Members:	Robert Clayton California Institute of Technology
	Ralph Archuleta University of California, Santa Barbara
	Karen McNally University of California, Santa Cruz
	Leon Knopoff University of California, Los Angeles
	Leonardo Seeber Columbia University
	James Mori United States Geological Survey
Ex-officio:	Thomas Henyey University of Southern California

Research Group Leaders

A: Master Model	Keiiti Aki University of Southern California
B: Strong Motion	Steve Day San Diego State University
C: Earthquake Geology	Kerry Sieh California Institute of Technology
D: Subsurface Imaging	Robert Clayton California Institute of Technology
E: Crustal Deformation	Duncan Agnew University of California, San Diego
F: Seismicity and Source Parameters:	Egill Hauksson California Institute of Technology
G: Earthquake Source Physics:	Leon Knopoff University of California, Los Angeles
H: Engineering Applications:	Geoffrey Martin University of Southern California

Southern California Earthquake Center

1992-93 Visitors and Visiting Post-doctoral Fellows

Visitor	Host Institution	Research Project
Francesca Ghisetti (Italy)	Lamont/UCSB (Seeber)	Parametric Growth Laws for the San Andreas Fault
Jean-Pierre Gratier (Grenoble)	UCSB/USC (Archuleta)	Strain Partitioning Compatibility between Faults, Creep, and Folds
Ruth Harris (NRC/USGS)	USGS (Stein)	3-D Dynamic Modeling Effects of Fault Geometry on Earthquake Ruptures in Southern California
Eugene Humphreys (Oregon State)	Caltech (Clayton)	Numeric Kinematic and Dynamic Modeling of Southern California Deformation
Mark Peterson (Post-doctoral Fellow)	Reno (Wesnousky)	Seismic Hazards Assessment, Southern California
Richard Snay (NOAA/Maryland)	UCLA (Jackson)	Comparing Geodetic Models for Horizontal Deformation in California
Dapeng Zhao (Post-doctoral Fellow)	Caltech (Kanamori)	3-D Seismic Velocity Model of the Crust and Upper Mantle beneath Southern California

GEOGRAPHIC INORMATION SYSTEMS WORKSHOP
SOUTHERN CALIFORNIA EARTHQUAKE CENTER
July 19, 1993

The SCEC GIS workshop was held at the University of California at Riverside on July 19, 1993. Forty participants from universities, industry, and government met to listen and discuss six presentations by SCEC researchers and one by scientists at Earthquake Engineering International. Abstracts from six of the presentations are included with this report. In addition, Eric Lehmer presented a demonstration of ALACARTE which is an interactive program written by the US Geological Survey for entry of digital geologic maps. Doug Morton reported the progress being made by USGS and CDMG scientists on the Southern California Mapping Project. This project is a 5-10 year effort to update geologic maps in southern California at the 1:100000 scale and prepare these maps digitally.

The workshop was also attended by several media personnel. One of these, a reporter from the Riverside Press-Enterprise, wrote a story about the workshop. This story is attached. The reporter left after two talks and unfortunately did not benefit from the rest of the workshop.

A list of the participants is attached, as are the minutes of the meeting taken by Stef Donev.

Stephen Park
October 28, 1993

Participants

Name	Affiliation	Phone
UNIVERSITIES:		
Stephen Park	UCR	909-787-4501
Anne Lilje	CIT	818-395-6897
Leslie Goodman	SCEC	818-304-8394
Blair Zajan	CIT	818-395-6932
Richard Aceves	UCR	909-369-9006
Jeff Knott	UCR	909-787-2194
Nadya Williams	UCSD	619-534-7072
Keith Stark	USCD	619-334-7692
Kathy Barton	UCR-Publ. Rltns.	909-787-5326
John Suppe	Princeton	609-258-4100
Maribeth Price	Princeton	609-258-3261
Karl Mueller	Princeton	609-258-6769
Sally McGill	CSUSB	909-880-5347
Des Andrews	USC	213-740-0605
James Chin	USC	213-740-7174
Ed Boring	UCSC	408-459-3725
Mitsuyuke Hosiba	USC	213-740-9316
Michael Forest	USC	213-847-7094
Getchen Murawski	USC	213-847-7094
Avijit C.	USC	213-847-7094
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Reno Barry	UCR	909-787-4501
Karen McNally	UCSC	408-459-4137
Eric Lehmer	SCEC-UCR	909-787-2104
Kerry Sieh	CIT	818-395-6115
PUBLIC SECTOR:		
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Rick Ranous	OES	818-304-8385
Roland Hall	USGS	909-787-2104
Dave Forwalter	OES	619-550-3908
Doug Morton	USGS	
PRIVATE SECTOR:		
Ron Eguchi	EQE	714-833-3303
Jack Wiggins	EQE	714-833-3303
Hope Seligson	EQE	714-833-3303
Emanuel Eger	EQE	714-833-3303
Jack Popejoy	SCEC PAB	213-650-3739

John Hansen	Leighton and Associates	714-250-1421
Stef Donev	SCEC Consultant	805-242-1462
Mark Legg	ACJA	310-378-6254
Eldon Gath	Leighton and Associates	714-860-7772
Gary Polakovic	Riverside Press-Enterprise	

GIS WORKSHOP SUMMARY

CAll TO ORDER:
It began at 1 pm. The following presentations were made:

1) SEISMIC VULNERABILITY ASSESSMENT FOR SOUTHERN CALIFORNIA

[Ronald T. Eguchi, Hope A. Seligson (EQE), James Goltz (OES)]

EQE demonstrated a computer program developed for the insurance industry to help predict levels of earthquake damage and destruction in specific areas. There was a discussion of how this program could be used in conjunction with another new program that is being developed, EPEDAT (Early Post Earthquake Damage Assessment Tool).

EPEDAT will help emergency response teams quickly determine where to send help, such as search and rescue squads, and make other important and timely decisions about what areas will need the most help in the case of a major earthquake.

During discussion, EQE representatives and James Goltz of OES pointed out that databases are still being prepared for EPEDAT to include lifelines (such as power corridors, pipelines, roads, bridges, etc.), as well as details about the types, size, and ages of specific buildings and what they are used for -- and when they are at peak use -- for all of southern California. It is expected that EPEDAT will also be able to predict damage to lifelines, other important structures, and estimate casualty figures.

2) GIS-BASED MAP OF WEAK MOTION AMPLIFICATION FACTORS AND ITS APPLICATIONS IN SOUTHERN CALIFORNIA

[James Chin (USC)]

A preliminary GIS-based map of weak-motion amplification factors in southern California was presented. It was constructed by combining empirical amplification factors measured at stations of the southern California seismic network.

There was discussion about the potential future benefits and uses of such information in terms of using it to more accurately estimate ground shaking from earthquakes.

Future research will focus on the site response problem at the Los Angeles basin by both seismological and geotechnical approaches.

3) DETERMINING THE LOCATION AND GEOMETRY OF ACTIVE BLIND THRUST FAULTS IN SOUTHERN CALIFORNIA

[John Suppe, Maribeth Price, and Karl Mueller (Princeton)]

There was a presentation of research to determine the location and geometry of major blind thrust faults in southern California and to identify potentially hazardous segments. There was discussion about using this information to develop slip maps for SCEC. The SCEC Executive Director was also requested to solicit better mapping resolution with digitized elevation data. There was also discussion about appropriate review processes from the USGS for releasing databases.

4) ALACARTE: SIMPLE DIGITAL GEOLOGICAL MAPS
[Eric Lehmer (SCEC-UCR)]

There was a demonstration of how the ALACARTE program can be used to prepare simple digital geological maps. The demonstration was followed by discussion about the different types of maps that could be produced from different databases and their usefulness.

5) SOUTHERN CALIFORNIA REGIONAL GEOLOGIC MAPPING PROJECT
[Doug Morton (USGS)]

Doug Morton discussed where the mapping project currently stands and the problems they are having with completing it. There was a suggestion that the SCEC Executive Director talk to the USGS to see it if could speed up the process.

6) THE LANDERS SURFACE RUPTURE: USE OF ARC/INFO AS A MAPPING AND ANALYTICAL TOOL
[Anne Lilje and Kerry Sieh (CIT)]

There was a demonstration of techniques for digitizing topological data for computerized map making. This was followed by a discussion of different ways to get the information on diskette or tape, and about when and in what forms the data would be released.

7) GENERATION OF PROBABILISTIC HAZARD MAPS FOR EARTHQUAKES
[Stephen Park and Eric Lehmer (UCR)]

There was a demonstration comparing different ways to predict ground motion associated with earthquakes: (1) a fault scenario, and (2) probabilistic hazard. The probabilistic hazard approach was presented as the more realistic of the two for southern California because there are so many different faults which can produce potentially damaging earthquakes. It was pointed out that the use of ARC/INFO has eliminated the need for gridded data sets.

Stef Donev
July 22, 1993

GEOGRAPHIC INFORMATION SYSTEMS WORKSHOP
UNIVERSITY OF CALIFORNIA, RIVERSIDE

Geology 1408
July 19, 1993 1-6 p.m.

SCHEDULE

SEISMIC VULNERABILITY ASSESSMENT FOR SOUTHERN CALIFORNIA
Ronald T. Eguchi, Hope A. Seligson (EQE), and James Goltz (OES)

GIS-BASED MAP OF WEAK-MOTION AMPLIFICATION FACTORS AND ITS APPLICATION IN SOUTHERN CALIFORNIA
James Chin (USC)

DETERMINING THE LOCATION AND GEOMETRY OF ACTIVE BLIND THRUST FAULTS IN SOUTHERN CALIFORNIA
John Suppe, Maribeth Price, and Karl Mueller (Princeton)

ALACARTE: SIMPLE DIGITAL GEOLOGICAL MAPS
Eric Lehmer (SCEC-UCR)

Break

SOUTHERN CALIFORNIA REGIONAL GEOLOGIC MAPPING PROJECT
Doug Morton (USGS)

THE LANDERS SURFACE RUPTURE: USE OF ARC/INFO AS A MAPPING AND ANALYTICAL TOOL
Anne Lilje and Kerry Sieh (CIT)

GENERATION OF PROBABILISTIC HAZARD MAPS FOR EARTHQUAKES
Stephen Park and Eric Lehmer (UCR)

Discussion

SCEC High-Resolution Imaging Workshop
July 15-16, 1993

Convened by

James F. Dolan
Seismological Lab, Caltech 252-21, Pasadena, CA 91125

David Okaya
Dept. of Geological Sciences, USC, Los Angeles, CA 90089-0740

Introduction

Urban southern California lies within one of the most seismically active regions in the world, and earthquakes represent a significant hazard to both people and property. Despite the certainty that damaging earthquakes will strike metropolitan areas in the future, accurate seismic hazard assessment is hampered by a continuing lack of basic data on many major active faults. In particular, recent research indicates that blind thrust faults underlie large portions of southern California, including virtually all of metropolitan Los Angeles. Yet little is known about the seismic hazards posed by these faults. There are several reasons for this dearth of information.

Until recently, earthquake scenarios for the Greater Los Angeles area focused primarily on the effects of a great earthquake (M=8) occurring on the San Andreas fault, which is located more than 50 km northeast of downtown Los Angeles. Except for a postulated M=7.5 earthquake scenario for the northern segment of the Newport-Inglewood fault zone, seismic hazard assessments generally did not include potentially seismogenic structures within the densely populated Los Angeles basin.

The M=5.9 Whittier Narrows earthquake of October 1, 1987 dramatically changed this view of the seismic hazards affecting urban Los Angeles. This moderate earthquake, which occurred on a shallowly north-dipping blind thrust fault just east of downtown Los Angeles, caused considerable damage and focused attention on the seismic hazards associated with the numerous structures located within the Los Angeles area. Because of the proximity of these structures to urban Los Angeles, moderate-to-large earthquakes (M=6 to 7) could cause as much damage as a much larger earthquake occurring on the San Andreas fault. The Whittier Narrows earthquake also pointed out the hazards associated with previously unrecognized blind thrust faults, which have been postulated to underlie a significant portion of the Los Angeles Basin (Davis and others, 1989; Hauksson, 1990; Wright, 1991; Shaw and Suppe, 1993).

Finally, despite the heightened awareness of the potential for destructive earthquakes on structures beneath metropolitan Los Angeles, little paleoseismologic information exists concerning urban blind thrust faults, although several research groups have begun studying these problems. Specifically, we have little or no information concerning recency of earthquake activity, recurrence interval, slip rates, or kinematics of fault movement for most structures in the northern Los Angeles basin. Part of the problem is that we only learned of the existence of these structures six years ago, but another part of the problem is inherent in studies of blind structures--conventional paleoseismologic and slip rate studies, which were developed primarily for surficial strike-slip faults, are not practical for deeply buried blind thrust faults.

With these problems in mind, we convened a SCEC workshop designed to explore the potential for illuminating the seismic hazard potential of active structures within metropolitan southern California through the use of high-resolution seismic reflection imaging (HRI) techniques. Our goals during this workshop, which was held on July 15-16, 1993 at Caltech, were four-fold: (1) gauge community interest in using high-resolution imaging to elucidate seismic hazards posed by urban faults; (2) foster interaction between researchers from different institutions who are interested in high-resolution research; (3) discuss the advantages and disadvantages of different imaging techniques, both those now available and those still techniques still considered experimental; and (4) define a pool of potential research projects from which we would choose a future research program. The meeting was highly successful and we made significant progress on all four of our goals.

Rationale for Proposed High-Resolution Imaging Research Program

What do we still need to learn about potentially seismogenic faults in urban southern California in order to make an informed assessment of the seismic hazards facing this densely populated region?

1) What is the three-dimensional distribution of faults in the region; particularly that for blind thrust faults? Knowledge of 3-D geometries are important in terms of understanding where to expect strong ground shaking as well as trying to understand the size of future earthquakes.

2) What are the current rates of fault movement on the blind thrust faults that underlie much of metropolitan Los Angeles? Faster strain accumulation implies potential for more frequent or larger earthquakes.

3) What is the paleo-earthquake history on individual faults? For a given fault, what are the recurrence intervals and the age of its most recent earthquake? Are there similar ages for earthquakes on apparently different fault strands?

How will high-resolution imaging help us to fill in these gaps in our knowledge of the seismic hazards facing Los Angeles?

1) Most data that are used to model blind thrust faults in southern California are based on oil industry multichannel seismic reflection data, which typically were designed to image moderately deep targets (1-4+ km). In general these data do not image the upper few hundred meters of section, leaving a significant data gap in our three-dimensional mapping of faults. High resolution imaging will fill this gap and allow us to directly correlate deep-penetration industry seismic reflection data with data from surficial trenching and geomorphologic studies.

2) Slip rates have been calculated for several of the major blind thrust faults that underlie urban southern California by two different teams of researchers (Davis and Namson; Suppe and Shaw). These rates have been calculated by two different methods: (A) Davis and Namson's work has used estimates of total fault displacement divided by the estimated time that the fault began moving (generally thought to be about 3.5-5 million years ago). Due to the large uncertainties of the onset of faulting these dates may only be approximate. (B) Suppe and Shaw have used growth wedge sedimentation to more accurately constrain rates of movement on several structures, using age control supplied by oil well data to constrain temporal changes in fault displacement. A critically important point about these two different types of slip rate studies is that both of them produce slip rates that are averaged over million-year time scales. Neither type of estimate includes information about the recent (i.e. past 50,000-100,000 years) rates of slip on these faults. Over time scales as long as this, faults can dramatically changes their slip behavior. Slip can increase or decrease, new faults can form, faults that were active a million years ago may have subsequently become inactive. Consequently, information on the recent fault behavior is essential for accurately assessing seismic risk. In the case of the Davis and Namson method, this lack of recent information is inherent in their analysis, but in the Suppe and Shaw growth-wedge technique, high-resolution imaging, when combined with a simultaneous program of continuously cored shallow borings (30-100 m), offers a potentially powerful method for obtaining accurate blind thrust slip rates for the recent past. Using ultra-high-resolution imaging techniques (UHRI, discussed below) we may even be able to extend slip rate data into the Holocene.

3) Understanding the earthquake history of an individual fault, or group of faults, provides important information about several critical components of any seismic hazard assessment: information about likely recurrence intervals gives us a general idea of the frequency of large earthquakes. In addition, when combined with slip-rate data that provide rates of strain accumulation, the recurrence interval data allow us to estimate probable displacements in future earthquakes. Finally, comparison of paleo-earthquake data from different faults, or from different segments of the same fault, allows us to speculate about the size of future earthquakes. For example, if paleoseismologic studies reveal that the most recent earthquakes on two different faults occurred at markedly different times, then we can begin to speculate that they may also break at different times in the future. If, on the other hand, ancient earthquakes have occurred at approximately the same time on different parts of the same fault system, then we might speculate that the entire fault system may break at the same time in large earthquakes.

Applications: A. Paleoseismology of surface faults

Trench-driven studies. In many cases trench data need to be tied to their overall structural context in order to accurately interpret paleoseismologic data. This problem is particularly important if a near-surface blind thrust component exists at the site. For example, in order to correctly interpret the paleoearthquake record at such a site, it is critically important to determine the location of the active axial surface. This in turn requires determination of the dip of the blind structure. Is it a foreland-propagating structure, or is it a backthrust? High-resolution imaging data (0-100 m depth) provides the most promising way to answer such questions by expanding the structural context of the trench data.

Reconnaissance studies. The most common way that geologists locate paleoseismologic trench sites is by geomorphologic analysis of fault-related landforms. However, in areas of rapid sedimentation or erosion the geomorphic expression of the fault may be either buried or obliterated. This is a particularly important problem in urban southern California, where the choices of trench localities are severely limited by cultural development and we may not be able to situate a trench in an area of good geomorphic expression. Furthermore, the vast majority of paleoseismologic trench studies are conducted by the consulting industry. Almost all of these studies are site-driven (e. g., power plants, bridges, buildings), and the trenches may therefore be forced to be located in geomorphically unfavorable locations. High-resolution imaging and UHRI provide potentially powerful tools for locating trench sites in these settings. These techniques are inexpensive, fast, and non-destructive (i. e., no excavation is required, an important consideration in densely populated urban areas).

Applications: B. Blind thrust faults

Use high-resolution imaging to correlate the location of strata containing peats with results from a 14C coring program in order to date paleo-earthquake ponding events. We have selected several sites that may be amenable to this type of analysis, which is based on analogy to the ponding that occurred during the 1980 El Asnam earthquake in Algeria.

High-resolution and UHRI of stratigraphic evidence for past earthquakes. Along the back limb of an actively growing anticline above a blind thrust fault, strata will be deformed during an earthquake. When high-resolution seismic reflection images of the growth wedges of such structures are combined with age data provided by ponded peat deposits, we may be able to resolve individual past earthquakes. This technique represents the only direct means of delineating past earthquakes on major blind thrust faults.

Methods of High Resolution Imaging

Methods available to SCEC

Several methods of high resolution imaging (10-1000 m) and ultra-high resolution imaging (0-10 m) are available to SCEC. Each method is optimal for a specific range of depths (Figure 1) and provides a characteristic range of resolution thicknesses. One method may be preferred over another depending on the geologic targets to be imaged. The methods are either available from collaborating institutions within the Los Angeles basin or from the USGS (see Appendix II). Collaborations with the USGS can take advantage of the internal/external funding approach of the USGS NEHRP program. Methods which we can propose to use:

MiniSosie A repeatable impact source. USGS/Denver. Depth range is 50 - 2000 m. Expected resolution of 2.5 - 15 m. USGS rate at $4000/day for entire crew.
1 KJ sparker A marine repeatable acoustic source. CSU/Long Beach. Depth range is 5-300 m; resolution of 2.5-10 m. Cost is approximately $50/km.
Weight drop An impact source. USGS/Denver or CSU/Fullerton. Depth range is 2-75 m. Resolution is 1.5 - 5m. USGS rate at $2500/day for entire crew. CSU/F rate is less.
Shotgun An explosive source. USGS/Denver. Depth range is 2-250 m; resolution is 1.5-5 m. USGS rate at $2700/day.
Sledge An impact source. USGS/Denver or CSU/Fullerton. Depth range is 2-75 m; resolution is 1.5-5 m. USGS rate at $2500/day for entire crew. CSU/F rate is less.
Hammer An impact source. USGS/Denver or CSU/Fullerton. Depth range is 0.5-10 m; resolution is 0.5-1.5 m. USGS rate at $2500/day; CSU/F rate is less.
Staple gun An impact source. CSU/Fullerton. Depth range is 0.5-10 m; resolution is 0.5-1.5 m. CSU/Fullerton rate of $500/day.
Ground penetrating radar Not a seismic source. CSU/Long Beach. Depth range is 0.2 to 3 m; resolution is 0.2-0.5 m. Soil conditions must be optimal to obtain good results.

Resolution concerns

Seismic source frequency bandwidth diminishes with depth of penetration. As a result, the resolving ability of a seismic source lowers with depth. The resolution provided by the above methods decreases with depth of penetration. For a fault whose structural setting is the imaging target, the MiniSosie or weightdrop source will suffice. For under 100 m depth, the shotgun or sledge source is more optimal. For trench-scale images, the higher resolution methods (hammer, staple gun) are recommended.

In seismic theory, resolution is often described as a fraction of the source's dominant wavelength. The resolving limit of a source is often estimated at 1/4 to 1/8 of its wavelength and thus is a function of source bandwidth and rock propagation velocity. Recent pilot tests of high resolution imaging methods [MiniSosie Palos Verdes profiles (1992), MiniSosie Santa Monica fault data (1993), hammer and shotput Santa Monica fault pilot (1993), and staplegun Santa Monica fault pilot (1993)] suggest the resolution of these methods is in general lower than what may be desired to identify very detailed stratigraphic or structural behavior. A major conclusion is that we in our fault study applications are pushing the limits of the resolution these methods can provide. As a result, modifications or improvements to these current techniques is desired in order to provide better resolution.

These seismic methods will never provide the same level of detail which is observable in exposures within a paleoseismologic trench. As a result, high resolution imaging methods must be used to take advantage of their strengths: depth information at costs less than coring or trenching, imaging in the lateral directions at relatively inexpensive costs, providing a regional 3-D structural setting to tie with surface geologic information.

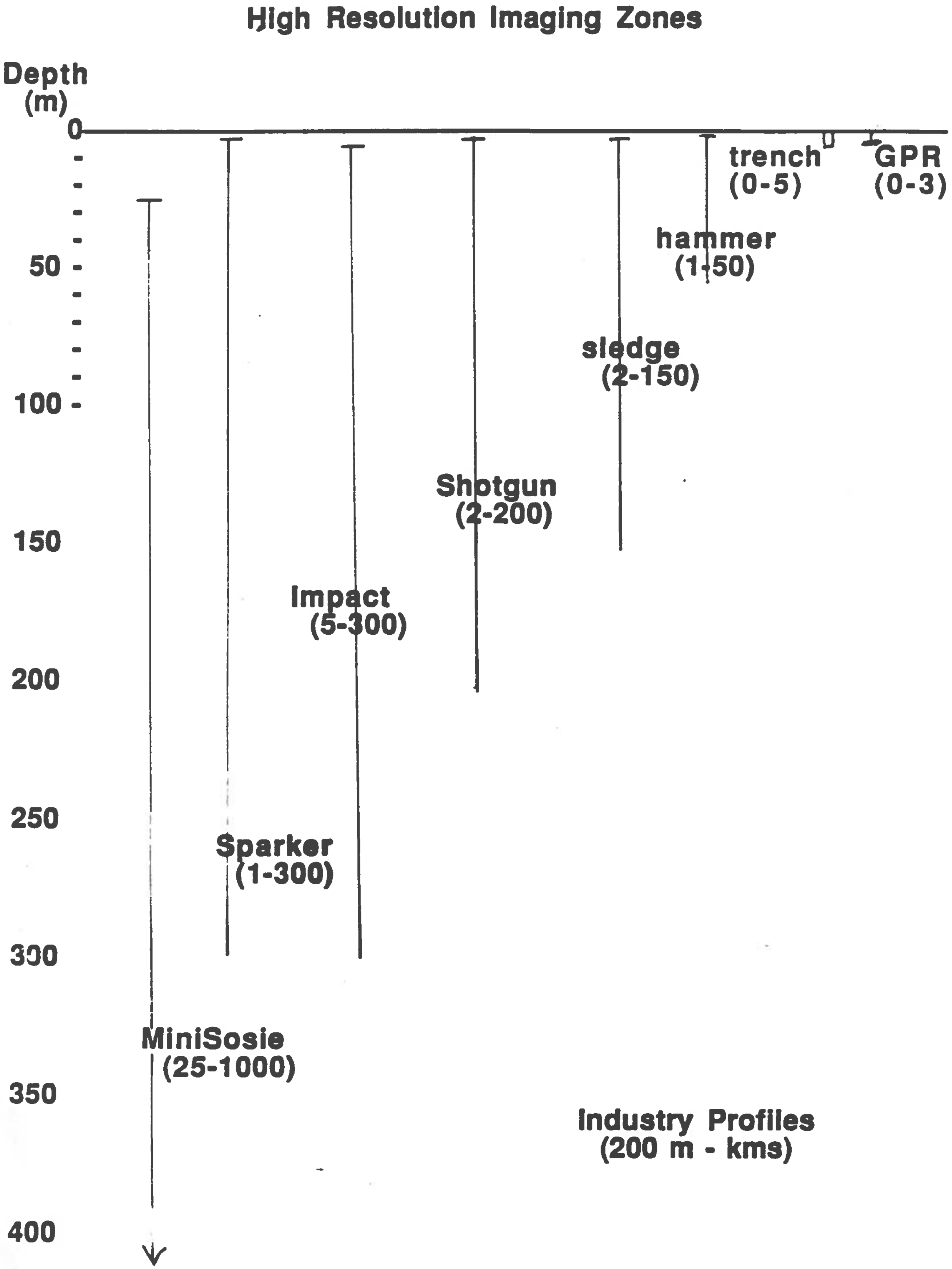
High Resolution Imaging Zones
Depth (m)
0
50
100
150
200
250
300
350
400
trench (0-5)
GPR (0-3)
hammer (1-50)
sledge (2-150)
Shotgun (2-200)
Impact (5-300)
Sparker (1-300)
MiniSosie (25-1000)
Industry Profiles (200 m - kms)

FIGURE 1

Program

We have chosen a pool of seventeen potential projects from which we will select 3-4 proposals/year to be submitted for funding. The 3-4 proposals chosen for submission each year will be determined by all those in the high-resolution imaging group. Ratings will be based on a standardized process. All members of the high-resolution imaging group will be asked to rank each proposal on a scale of 1-10 based on the following factors:
(1) The 'potential' seismic hazard posed by the structure in question. This criteria will be based on the potential size of the earthquakes on the structure and its proximity to major population centers.
(2) The likelihood that a late Quaternary sedimentary record is preserved at the site.
(3) The likelihood that datable material will be recoverable within a companion study of continuously cored borings.
(4) Site-specific logistics (i. e., our ability to acquire the data, ease of permitting and access).
(5) Cost of acquisition.
(6) The background information available at the site (i.e., our present understanding of the exact location, geometry, and kinematics of the structure).
We wish to emphasize that we are not constrained to only the seventeen projects that we have initially proposed. As new ideas and/or new researchers become involved in the high-resolution imaging group we will entertain any new proposals.

Proposed High-Resolution Imaging Studies

The following is a list of the seventeen projects that we believe hold the most promise for high-resolution imaging research in southern California. Most of these proposed studies are located in major urban areas and most focus on obtaining paleoearthquake information and recent slip rates for major blind thrust faults. Such research represents a new strategy for SCEC. As we discussed above, high-resolution imaging holds great promise for understanding the seismic hazards posed by these difficult-to-study structures. We wish to emphasize that there was no inherent bias among the workshop participants against high-resolution studies of major strike-slip faults. However, we did reach a consensus that, given the limited funds available for this type of research, we should focus on blind thrusts faults, which are not amenable to more conventional research techniques (e. g., paleoseismologic 2-D and 3-D trenching).

(1) La Cienega area northeast of the Baldwin Hills. Paleoseismology of Compton-Los Alamitos blind thrust fault, which underlies most of the western Los Angeles basin. Datable peat should good provide age for ponding events of ancestral Los Angeles River caused by uplift of the river channel during Compton-Los Alamitos fault events.

(2) Los Angeles River through downtown Los Angeles. Balanced cross section modelling and geomorphologic analyses indicate that downtown Los Angeles in underlain by one, and probably several, splays of the Elysian Park blind thrust system (a small part of which broke during the 1987 Whittier Narrows earthquake). Exact geometry and location of these structures is poorly known.

(3) Whittier Narrows. Paleoseismology and structure of eastern Elysian Park blind thrust system, which underlies much of the northern Los Angeles basin. Dark colored, organic-rich sediments north of Whittier Narrows hold promise of excellent age control for high-resolution data.

(4) Santa Ana River near Corona. Paleoseismology of the Puente Hills portion of the Elysian

Park blind thrust system. Potentially organic-rich sediments near Prado dam site will provide age control for paleoseismologic studies based on high-resolution imaging. Possible correlation of research effort with pending major geotechnical studies for Prado Dam.

(5) Santa Ana River flowing across the southern portion of the Compton-Los Alamitos blind thrust fault. Peats in this area will provide age control for high-resolution data.

(6) Northern San Fernando Valley. Paleoseismologic studies of the western Sierra Madre, Mission Hills, and Northridge Hills thrust faults.

(7) Malibu. Paleoseismology, structure, and location of the Malibu Coast fault. Possible combined onshore-offshore study. Paleoseismologic data from the Malibu Coast fault may provide clues about the earthquake history of the large Santa Monica Mountains blind thrust, to which it is mechanically linked at depth.

(8) Century City-Western Beverly Hills. Structure and paleoseismology of the west Beverly Hills lineament, which we believe to be a northern extension of the Compton-Los Alamitos blind thrust fault.

(9) South Hollywood. Recent research indicates that the densely urbanized area just south of Hollywood is underlain by at least one, and possibly several, shallow blind thrust faults.

(10) Ventura syncline/fault. Recent studies indicate that this structure represents an active axial surface. High-resolution imaging of this structure may represent our best chance to define paleoearthquakes on the Oak Ridge trend, one of the largest thrust faults in the western Transverse Ranges.

(11) Alternatively, we could study the paleoseismology of the Oak Ridge trend offshore using marine-based high-resolution imaging.

(12) Coast south of Ventura. High-resolution imaging of the onshore active axial surface of the Oak Ridge trend.

(13) Carpenteria. Major backthrusts of the Oak Ridge system. Possible ponding events may provide age control for high-resolution data.

(14) Camarillo. Imaging of growth wedge of back limb of Oak Ridge structure. Provide structural context for extensive paleoseismologic trenching program of the Springville fault.

(15) Offshore Palos Verdes fault. Both to north and south of Palos Verdes Peninsula. Paleoseismology, structure, and exact location of fault poorly known, especially north of peninsula in Santa Monica Bay. Potential correlation with deep-penetration multi-channel profile south of the peninsula.

(16) Offshore Santa Barbara Channel. Recent growth wedge sedimentation, slip rates, and paleoseismology of major blind structures offshore Santa Barbara.

(17) Offshore borderland. Although the offshore borderland contains several major active faults (e.g., San Clemente fault) that are capable of producing damaging earthquakes, this area has historically been underfunded with respect to onshore seismic hazards studies.

Summary of Workshop Results

A major conclusion reached at the workshop was the necessity of a program of high-resolution imaging in urban Southern California. There was general agreement that high-resolution imaging held great promise for better understanding the seismic hazards posed by the many blind thrust faults that underlie much of urban southern California. Many attendees also expressed delight in the diverse range of disciplines which would be brought together in order to conduct high resolution imaging studies.

However, there was also general agreement among the workshop attendees that, except for offshore techniques, the data quality of easily accessible high resolution imaging methods is not yet optimum. In particular, several attendees expressed doubt that current techniques have sufficiently precise resolution to image shallow fault zone geology.

Given the questions concerning data quality and resolution, we recommend a two-phase program in high resolution imaging studies. We suggest that active field projects are not immediately conducted. Rather, a set of small experiments should be conducted to refine existing methods as well as to explore new field approaches. In particular, we would like to pursue an experimental program of S-wave imaging which has the promise of much higher resolution that standard P-wave techniques. Once we have identified specific techniques that are capable of providing sufficient resolution, we will then propose an active research program of 3-4 campaigns/year.

APPENDIX I

Workshop Attendance List

Rob Clayton
Jim Dolan
Dan Francis
Eldon Gath
Pat Hart
Egill Hauksson
Tom Heaton
Tom Henyey
Mark Legg
Craig Lippus
John Louie
Karl Mueller
Jay Namson
David Okaya
Steve Park
Tom Pratt
Tom Rockwell
Kaye Shedlock
Kerry Sieh
David Sigurdson
Bill Stephenson
Joann Stock
John Suppe
Mary Templeton
Pat Williams
Bob Yeats

APPENDIX II

Reflection/Refraction techniques

Thomas Pratt
Kaye Shedlock
(Bill Stephenson, Jack Odum, Rob Williams)

U.S. Geological Survey, MS 966, Denver Federal Center, Denver, CO 80225

SOURCE	CREW SIZE	RECEIVER SPACING	DEPTH RANGE	EXPECTED RESOLUTION[1]	FIELD COSTS PER DAY[2]	DISTANCE PER DAY
Vibroseis	12 - 15	10m - 100m	300m - 40 km	10m - 60m	$5000 - $15,000	1 km - 10 km
Mini-Sosie (wackers)	8	3m - 15m	50m - 2 km	2.5m - 15m	$4000	360m - 1.8 km
explosives (kinestik)	5 - 6	3m - 15m	50m - 2 km	2.5m - 15m	$4000	300m - 1.5 km
gun (12-gauge/30-06)	4	0.25m - 5m	2m - 250m	1.5m - 5m	$2700	100m - 1.5 km
weight drop/hammer	4	0.25m - 4m	2m - 75m	1.5m - 5m	$2500	100m - 1 km
shotput and ballpeen hammer	4	0.1m - 1m	0.5m - 10m	0.5m - 1.5m	$2500	30m - 300m
Ground-pentrating radar	3	0.1m - 4m	0.5m - 30m	0.25m - 2.0m	$2500	300m - 1.5 km

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[1] Minimum fault offset (vertical) that can be confidently resolved, or minimum distance between two objects which is distinguishable. Resolution is a function of the material velocity, source frequency, and reflector geometry and can vary considerably depending upon local conditions.

[2] Approximate field costs including salary, overhead, per diem, overtime, and equipment. Travel days cost about the same as data acquisition days. Does not include data processing and analysis costs. Costs can be split between an internal and external USGS NEHRP proposal, or done on a contract basis.

Summary of Education and Outreach Activities

Karen McNally

During the last year the Education and Outreach Program has followed directions and priorities specified by (1) the SCEC Advisory Council and (2) the joint California Governor's Office of Emergency Services (OES) /SCEC Work tasks proposed to Federal Emergency Management Agency (FEMA). The architecture of this Program is essentially now complete and follow modern management concepts and principles.

The SCEC Advisory Council had strongly urged that Strategic Planning for outreach be conducted, and that activities pertaining to the release of SCEC products be given the highest priority.

Strategic Planning has involved both researchers together with users of SCEC products and services ("stake holders") via a joint user/research Policy Advisory Board (PAB), and Element Committees. Five major user groups have been identified and are represented both on the PAB and by program Element Committees: Government, Educators, General Public (via the Media, PIO's and other formal education avenues such as Museums, brochures, phone hotlines etc.), Business and Industry, and Engineers. Each of these audiences has specific needs for the format, scales, distribution mechanisms, etc. for SCEC products and information to be effectively communicated. The Element Committees provide the necessary advice and opportunities for knowledge transfer between users and researchers. The Committees also serve to help SCEC with assessments of the needs for SCEC products and/or services, distribution and effective communications of same ("train the trainer" principles), and to prevailed a role of "ownership" for users in the SCEC Outreach program. OES, through a Memorandum of Understanding (MOU) between SCEC and OES (revised during this year), has provided valuable assistance in developing the PAB and Element Committees, relying on their extensive contacts with user communities developed over the last decade. OES has also helped lead the Strategic Planning forums, the development of SCEC Products' Applications and Dissemination Plans, and the development of a model for workshops to release SCEC annual reports.

Numerous specialists have contributed expertise to assist SCEC through the PAB, committees, workshops and as individuals. As a result the following will have been completed, ready for newly hired SCEC staff to develop and maintain, by the end of this fiscal year: 1) A SCEC Education and Outreach Five-Year Workplan Outline, 2) A SCEC Products' Applications & Distribution Plan, 3) An E & O Strategy Plan, Policy Advisory Board, and Element Working Committees, 4) A Needs Assessment Plan for Educational Assistance, grades K through 16, by SCEC, 5) A GIS Workshop and Strategy Summary as the first step toward expansion of SCEC communications through GIS products, 6) General brochures for SCEC, 7) An Earthquake Question & Answer Booklet for Public distribution, 8) A workshop plan designed for release of SCEC products and reports, 9) Documentation of the SCEC Education and Outreach program development and strategic planning process

It is also noted that existing educational texts and curricula have been reviewed, the first undergraduate student intern was mentored through the outreach program, and NSF sponsored meetings on Diversity in the Technological Workforce, and for Education Coordinators, have been attended. The Outreach program has also provided advice and assistance with the SCEC "Phase I" and "Phase II" reports.

Project: GIS Facility for Southern California Earthquake Center
P.I.: Stephen K. Park
Institution: University of California, Riverside
Date: November 25, 1993

Activities in GIS in the last year include accomplishments in data base design and compilation, generation of products for SCEC scientists, presentation of a GIS workshop, and completion of an integrated package for liquefaction mapping.

Data bases which have been completed this year and are available to SCEC scientists include faults, population, and regional geology. The fault data base includes all active faults identified by Wesnousky (1986). Alquist-Priolo faults and zones were digitized at a 1:24,000 scale to form the basic geographic data. Wesnousky (1986) identified faults in addition to the A-P faults however, and these faults were taken from the state 1:250,000 sheets. The individual traces were then collected into the segments identified by Wesnousky (1986) and then tagged with slip rates and recurrence times. The result is an attributed map that allows a user to select a segment, examine all traces in that segment, and access the slip rates and recurrence times. Additionally, Eric Lehmer has written PROBE, a user-friendly ARC/INFO module that utilizes this data base to predict the distribution of probabilities of a user-specified PGA. It also allows a user to segment the faults in a different manner and look at the probability from a single fault. As originally designed, PROBE is slow and Eric is making modifications to speed it up. In addition to the faults, we have also compiled a population data base from TIGER files that will serve as a useful overlay for hazard maps. The regional geology data base is based on the 1:750,000 state geologic map and has been discussed in previous reports. We are now examining how to make all of these data bases available outside of ARC/INFO as ASCII files for those who have other requirements.

Most of our effort in generation of products for SCEC scientists has been focused on creation of figures for the SCEC Phase II report. We have been responsible for formatting various data in a common frame of reference for use by Steve Epstein. Data include strain maps from Steve Salyards, our population and fault data, and hazard maps from Merdad Mahdyiar. In addition, we have provided the fault data to OES.

We presented an afternoon workshop on GIS for the user community in July. This workshop featured talks by EQE, representatives from the USGS, and SCEC scientists who were using GIS in their research. Attenders came from SCEC, OES, private companies, and government agencies.

Finally, I have completed an integrated package in ARC/INFO for evaluating the liquefaction potential of the San Bernardino basin. With variations of ground water level in the basin of 30 m or more in the past 50 years and up to 6 m in one year, an analysis of liquefaction potential based on the water table from previous years may be very erroneous. A graduate student, Jeff Knott, compiled the engineering data needed for this study. The data were obtained from his former employer, CalTrans. The integrated package incorporates the local geology (Figure 1), standard penetration tests from wells in the basin, the topography, and the water table into a prediction of the liquefaction potential within the basin. The analysis is with a grid with a cell size of 90m X 90m. Data bases of the geology, the water table, and the engineering data have been compiled and are used by the program.

Charts created by Seed and Idriss correlating the cyclic stress ratios to blow counts are used, as are their equations for critical cyclic stress ratios needed for liquefaction. These critical cyclic stress ratios were then converted to critical accelerations and compared to predicted acceleration estimated from the Joyner-Boore curves for the San Bernardino segment of the San Andreas fault. These comparisons were done at four depths, 10m, 20m, 30m, and 40m. A cell was assigned a high risk if critical accelerations were exceeded at all four levels, while a low risk consisted of exceedance at only one level. The resulting map (Figure 2) shows that the liquefaction hazard is high only where the water table is close to the surface and within loose soils. The advantage of this integrated package is that different algorithms can readily be compared without much effort because the data bases are managed by ARC/INFO. This package also demonstrates the analytical capabilities of ARC/INFO which transcend its simple graphical facilities.

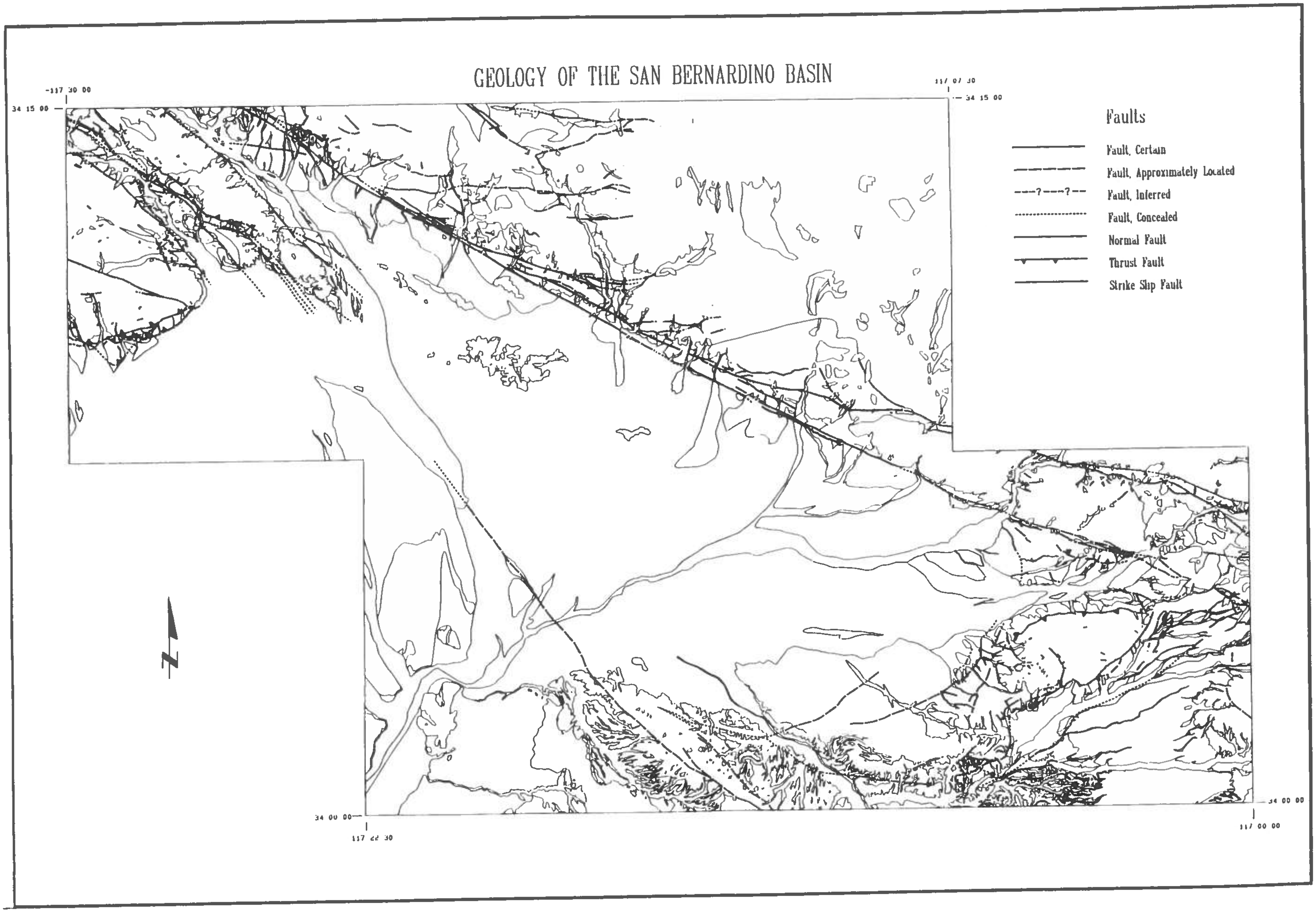
Publications

Park, S.K., M.J.S. Johnston, T.R. Madden, F.D. Morgan, and H.F. Morrison, Electromagnetic precursors to earthquakes in the ULF band: a review of mechanisms and observations, Rev. Geophys., 31, 117-132, 1993.

Figure 1 - Geologic map compiled from USGS open file reports and unpublished sources. For the liquefaction analysis, the units within the basin were generalized into three units: loose, unconsolidated Holocene sediments; older, partially consolidated sediments; and older Quaternary alluvium and Tertiary sediments.

Figure 2 - Liquefaction hazard map for San Bernardino basin. White represents a high risk, dark grey represents low risk, and black represents no risk. Most of the risk is concentrated along the Santa Ana river and at the mouth of washes along the front of the San Bernardino mountains. I-15, I-215, and I-10 are shown for reference.

Figure 1


GEOLOGY OF THE SAN BERNARDINO BASIN
-117 30 00
34 15 00
117 07 30
34 15 00
Faults
Fault, Certain
Fault, Approximately Located
Fault, Inferred
Fault, Concealed
Normal Fault
Thrust Fault
Strike Slip Fault
N
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117 22 30
34 00 00
117 00 00

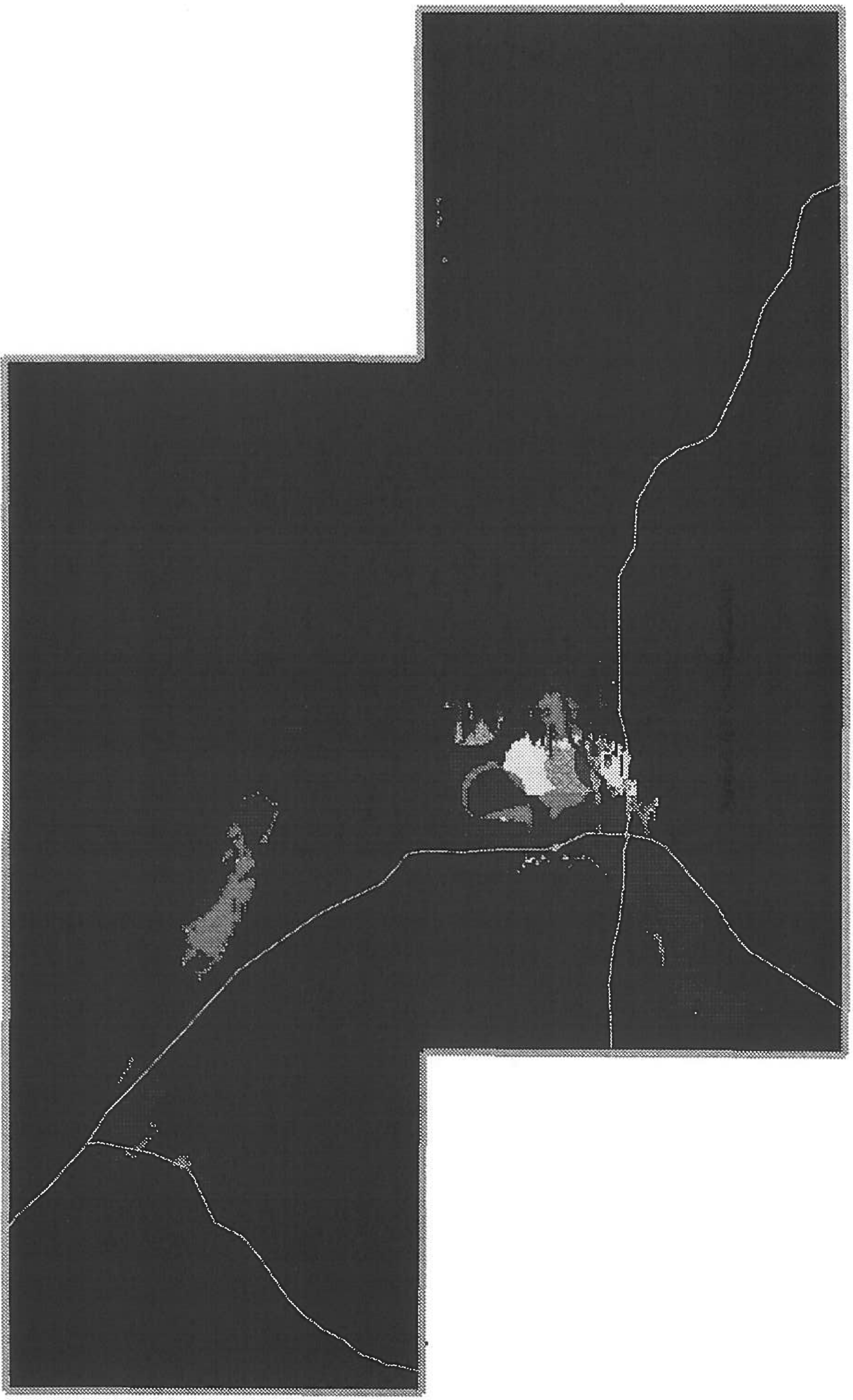

Figure 2

PROGRESS REPORT
SOUTHERN CALIFORNIA EARTHQUAKE CENTER

Computational Support for Paleoseismic and Neotectonic Studies

Anne Lilje and Kerry Sieh, Division of Geological and Planetary Sciences,
Caltech, Pasadena, California

During the past year, several projects have been completed and others are nearing completion. These projects include the Landers ARC/INFO database, Los Angeles area geomorphic analysis and topographic map compilation, and the completion of the base TMAP package for paleoseismic studies.

The Landers ARC/INFO database

The Landers ARC/INFO database is complete. This database contains a map of the Landers fault. In addition to the fault topology there is a catalogue of 1403 slip measurements. Measured attributes stored in the database include lateral slip measurement and associated error, vertical slip measurement and error, aerial photograph number, quality of measurement, observer, and date observed. The topology of the fault trace is currently available by anonymous ftp from harimau.gps.caltech.edu (13.1.215.65.14). Both ASCU and ARC/INFO formats can be obtained.

Complementing the Landers Database is a set of Arc Macro Language tools that perform such functions as interactive display of these data and construction of slip curves. These tools are menu driven and will be available upon request.

Los Angeles Area Tectonic and Geomorphic Analysis

Under the supervision of Jim Dolan, the compilation of circa 1920's 5 foot-interval contour maps for the downtown Los Angeles, Hollywood and Santa Monica have been completed. These maps are functional surface models containing latitude, longitude and elevation information. Additional sections of the Los Angeles area will be completed in the coming months.

In addition to topography, the digitization of surficial traces of active folds, faults and surface geology has been completed for much of the northern Los Angeles Basin. For more information on this database, please contact Jim Dolan.

Topographic and Trench Mapping Software (TMAP)

TMAP is mapping software tailored for paleoseismic excavations and topographic maps. The TMAP base package was completed this year and additional modules are now being considered, expanding it's present capabilities. At the moment, TMAP performs logging of topographic data from a single observation point as well as trench mapping from a single observation point. It is planned this year to expand these capabilities to multiple observation points, and multiple trench sites.

EARTHQUAKE EXHIBITS
AT THE LOS ANGELES STATE MUSEUM OF SCIENCE AND TECHNOLOGY

Charles G. Sammis
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Progress Report to the
Southern California Earthquake Center

1 December, 1993.

The earthquake exhibit at the California state museum is one of their most popular attractions for both adults and the thousands of field-tripping school children who visit each year. Although there were many good exhibits prior to the SCEC involvement, the information content was very low.

In order to increase the information content of the earthquake exhibit, we have completed the following exhibits:

1) A paleoseismicity display.

We obtained permission to use a large-format color photo of Kerry Seih's trench wall taken several years ago by a free-lance photographer for the LA.. Times color section. A 3 by 4 foot light box was constructed to back-light this image. The exhibit includes:

a) Information about the site, sag pond, and peat formation.
b) Information about radiocarbon age dating.
c) Identification of the events which can be seen in the photo.
d) A time line showing past events with a discussion of the problems involved in predicting the next big one

2) A computer display of world seismicity through time.

We are using a program developed at SUNY Binghampton which plots earthquake epicenters through time on a world map. Each earthquake appears initially as a bright yellow spot which fades to red with time. As the program runs the plate boundaries are clearly outlined in red. This computer display is supplemented with text about the different types of earthquakes at the different types of plate boundaries. We also explain first-order observations such as the arcuate shape and greater width of earthquake belts in subduction zones as compared with midocean belts.

This program can also be run in a mode in which it plots seismicity through time on a California map. Text accompanying this display emphasizes that the San Andreas fault system is not the plate boundary, but that deformation associated with the relative plate motion is spread across the entire state. .

3) The CUBE display

We installed a CUBE (CalTech- USGS Broadcast of Earthquakes) display at the museum, thus allowing visitors to see the most recent seismic activity in Southern California in something approaching real time.

We are now in the process of preparing brochures to accompany the exhibit. We hope to have two brochures, a one page handout of earthquake questions and answers that everyone can have and a more detailed guide aimed at group leaders (such as school teachers) and available from the museum staff.

PERMANENT GPS GEODETIC ARRAY OPERATIONS AT SIO
(1993 SCEC ANNUAL PROGRESS REPORT)

Yehuda Bock, Peng Fang, Shelley Marquez, Keith Stark and J. Zhang
Scripps Institution of Oceanography, IGPP 0225, UCSD
9500 Gilman Drive, La Jolla, CA 92093-0225
(619) 534-5292 (Ph), (619) 534-5332 (Fax); bock@pgga.ucsd.edu

1. Introduction

The Permanent GPS Geodetic Array (PGGA) has been operated in southern California since the spring of 1990 by SIO and JPL with assistance from Caltech, MIT and UCLA. Funding for the operations and analysis of the network is provided by SCEC, NASA, NSF and USGS. The goals of the PGGA are to monitor crustal deformation related to the earthquake cycle in California, continuously, in near real-time and with millimeter accuracy. The roles of the PGGA also include providing reference sites to support detailed GPS geophysical surveys in California. The Landers earthquake sequence generated the first real geophysical signals that were detected by PGGA.

2. Accomplishments

(a) Six new sites were added to the PGGA in 1993 at Blythe (with Riverside County Surveyor's Office and USGS Pasadena), China Lake (with MIT), Lake Mathews (with Riverside County Flood Control and Water Conservation District), Palos Verdes (with Caltech and USGS Pasadena), Monument Peak (with Goddard Space Flight Center) and Yucaipa (with UCLA) (Figure 1). Monumentation at Monument Peak was performed by Frank Wyatt.

b) Precise satellite ephemerides, improved earth orientation parameters (polar motion), and coordinates for the PGGA stations have been generated daily since August 1991 in support of GPS surveys in southern California with a 5-7 day delay. SIO has served since June 1992 as a Global Data Center and Global Analysis Center for the International GPS Service for Geodynamics (IGS).

c) The PGGA was instrumental in supporting and determining coseismic and postseismic displacements associated with the Landers earthquake sequence. Coseismic displacements have been reported by Blewitt et al. [1993], Bock et al. [1993] and Hudnut et al. [1993] and postseismic displacements by Shen et al. [1993] and Wdowinski et al. [1993].

d) A bulletin has been distributed electronically every week to users of the PGGA which provides the repeatability of the horizontal and vertical components of the PGGA stations based on the SIO orbits. The horizontal components are on the average at the 5 mm level and the vertical components at the 10-20 mm level for each seven day period covered in the bulletin. Considering that the nearest global tracking station is in Penticton, British Columbia, at a distance of 1800 km, the short-term station repeatability corresponds to about 3 parts per billion in the horizontal and 10 parts per billion in the vertical.

(e) The longer-term repeatability of the PGGA time series has been evaluated. From 70 days of observations, we were able to detect significant sub-centimeter-level coseismic (horizontal) displacements from the Landers earthquake sequence of 28 June, 1992. These displacements computed with respect to the global reference frame agreed with displacements determined from variable slip elastic dislocation models, and with an independent analysis by a group at JPL at the several-millimeter level, consistent with several parts per billion resolution [Blewitt et al., 1993; Bock et al., 1993].

f) Compression across the L.A. Basin has been determined from only several months of PGGA data. In Figure 2, we show the complete six-month time series of daily solutions for the 55-km baseline between the two PGGA sites spanning the Los Angeles Basin. We compute 5.5 mm/yr of compression which compares well with earlier estimates obtained from several years of periodic occupations with VLBI and GPS [Feigl et al., 1993].[1].

(g) Distributed processing schemes for PGGA and IGS analysis has been investigated since the numbers of global and PGGA networks are increasing steadily. Since the time required in GAMIT for data editing increases by a factor greater than the number of stations, and the time required to invert the normal equations by approximately the cube, processing of two smaller networks is more efficient than one large one. To test the feasibility of this concept, we reanalyzed the 70 days of observations from 1992 used to determine coseismic displacements from the Landers earthquake. One network consisted of the global network (26 stations) plus two PGGA stations (DS10 and JPL1), the other the 5 PGGA stations operating at that time (including DS10 and JPL1). We then combined the (2 x 70) solution files from the separate analyses using the GLOBK software package. The coseismic displacements estimated from this analysis were statistically equivalent to those obtained using simultaneous processing (Figure 3).

(h) The feasibility of near real-time processing has been tested. In Figure 4 we show the time series of station positions for the 91-km baseline between the PGGA sites at Lake Mathews and Palos Verdes, computed using SIO orbits that have been extrapolated for 24 hours. There is no significant degradation in the repeatability (2-4 mm in the horizontal and 20 mm in the vertical) compared to using orbits estimated from the same day's data (there is significant degradation when extrapolating the orbits 48 hours). This example implies that we could compute useful orbits in almost real-time (except for anomalous maneuvers of the satellites) if data from the global tracking network could be available within 24 hours.

i) A PC-based bulletin board has been set up by the Scripps Orbit and Permanent Array Center to supply PGGA data and orbits to the general public, as a SCEC outreach program.

References

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Bock, Y., J. Zhang, P. Fang, J.F. Genrich, K. Stark and S. Wdowinski, One year of daily satellite orbit and polar motion estimation for near real time crustal deformation monitoring, Proc. IAU Symposium No. 156, Developments in Astrometry and their Impact on Astrophysics and Geodynamics, I.I. Mueller and B. Kolaczek, eds., Kluwer Academic Publishers, 279-284, 1992.

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Shen, Z., D.D. Jackson, Y. Feng, M. Cline and M. Kim, Postseismic deformation following Landers earthquake, California, June 28, 1992, submitted to Bull. Seismol. Soc. Amer. for Special Issue on the Landers earthquake sequence, 1993.

Wdowinski, S., Y. Bock, P. Fang, J.F. Genrich, D.C. Agnew and F.K. Wyatt, The 1992 Landers earthquake_ sequence: Detection of coseismic and postseismic surface displacement, *Eos, Trans. Amer. Geophys. Union*, *73,* 364, 1992.

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[1] The determination of compression across the L.A. Basin using PGGA data is being studied with Dr. Ken Hudnut, USGS Pasadena office.

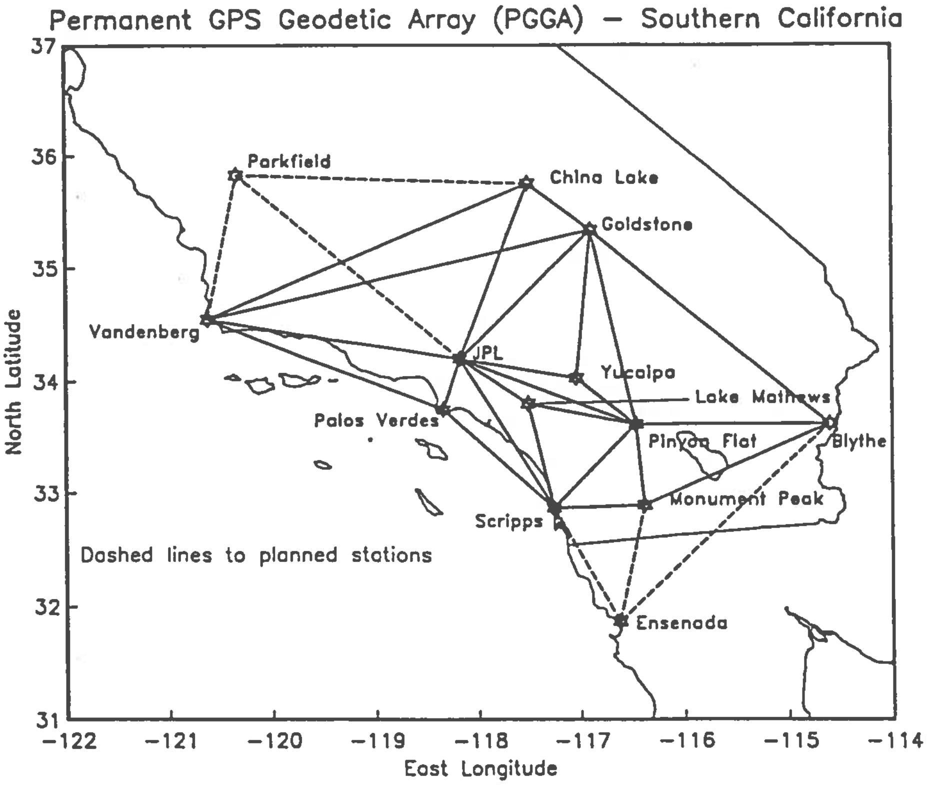
Figure Captions

Figure 1: The Permanent GPS Geodetic Array (PGGA) in southern California.

Figure 2: Time series for daily baseline determinations between the PGGA sites at the Jet Propulsion Laboratory (JPL1) and Palos Verdes (PVEP), in terms of north, east, and vertical components and length. Each point represents a solution based on 24 hours of data. The repeatability (rms scatter) is shown for each component and the straight line fit to the horizontal components and length (denoted by Rate in mm/yr), indicating about 5.5 mm/yr compression across the L.A. Basin.

Figure 3: Observed (solid arrows) and modeled (blank arrows) displacements at four of the PGGA stations in southern California due to the Landers and Big Bear earthquakes of 28 June 1992. We show the displacements and 95% confidence ellipses computed processing the PGGA and IGS data in a simultaneous global solution (unshaded ellipses) and using the distributed processing approach explained in the text (shaded ellipses). The observed displacements are with respect to a global reference frame and, therefore, indicate absolute displacements of the California sites. The contours of displacement magnitude and the computed displacements are based on an elastic halfspace assumption for the behavior of the Earth's crust (all units mm). The surface trace of the Landers rupture is indicated by a heavy line and for the Big Bear earthquake by a dashed line.

Figure 4: Time series for daily baseline determinations between the PGGA sites at Lake Mathews (MATH) and Palos Verdes (PVEP), in terms of north, east, and vertical components and length. Each point represents a solution based on 24 hours of data but using the SIO orbits extrapolated with numerical integration by 24 hours.



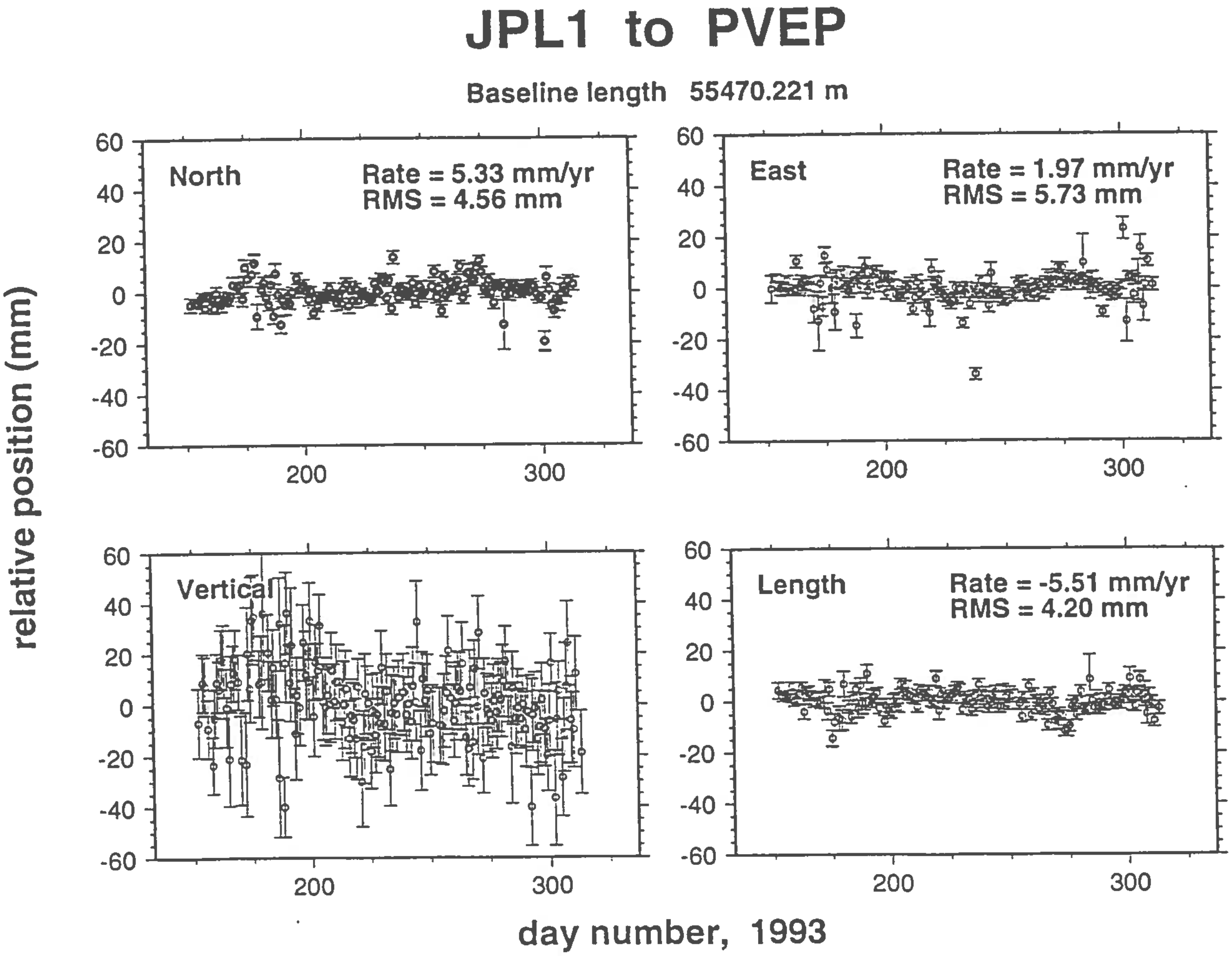
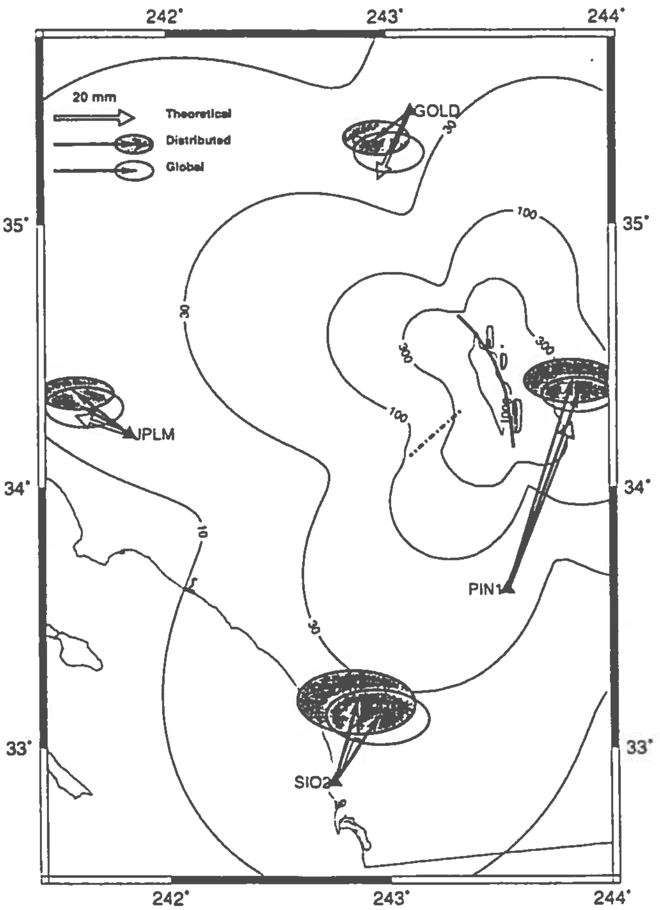


Figure 1 (top); Figure 2 (bottom)



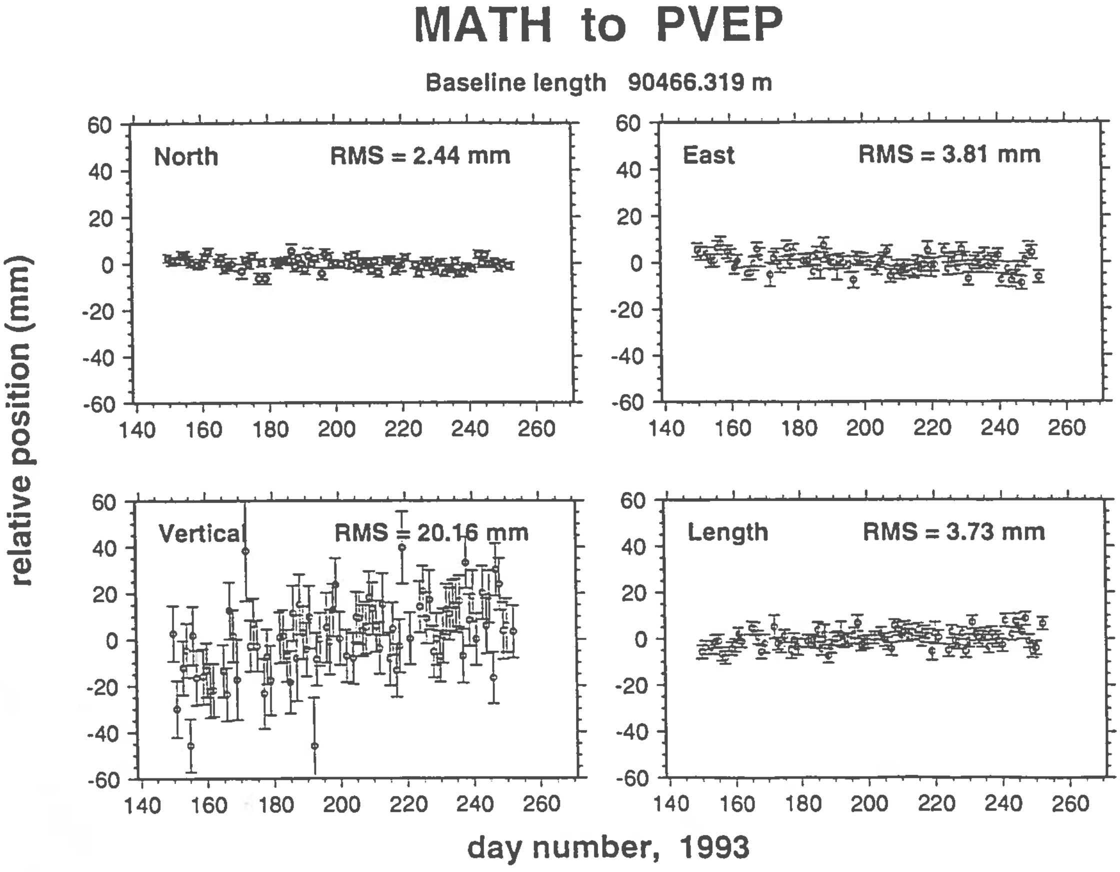


Figure 3 (top); Figure 4 (bottom)

Southern California Earthquake Center
Crustal Deformation Working Group: Infrastructure

David D. Jackson
Department of Earth & Space Sciences
University of California
Los Angeles, CA 90024

Duncan Agnew
Inst. of Geophysics and Planetary Physics
University of California
San Diego, CA

November 29, 1993

Support of the Permanent GPS Geodetic Array

We and the rest of the southern California geodetic community have come to rely on the PGGA network of continuous GPS stations. We support this network by funding staff at UCSD who process the data, research on the application of these data to improving regional survey results, and by making the data available to the surveying community. Stations are now operating at Goldstone, Pinon Flat, Scripps, JPL, Vandenburg, Lake Mathews, and Palos Verdes. Data from the array were important in detecting rapid postseismic strains following the Landers Earthquake.

GPS surveying

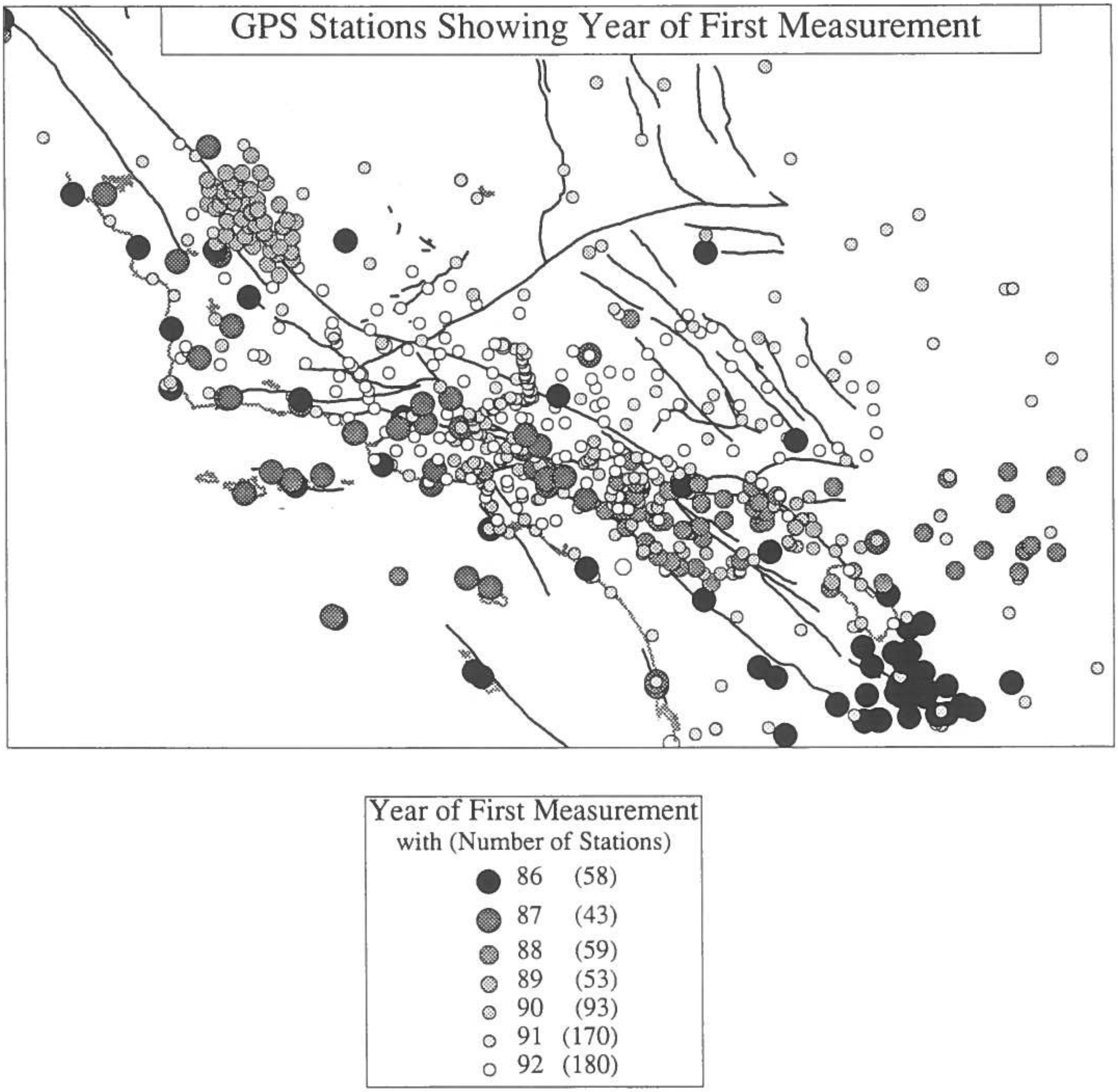
SCEC funded a large GPS survey following the Landers earthquake, which continued into 1993. We also cooperated with Ken Hudnut of USGS in the 1993 "Intercounty GPS Survey", and on our own resurveyed about 20 sites in the LA basin and San Gabriel Mountains.

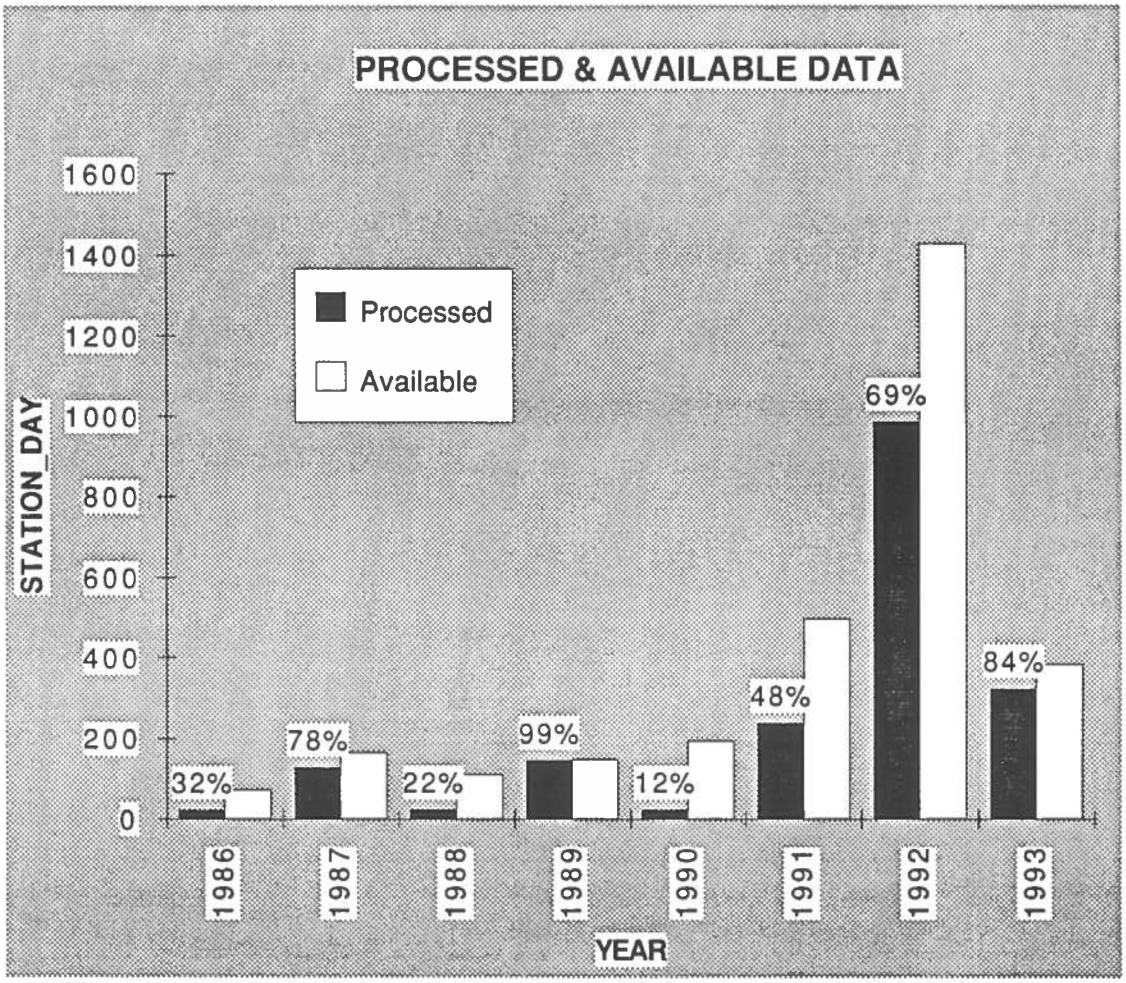
GPS data archiving

We continue to serve as a repository for both our own and contributed GPS data in southern California. We reformat the data to the standard RINEX format as necessary, and check that the data, log sheets, and site descriptions are consistent. Figure 1 shows a map of the sites, coded by year of first observation, for which we have complete data of geodetic quality. With a total of over 750 sites, southern California has a better coverage than anywhere else in the world. From these data we are making more and more accurate velocity estimates. We provided our geodetic velocity estimates for fifty sites to Steven Ward of UCSC, who used them to compile a geodetic strain estimate for use in the Phase 2 Seismic Hazard report.

GPS processing

We process the better GPS data using GAMIT software, and uniform assumptions, to estimate the coordinates and velocities of the monuments in the southern California. Processing is typically the most time-consuming part of GPS, and it is especially challenging with data contributed from many sources. Nevertheless, we are keeping up well with incoming data. Figure 2 shows the available and processed data as a function of year. 1992 was anomalous because of the huge quantity of data collected following the Landers earthquake. We have completed processing most of these data, and we are keeping up with the newly collected data as well.


GPS Stations Showing Year of First Measurement
Year of First Measurement
with (Number of Stations)
● 86 (58)
● 87 (43)
● 88 (59)
● 89 (53)
● 90 (93)
○ 91 (170)
○ 92 (180)


PROCESSED & AVAILABLE DATA
Processed
Available
STATION_DAY
1600
1400
1200
1000
800
600
400
200
0
32%
78%
22%
99%
12%
48%
69%
84%
1986
1987
1988
1989
1990
1991
1992
1993
YEAR

PI: Robert Clayton

STATUS OF THE SCEC DC

The SCEC Data Center (SCEC_DC) has been online and accessible over Internet since January of 1992. The number of researchers accessing the SCEC_DC is currently 138 and has been steadily increasing over time (Figure 1). The current archive consists of the following data types:

1) Short period network data recorded by the SCSN from July 1981 through January 1983, and August 1983 to the present (~ 237 Gbytes).

2) ASCII Data and Catalog Files containing event information associated with each digital seismogram (~500 Mbytes).

3) Triggered TERRAscope data for local and teleseismic events from September 1990 through the present (~1.5 Gbytes).

4) GPS RINEX data from July 1 through July 25, 1992 (~0.7 Gbytes).

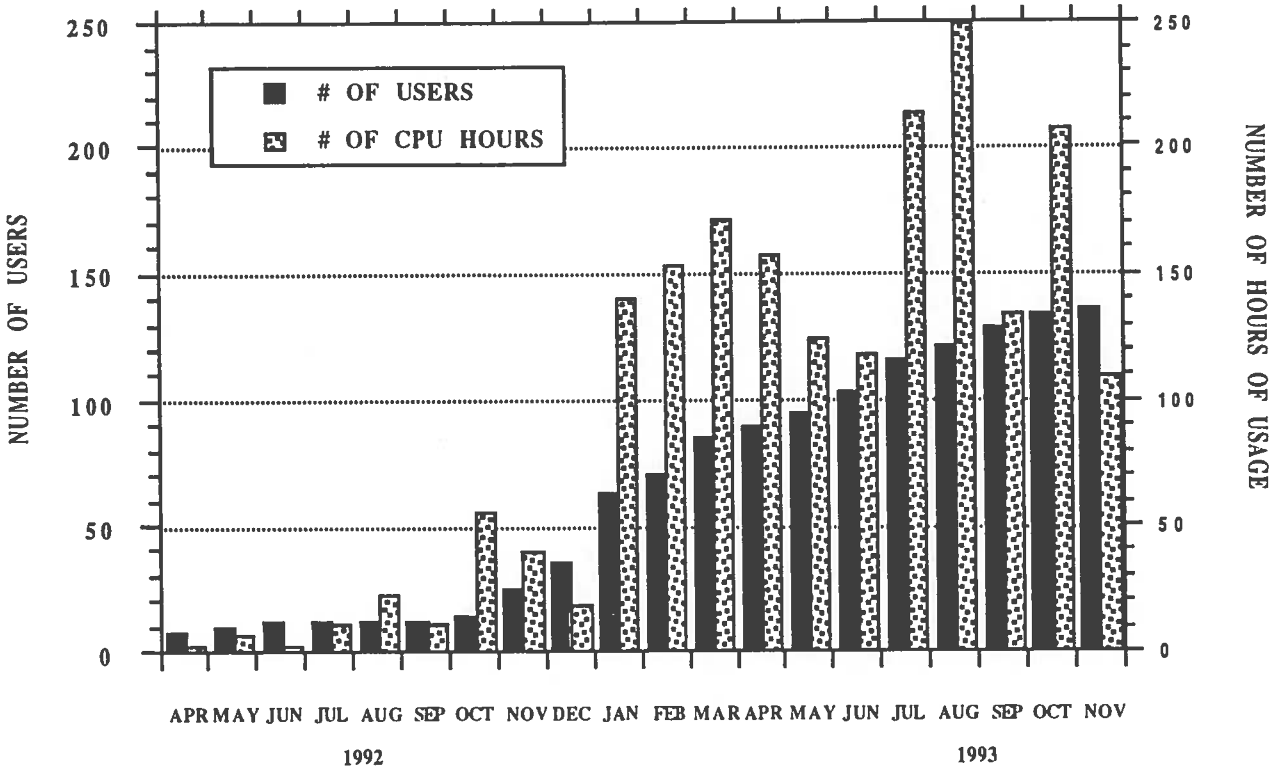
To data, old phase and amplitude data from 1933 through 1960 has been entered into SCSN catalogs. The years 1957 through 1959 have been checked and relocated. Processing of the Landers earthquake sequence has slowed the further analysis of this data set.

In the past year, processing of older data has focused on the Joshua Tree-Landers-Big Bear earthquake sequence. Preliminary processing of M2.5 and greater events through December of 1992 has now been completed (Figure 2). Since January of 1993 preliminary processing has been completed for all recorded events and these data are available online at the SCEC_DC. All of the processed 1992 data is expected to be online by the end of the year. (Approximately seventy-five percent of the 1992 data is currently available.)

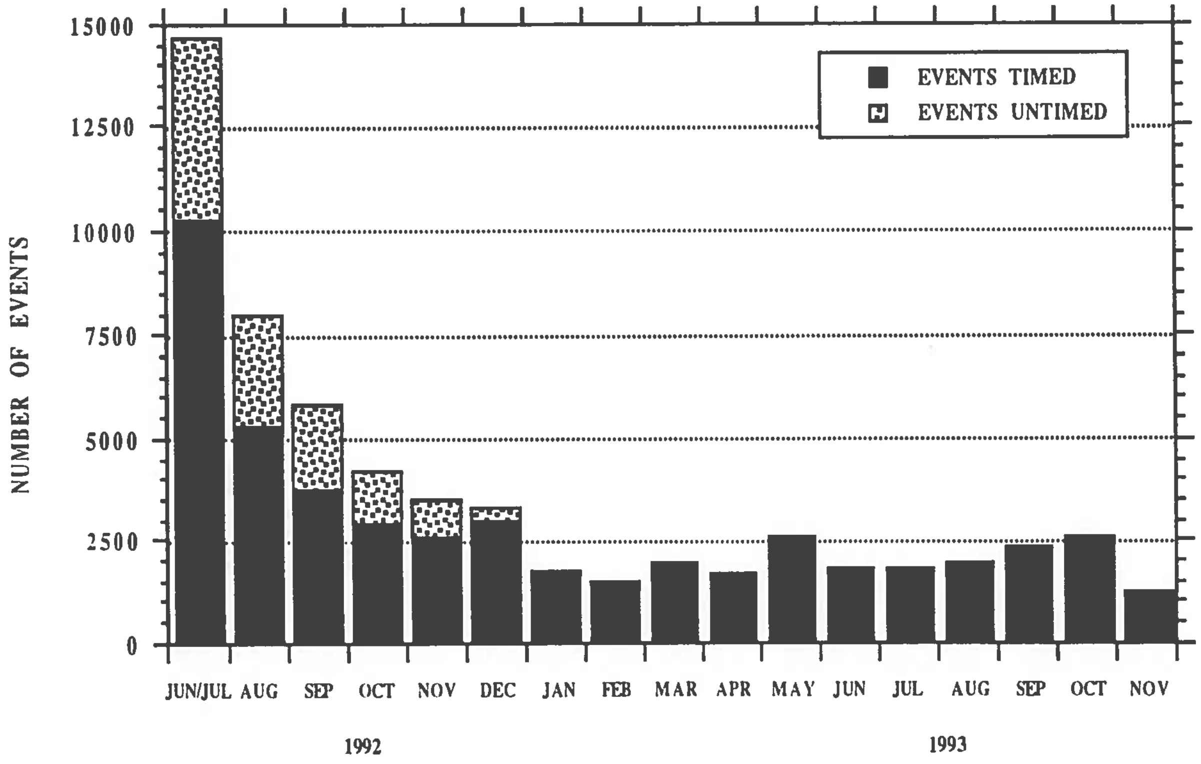
Considerable effort is also being directed towards quality control of the data in the SCEC_DC database. Internal checks, as well as discrepancies pointed out to us by the increasing user population, have revealed that there are some problems. These include time synchronization, station identification and station/channel cross-talk.

Work has begun on implementing a database system which spans the various types of data (e.g. portable seismic data, TERRAscope and Strong Motion) associated with a particular earthquake. The Database is currently being built from binary versions of the ASCII data files. Information regarding seismic station locations/instrument response/histories is already available online in ASCII data files. This information, as well as database sorting and searching capabilities will be incorporated into the Database. In addition, programs to convert the archived digital data into such commonly used formats as SAC, AH and XDR are now accessible and actively being used by SCEC_DC users.

SCEC DATA CENTER ACTIVITY
(Figure 1)



STATUS OF LANDERS AFTERSHOCK PROCESSING
(Figure 2)



1993 SCEC Annual Report:

SOUTHERN CALIFORNIA STRONG-MOTION DATABASE SMDB

P.I.: Ralph J. Archuleta, Institute for Crustal Studies, UC Santa Barabara

The Strong-Motion Database SMDB was designed for the Southern California Earthquake Center to provide a fast and easy access to the strong-motion data. The database combines the following features:

- it has a menu-driven user-friendly interface (Figure 1);
- both parametric and time-series data are available from the database;
- the parametric data are accessed through the network database model;
- the time-series are stored on-line in SAC format.

SMDB now contains the data on 85 earthquakes, 374 stations and 1911 components, including the released CDMG records of the 1992 Cape Mendocino and Landers earthquakes.

SMDB and its manual (The SMDB User's Guide) are now available for the users of Sun 4 workstations with X-Windows via Internet.

The SMDB User's Guide is stored on the computer "quake" at ICS as a text file in the directory /local/ftp/scecdb. One can "ftp" it to a local computer as described below.

1) Initiate ftp (file transfer program) to the ICS computer

```
ftp 128.111.254.236
```

2) Log into the ICS computer as "anonymous"

```
Name  (128.111.254.236:UserName):  anonymous
```

("UserName" here is the User's login ID). The User will get

```
331  Guest  login  ok,  send  ident  as  password.
Password:
```

3) Type in your e-mail address as a password (it won't be echoed back). The User will see

```
230  Guest  login  ok,  access  restrictions  apply.
ftp>
```

4) Set the transfer mode to binary

```
binary
```

5) Go to the proper directory

```
cd scecdb
```

6) Transfer the file

```
get smdb.manual
```

7) Quit ftp

```
quit
```

The procedure of accessing the database is as follows.

1) Append the host "quake" to the local computer with the command:

```
xhost + quake.crustal.ucsb.edu
```

2) Initiate a call to "quake" by issuing either of these two commands:

```
telnet 128.111.254.236
telnet quake.crustal.ucsb.edu
```

3) Answer the prompts for **`login:`** with `scecdb` and for **`Password`**: with `strongmo` (current password for SMDB, subject to periodic changes):

```
login: scecdb
Password:
```

(for Password nothing appears on the screen)

If everything goes successfully the User will have logged on to quake

4) Identify the User

```
Enter user_id for the database:
```

Each SMDB User must have his personal user_id (8 letters or less) to be able to enter the database. One may contact us about assigning a user_id at: alla@quake.crustal.ucsb.edu

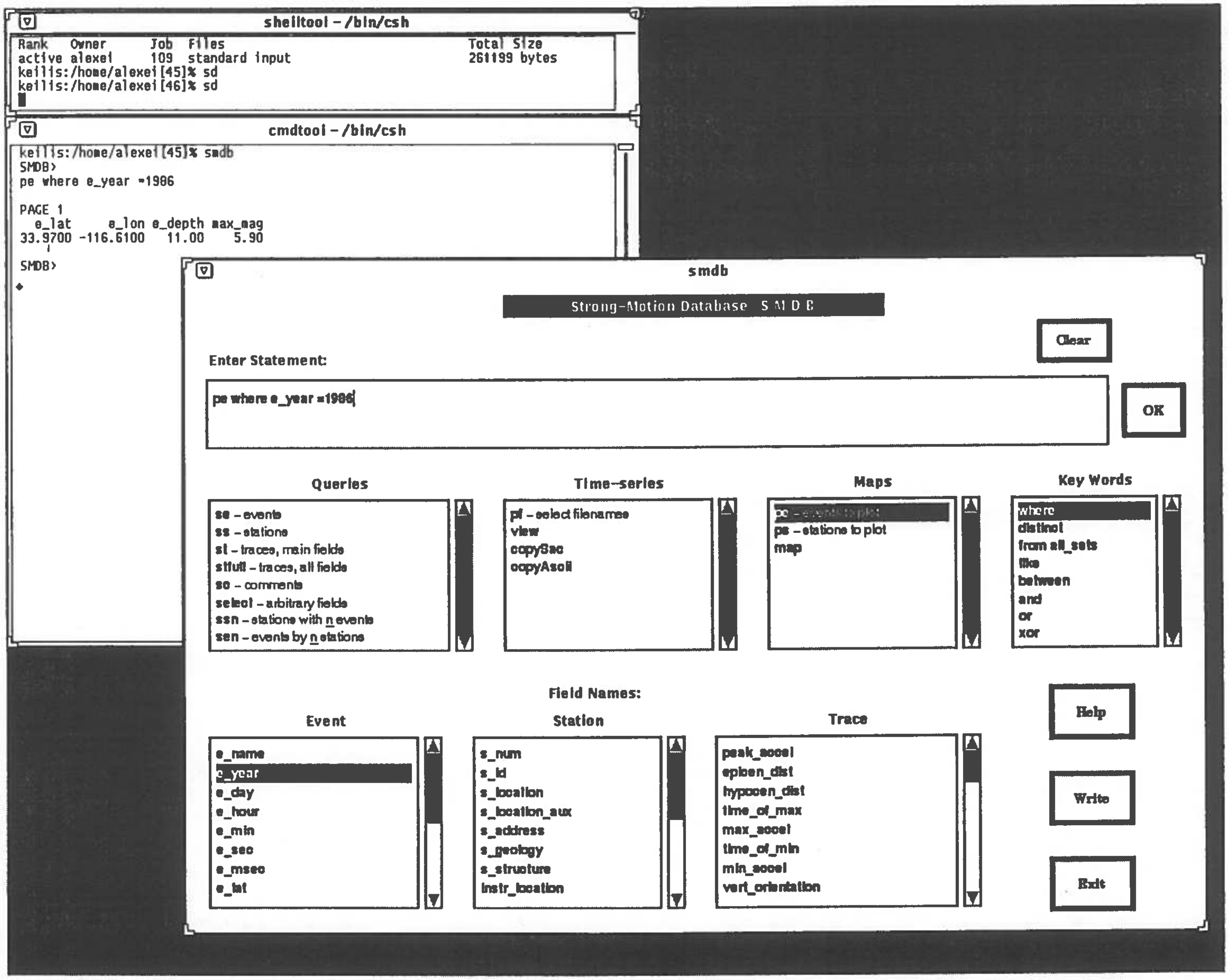
5) Identify the local computer (to set the environment variable DISPLAY)

```
Enter the name of the machine you are sitting at:
```

(usually it is a `machine_name:0`).

If the environment is set up properly, a new window with the database menu is opened and the database prompt **`SMDB>`** appears in your application window. Database statements may now be entered in the "Enter Statement" subwindow of the menu window. Clicking on the "Help" button (or typing the word "help" in the "Enter Statement" subwindow) will print out in the application window a part of the User's Guide about the major possibilities of SMDB and some useful tips, namely, how to get help on certain menu items and how to ftp the SMDB User's Guide to the local computer.

In case of any problems or to get more information please contact Alla Tumarkin at: alla@quake.crustal.ucsb.edu.



```
Rank    Owner        Job   Files                              Total Size
active alexei        109   standard input                     261199 bytes
keilis:/home/alexei[45]% sd
keilis:/home/alexei[46]% sd
```

```
keilis:/home/alexei[45]% smdb
SMDB>
pe where e_year =1986

PAGE 1
  e_lat      e_lon e_depth max_mag
33.9700 -116.6100   11.00    5.90

SMDB>
```

Enter Statement: pe where e_year =1986

PROJECT REPORT: **Near Real-Time Data Transmission from Piñon Flat Observatory**

PROJECT PERIOD: April 1, 1993 — January 31, 1994

SUBMISSION DATE: November 30, 1993

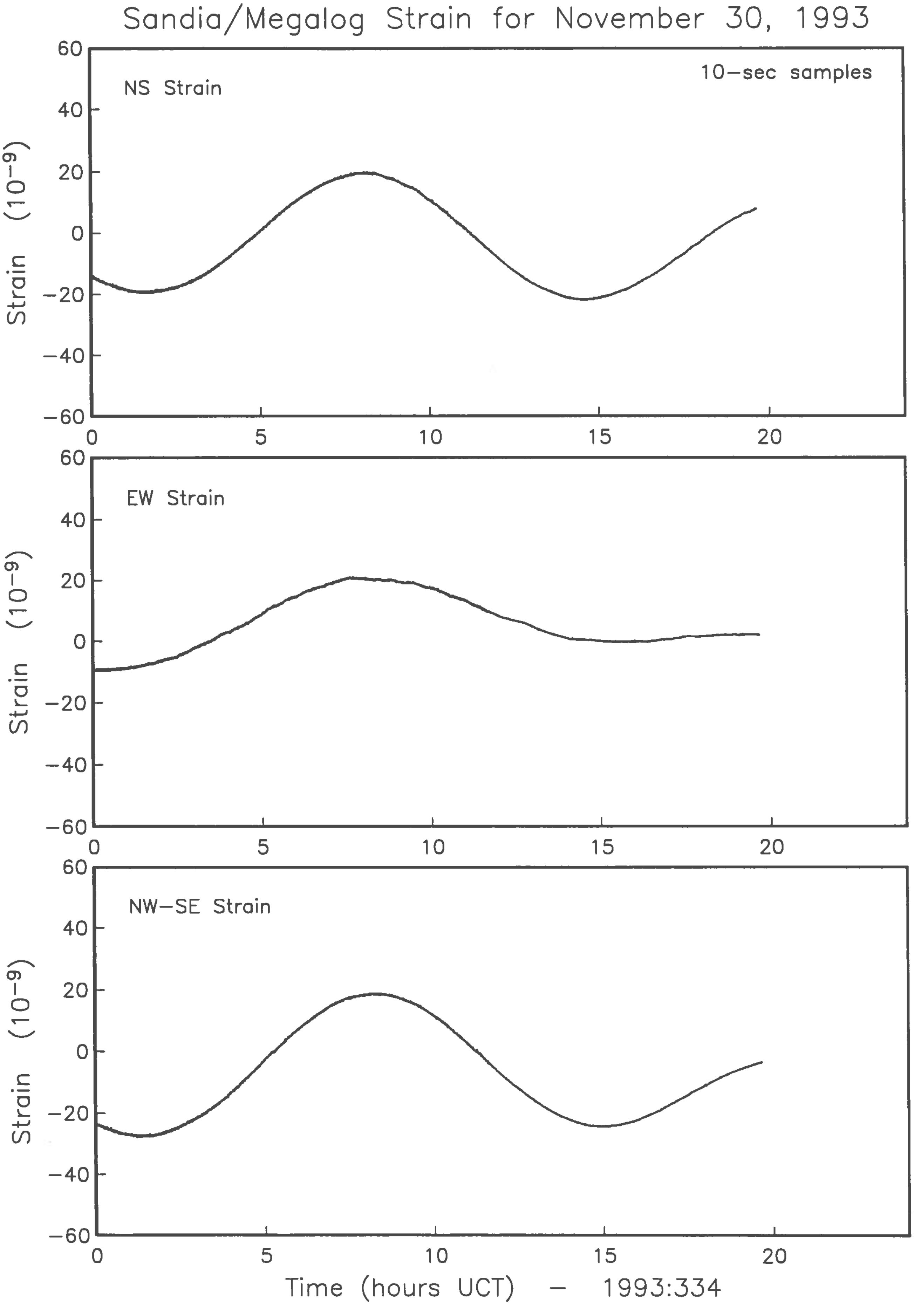
PRINCIPAL INVESTIGATOR: Duncan Carr Agnew, Professor, Geophysics - (619) 534-2590
ASSOCIATE INVESTIGATOR: Frank K. Wyatt, Senior Development Engineer - (619) 534-2411
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography, MC 0225
University of California, San Diego
La Jolla CA 92093-0225

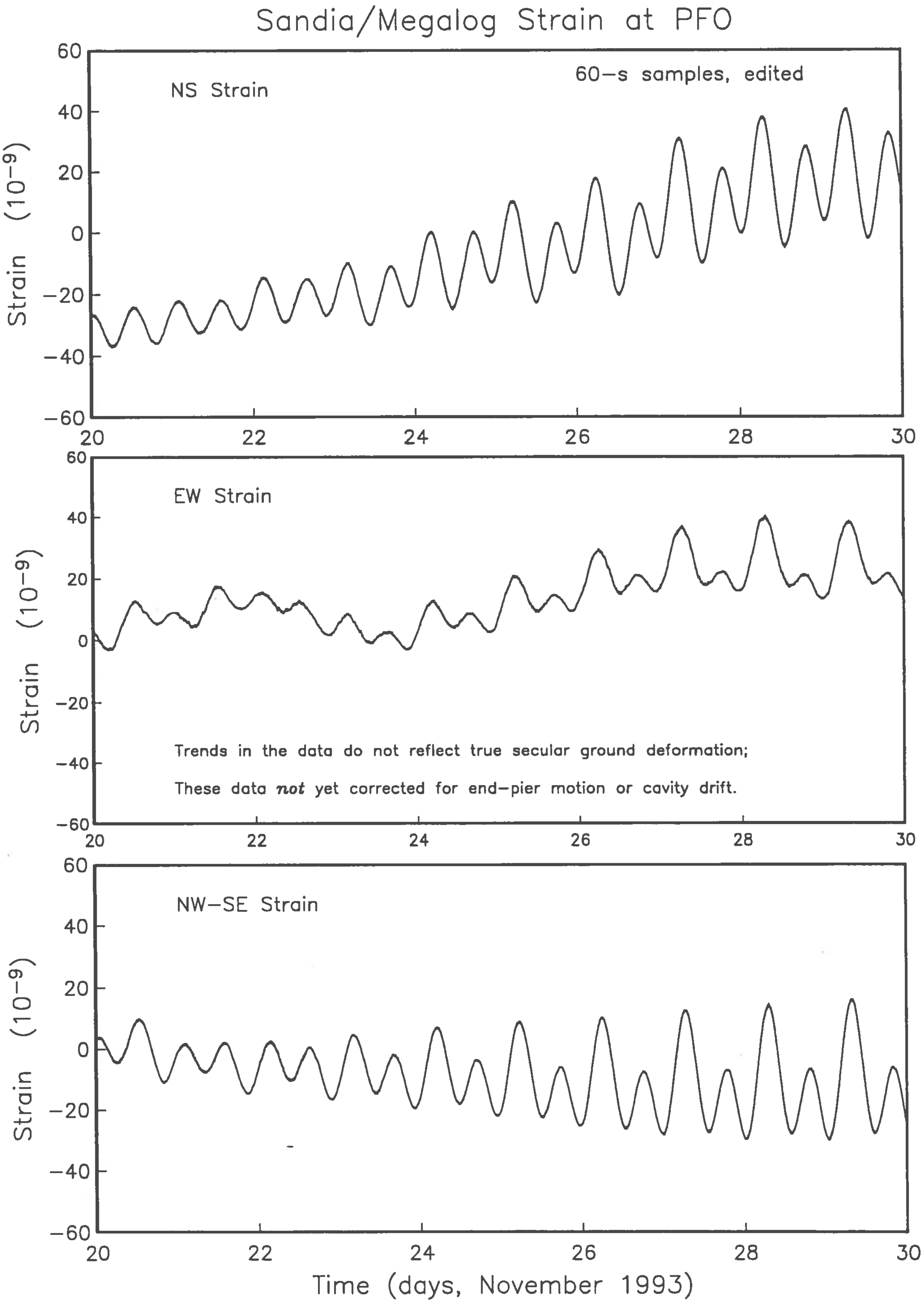
The Southern California Earthquake Center supports infrastructure activities at Piñon Flat Observatory, most notably a long-term program to make the precise strain data collected at PFO more readily available. In addition, some work has been supported on development of a ''test range'' for GPS measurements, using the existing two-color EDM network measured by the USGS at Pinyon Flat; we reobserved the stations of this net in the spring of 1993, to produce new results after the distortion of the net by the Landers earthquake.

DATA ACCESS: While our focus on long-term strain monitoring and research has meant that we have not usually needed real-time data from the PFO strainmeters, the need for such access to the data was vividly demonstrated following the Landers earthquake. In order to provide more rapid access we proposed to replace our existing field system with a PC-based datalogger communicating directly with a lab workstation using the *SLP* or *PPP* protocols; this would give us real-time data for up to 32 channels (the limit being set by telephone line bandwidth). The data files on the workstation would then be immediately accessible on our local network. We made good progress on developing the necessary code (an extension to code already written for the PC to be used as a slow-speed datalogger) until our programmer (an undergraduate) was hired away by Microsoft. The code so far produced requires further testing, which we have not yet had the personnel to do.

As an immediate solution to the problem, we therefore adapted a digital telemetry system developed for PFO by Sandia National Labs in the mid-1970's, and upgraded by them about ten years ago. Its main disadvantage for real-time use, apart from being highly specialized and potentially hard to service quickly, is that the local recording system uses 9-track tape, restricting immediate access. By modifying a spare PC already set up for use as a data recording system, and installing *NFS* software to enable it to write directly to a SUN workstation disk, we have been able capture the telemetered signals here in the lab, and to make the data available in real time in a machine that is accessible over the Internet. We have installed anonymous *ftp* on this machine (ramsden.ucsd.edu) so that the data files may be accessed by interested researchers. Figure 1 shows the most recent data (up to press time), and Figure 2 the previous 10 days. For the 10-day segment the deficiency of the ''uncorrected'' data is obvious; virtually all of the long-period signal evident in such recordings is removed when corrections for end-pier motion and laser-frequency drift are applied.

Although we anticipate some use of these real-time data, it remains the case that considerable post-processing of the data is needed to produce the true measure of earth deformation from many of the better instruments at PFO (as evidenced by the data of Figure 2). This processing is a highly skilled task, which often requires looking at long spans of data, and thus inevitably lags behind real time. We intend to archive much of the processed data in the SCEC database prior to the end of this grant period. We will also continue to work on software to allow partially-processed data to be available as soon as possible after the raw data are collected.


Sandia/Megalog Strain for November 30, 1993
10–sec samples
NS Strain
EW Strain
NW–SE Strain
Strain (10⁻⁹)
60
40
20
0
−20
−40
−60
0
5
10
15
20
Time (hours UCT) – 1993:334



Trends in the data do not reflect true secular ground deformation;

These data ***not*** yet corrected for end–pier motion or cavity drift.

PI: Ralph Archuleta

Portable Broadband Instrument Center (PBIC)
1993 Annual Report

Earthquake response

The Joshua Tree/Landers/Big Bear aftershock sequences occupied the attention of the PBIC for part of 1993. The PBIC finished the preliminary data association for the Joshua Tree portable aftershock deployment about mid-year. The associated dataset was delivered to the SCEC Data Center shortly thereafter. It has since been forwarded to UCSD where it is currently being phase picked and put into a format suitable for the Data Center's database. The adjoining table describes the event association performed at the PBIC on the portable dataset. The stations column represents the number of portable stations that recorded a given event.

Stations	Events
10	75
9	114
8	236
7	352
6	660
5	1232
4	1867
3	2689
2	3491
Total	10716

Equipment Usage

The following table summarizes the projects that utilized PBIC equipment in 1993. The vast majority of equipment remained up and in the field the entire year.

Dates	Institution	PI(s)	Experiment
09/21/92-07/19/93	USC	Abercrombie	Cajon Pass
09/21/92-10/25/93	USC	Yong-Gang Li	LA Basin
01/11/93-10/20/93	UCSB	Archuleta	Keenwyld
03/11/93-10/25/93	UCSB/USC	Archuleta/Chin	LA basin
09/13/93-10/14/93	LLNL	Goldstein/Rock	NTS Explosion
06/25/93-10/25/93	Princeton/UNR	Phinney	Sierra Transect
11/03/93-12/20/93	UCLA	Davis	SCEC/LARSE project

The PBIC has assisted in the deployment and maintenance of several portions of the SCEC/LARSE experiment spread. The PBIC has also assisted USC with the recent reinstallation of the Cajon Pass site using PASSCAL equipment.

Hardware

One recording system was stolen from the Cajon Pass site in July. A replacement system has been ordered with the majority of the cost covered by UCSB insurance. Several solar panels have been stolen from various experiment sites.

The two 24 bit DASs purchased early in 1993 have not performed quite as expected. There were several software problems that arose in early field deployments and an intermittent hardware problem with one unit that has not been resolved yet.

Eight GPS subsytems have been ordered to upgrade the PBIC's current stable of instruments to the more modern timekeeping system.

Purchases with this years equipment funds consisted of three more portable recorders, passive sensors and I/O devices. The recorders have increased dynamic range (24 bits) in response to PBICC recommendations. All new DASs are equipped with GPS timing subsystems.

Sensor Calibration

The PBIC is in the process of calibrating all of the SCEC sensors. It is hoped that an organized system of calibration will provide the SCEC user community with better response information for detailed analysis. This system should also provide tracking of sensor response changes over time and earlier detection of sensor problems.

The PBIC has integrated sensor response software from LLNL with a series of shells providing a means for performing organized calibrations. An additional program produces PostScript files describing sensor response characteristics in detail. Each page contains information about when and where calibrations were run, sensor parameters taken from the manufacturer's specification sheets, parameters derived using the LLNL software and four graphs depicting the sensor's response (Figure 1). The graphs provide a means of viewing the velocity sensitivity, phase shift, group delay and the actual data, both recorded and modeled, used to derive the calibration information. The sheet also includes the exact SAC routine call to deconvolve the recorded data back to earth motion. Copies of the PostScript files are maintained in the anonymous ftp account at quake.crustal.ucsb.edu:/scec/Cal.

PBIC personnel are collaborating with engineers at USC on methods of calibrating sensors that do not have calibration coils using these software packages. Hardware development has included fabrication of a box that can be used to provide a step response to the signal coil of a geophone and record the output.

Software

Development has continued on several software packages. Interaction with the PASSCAL programming group increased dramatically after the PASSCAL sponsored, April workshop in Boulder, CO. SCEC software is now included in the standard PASSCAL software release. In addition, modifications to PASSCAL software made by the PBIC have been integrated into the standard software.

The anonymous ftp account at quake.crustal.ucsb.edu has been reorganized. SCEC supported software is now in its own directory (/scec). The account is still in the process of being organized to provide SCEC members access to the most current information and software. The PBIC is now maintaining a copy of the most current PASSCAL software release at this site.

I47

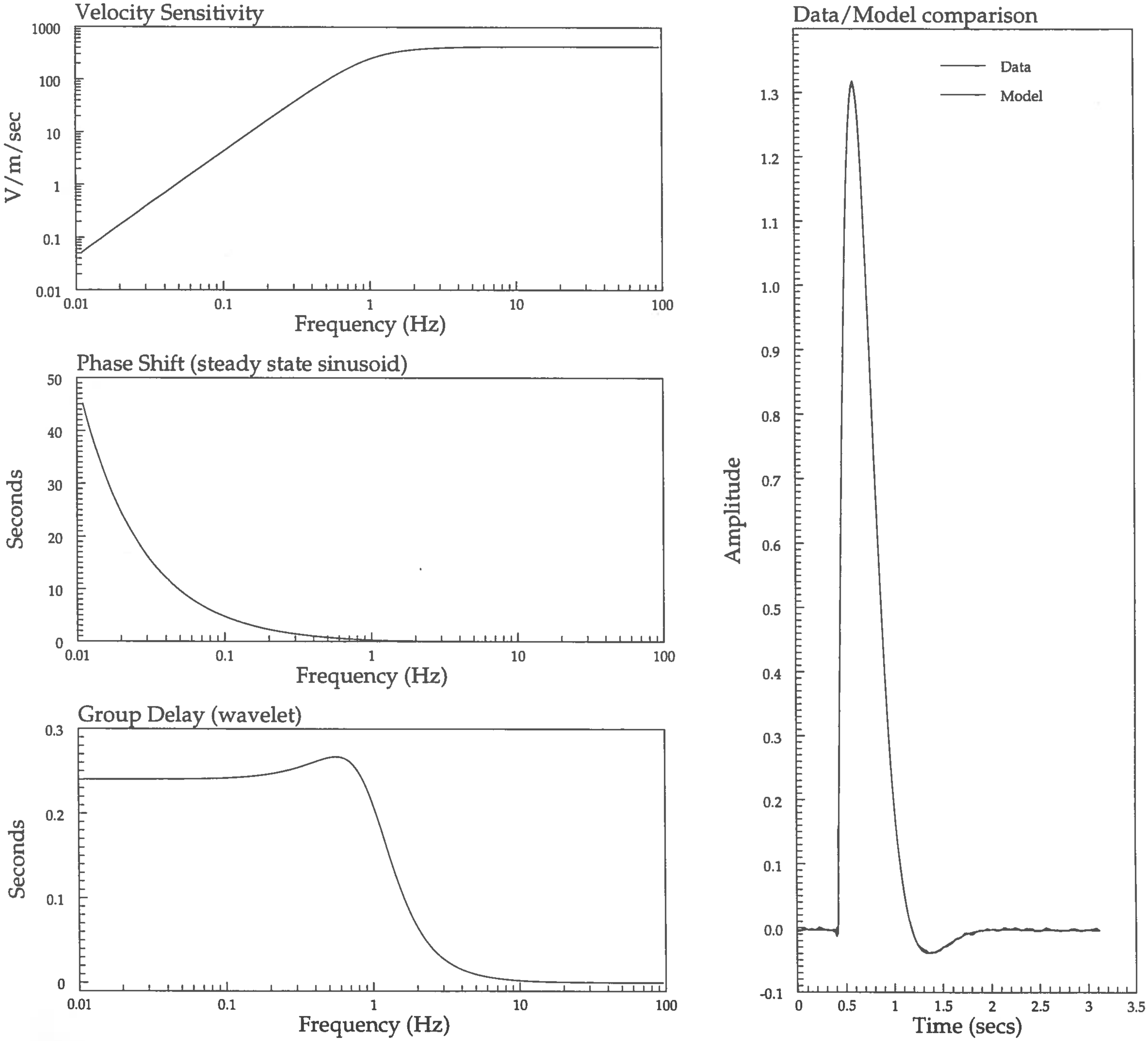
Figure 1: SCEC Sensor Calibration Sheet

Date Measured: **11/03/93** Property of: **SCEC** Site: **PBIC-Lab**

Sensor Info (mfgr/calced) - Model: **L4C-3D** SN: **1109** Comp: **T**

R_c: **34359 Ω** R_d: **54910 Ω** G_d: **426.2** v/m/s

Measured Info (from id)- Freq: **0.997** Hz Damping: **0.752** Gain: **18.7** (unused)



Data recorded with this sensor can be deconvolved back to earth motion using the TRANSFER subroutine in SAC as follows:

To velocity - (from .2 to 30 hz with taper outside that range)

transfer from general n 2 freeperiod 1.003 m 426.2 d 0.752 to none freq .1 .2 30 40

To displacement - (from .2 to 30 hz with taper outside that range)

transfer from general n 3 freeperiod 1.003 m 426.2 d 0.752 to none freq .1 .2 30 40

SCEC Project: Progress Report, 01 Dec. 1993

PIs: Egill Hauksson and Hiroo Kanamori
Institution: California Institute of Technology
Title: **Enhancement of TERRAscope**

INVESTIGATIONS

This project provides support for the installation and operation of the TERRAscope broad-band seismic network. Earthquake data from TERRAscope contribute to the goals of the master model and the seismicity and source processes groups. The TERRAscope project is continuing on schedule. We are doing preparation work for the installation of the next four stations, SNS, GLA, REN, and CWC. We continue to develop software for real-time acquisition and analysis of the TERRAscope data. Scientific analysis of the data is being undertaken by both faculty and graduate students here at Caltech as well as at other institutions around the country.

RESULTS

We report the following accomplishments:

In 1993 we installed 6 new TERRAscope stations (Figure 1). Assembly and preparation work has been underway since May 1992. The stations installed in 1993 are: USC, NEE, VTV, RPV, and DGR. In addition the station SMT was installed by the US Geological Survey Office in Pasadena.

The major responsibilities of the field technician are assembly, installation, and field maintenance of broad-band stations in southern California. Most of the hardware for the TERRAscope stations is purchased as independent modules from outside vendors. Under the direction of Wayne Miller, our senior electronics engineer at Caltech, we assemble the different modules and build our own power supplies, including backup power. We also put a large effort into lightning protection. About one month of field technician time is needed to prepare equipment in the laboratory before field installation of each station. After field installation we find that we need to visit each site on the average about 5 to 10 times until all the problems with telephone lines, extraneous noise sources, and computer crashes are sorted out. Support from SCEC for a field technician has ensured rapid deployment of new stations and continuity of high quality data.

Real-time Telemetry

We transmit TERRAscope data continuously from the remote sites to Caltech in Pasadena, to analyze the data as soon as the earthquake begins. Presently we are receiving continuous data at Caltech from five TERRAscope stations. Two Los Angeles basin stations PAS and USC are connected to Caltech by dedicated Advanced Digital Network (ADN) telephone lines. Two stations, Needles (NEE) and Victorville (VTV) are connected to the microwave communication system operated by the Southern California Gas Company and transmitted to Monterey Park. These two signals are transmitted by an ADN line from Monterey Park to Caltech. The fifth station, Lake Isabella (ISA) is transmitted by a VSAT satellite link from ISA to Golden Colorado and then back to Caltech in Pasadena. This allows us to provide a copy of the data to the US National Seismic Network (USNSN) real-time.

We are negotiating with the Department of Water and Power of the City of Los Angeles to transmit TERRAscope data on their microwave link from Mammoth Lakes Airport (MLA) and Cotton Wood Canyon (CWC) to the Los Angeles area where we would lease a short ADN phone line to bring the signals back to Caltech.

The cooperation with the Southern California Gas Company and the Department of Water and Power is resulting in considerable cost savings for TERRAscope. We hope to investigate other possible avenues of cooperation to make data available real-time from more station and to further enhance the real-time capabilities of TERRAscope.

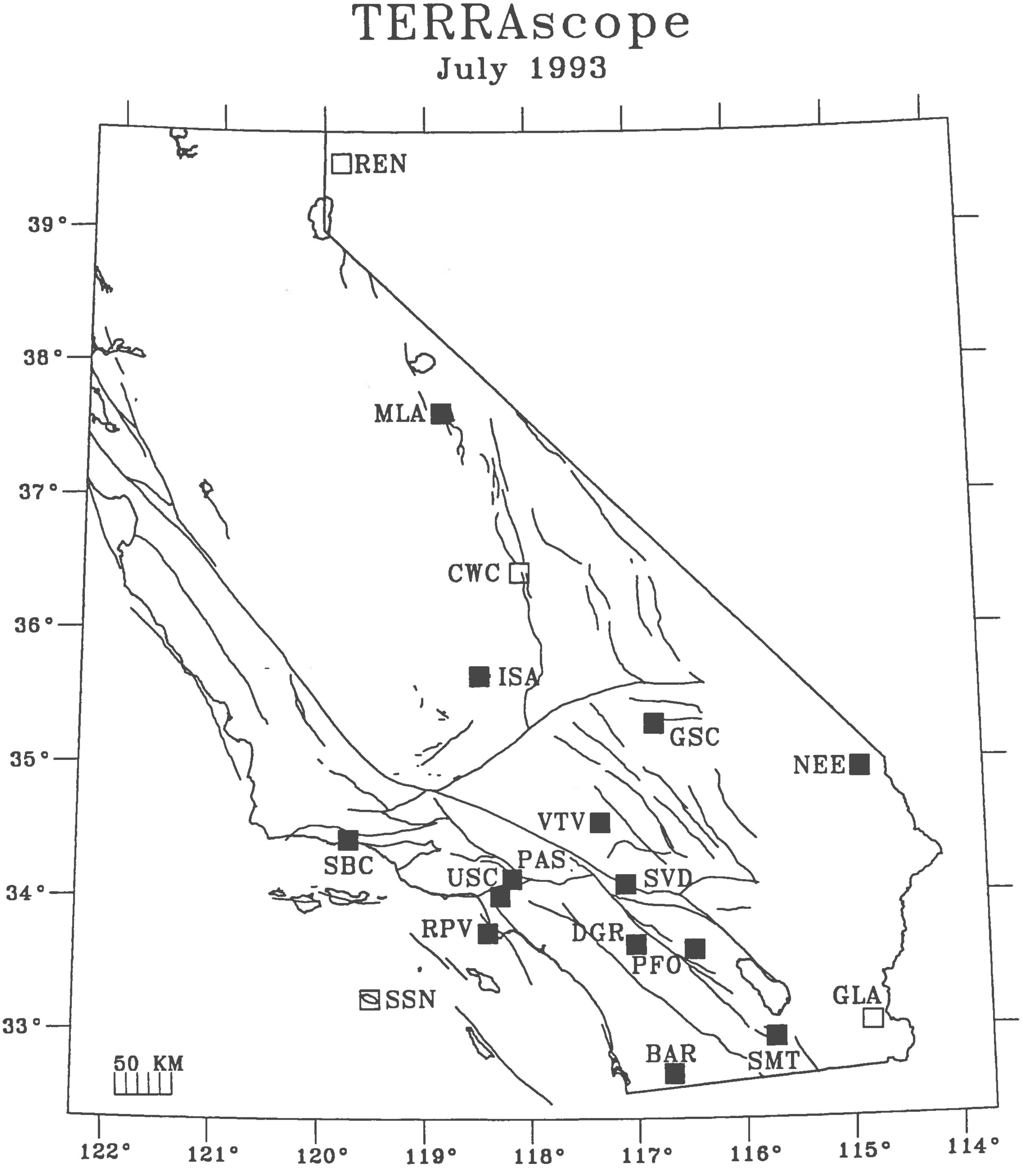


Figure 1. TERRAscope, broad-band seismographic network. Filled squares represent installed stations; open squares are stations to be installed in 1994.

Group A: Master Model Construction and Seismic Hazard Analysis

Group Leader: Keiiti Aki

Group A, Continued

Group A: Master Model

Group Leader: Keiiti Aki

As stated in our original center evaluation criteria, 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. During the first two and three quarters years, we made considerable progress in developing both methodology and prototype products. The 1992 Landers/Big Bear earthquakes, early in our second year, helped provide a research focus and accelerate work toward our goal. The earthquake sequence established deadlines for SCEC to produce first-generation master model products - - namely the Phase I and Phase II reports.

The key work in master model construction is the integration of earth science information relevant to earthquake hazards. In the Phase I report, we addressed the implications of the Landers-Big Bear sequence on the future seismic hazards in southern California for the time frame of about 1 year, and focused on nearby active faults. In Phase II, we are addressing the seismic hazards for the longer period up to 30 years and for the whole of southern California. Through the work of preparing these reports, I believe that we have achieved the integration of information from various disciplines.

At a recent meeting on Phase II report participated by members of NEPEC, CEPEC and the user community, our procedure for integrating geological, seismological and geodetic data for probabilistic seismic hazard estimation received a consensus endorsement. The SCEC model being developed for Phase II report was also presented to a workshop, held on Nov. 8-9, 1993, attended by about 40 leading scientists and engineers of various disciplines working on seismotectonic models at various government agencies, private consulting companies and universities.

In the current SCEC model, the following two categories of earthquakes are considered. One is the so called "characteristic earthquake" directly related to a given fault segment. The other is the "distributed earthquakes" associated with a given area of seismic potential. The reason for the above division is due to the nature of data and their availability from various disciplines. For example, the paleoseismology gives the dates of past earthquakes, amount of slip during each event and slip rate at a trench site. These data are used to estimate the parameters of an earthquake characteristic to the line segment of fault passing the site. The strain accumulation inferred from geodetic survey, on the other hand, is associated with an area rather than a fault line. Likewise, the frequency of earthquakes in a certain magnitude range is also estimated for an area.

In order to accommodate all available data for earthquake potential, we divided the whole of southern California into 65 seismic source zones, and classified each zone into three types (A, B and C) according to the availability of data. "Type A" zones include fault segments for which the paleoseismological data are sufficient for the analysis of time-dependent conditional probability of failure based on the time of last event and statistical distribution of recurrence time interval. In 1988, the Working Group on California Earthquake Probabilities published results of such analyses. Currently, there are 17 Type A zones in southern California including major segments of the San Andreas, San Jacinto, Elsinore and Imperial faults.

"Type B" zones also include major fault segments, but the paleoseismological data are not sufficient for the conditional probability analysis. "Type C" zones are not dominated by any single major faults, but may contain diverse and/or hidden faults. There are currently 24 Type B and 24 Type C zones in southern California. With the improvement in data coverage by paleoseismological studies, some Type B zones will be upgraded to Type A, and some Type C zones to Type B.

The current SCEC database for Type A zones include compilation of slip rate, displacement, recurrence time and last date of the characteristic earthquake with their uncertainties. This database represents a consensus among a group of earthquake geologists under the leadership of D. Schwartz of the U. S. Geological Survey. The group also provided with the slip rate with uncertainty as well as the estimate of maximum magnitude for Type B and C zones.

Probabilities for characteristic earthquakes in Type A zones were calculated by a method modified from the one used by the 1988 Working Group. One modification is a significantly reduced periodicity in the statistical distribution of recurrence interval. The other major modification is the introduction of "cascades model", which allows simultaneous failure of contiguous fault segments and tends to reduce the probability of earthquake occurrence for a fixed frequency of segment failure.

For Type A zones, in addition to characteristic earthquakes, we consider also "distributed earthquakes" which are assumed to be Poissonian in time, equally probable anywhere in a given zone, and having the Gutenberg-Richter magnitude distribution truncated at the characteristic earthquake magnitude. We assumed that the b-value is 1.0, and estimated the a-value from the annual rate of earthquakes for M>6 in each Type A zone inferred by a spatial smoothing (Kagan and Jackson, 1993) of the modified Ellsworth catalog. We removed the large earthquakes to avoid double-counting in Type A zones for which the characteristic earthquakes are already treated separately.

For Type B zones, we assumed that "distributed earthquakes" follow the Gutenberg-Richter relation truncated at the maximum possible earthquake M_X defined for each zone, and also included "characteristic earthquakes" by allowing for the occurrence of "extra" earthquakes with magnitude M_X at the annual rate f. We fixed the a-value for distributed earthquakes from the rate for M>6 inferred from the modified Ellsworth catalog with characteristic earthquakes included for Type A zones. The rate f of extra earthquakes was then set so that the predicted seismic moment (see below for its definition) rate matches the "observed" moment of rate. For Type B zones, we take as the "observed" moment rate the geodetically inferred (Ward, 1993) rate, except in a few zones where geologically observed slip implies a higher moment rate. For Type C zones, we only considered "distributed earthquakes" obeying the Gutenberg-Richter relation truncated at M_X. The a-value is adjusted to match the moment rate implied by the geodetic strain data, except where the observed seismicity suggested a higher rate.

The above procedure uniquely characterizes the seismic sources for the whole of southern California. The above characterization integrates the three basic data sets (paleoseismology, earthquake catalog and geodetic strain data) through the concept of seismic moment. Seismic moment is a measure of earthquake size, directly related to parameters of the causative fault. It is proportional to the total slip added up over the entire rupture area and can be measured by seismology (from the amplitude of seismic waves), geology (from the measured fault length and slip), or geodesy (by deducing fault slip on the rupture surface from observed displacements on the earth's crust that stores the strain). Thus, the rate of seismic moment release in a region can be estimated from each of the three data sets and compared with each other.

Following the procedures described in the preceding section, parameters of both "characteristic" and "distributed" earthquakes are determined for all the 65 zones in southern California. These parameters of the first-generation master model enable us a variety of predictions with regard to future seismicity and seismic hazard in southern California.

First, the annual rate of earthquakes with magnitude greater than 7 was calculated for the whole of southern California. It was found that the predicted rate exceeds several times the historic rate since 1850. This large discrepancy was attributed in part to the low value of maximum possible magnitude M_X assigned to each zone. The lower M_X requires the higher rate of occurrence to account for a given seismic moment rate.

By arbitrarily restricting the minimum M_X to be 7.5, the predicted rate was reduced to about twice the historic rate since 1850.

There are several possibilities for explaining the above discrepancy.

(1) The overestimation of predicted rate may be due to the accumulation of conservative judgment bias applied to parameter estimation for each zone.

(2) The geodetic strain rate used for inferring the seismic moment rate for zones B and C may be released in part aseismically without earthquakes.

(3) The maximum magnitude may be larger than 7.5. This possibility finds support from the observed multiple segments of several separate faults ruptured during the 1992 Landers earthquake. Applying a single Gutenberg-Richter distribution truncated at 8.1-8.3, S. Ward was able to explain both the total seismic moment rate and the historic earthquake rate.

(4) The historic seismicity in southern California since 1850 might have been anomalously low as compared to the long-term seismicity inferred from geological and geodetic data.

Finally, the preliminary SCEC model was compared with the USGS model which has been used for constructing seismic hazard maps included in NEHRP Recommended Provisions for the Development of Seismic Regulation for New Buildings published by FEMA. For this comparison, M. Mahdyiar of Leighton and Associates combined the SCEC model, in which the minimum M_X was chosen to be 7.0, with the Joyner-Boore attenuation relation. The calculation was made for the spectral accelerations at periods 0.3 and 1.0 sec for the exceedance probability of 10% in 50 years. The resultant maps were very similar to those based on the USGS model, except that the pattern is more detailed for land and less so for off-shore in the SCEC maps as compared to the USGS maps. In spite of the high predicted rate of earthquakes as compared to the historic rate mentioned above, the SCEC maps generally show lower values of acceleration spectra as compared to the USGS maps.

SCEC Progress Report: Groundwork for a Master Model
Period: Feb 1, 1993 - Jan 31, 1994
P.I.: Steven G. Wesnousky

The intial stages of this project were primarily aimed at updating the geological data set bearing on the slip rates and paleoearthquake histories for southern California. It is that data which will provide the underpinnings of any seismic hazard analysis for the region. We have essentially completed this aspect of the project. The data has been synthesized into the following report:

> Petersen, M. D., and S.G. Wesnousky, Fault Slip Rates and Earthquake Histories for Active Faults in Southern California, submitted for consideration of publication in the Bulletin of the Seismological Society of America, August 1993.

In turn, the report has provided the basis for the Geology Working Group, of which I am a member, to provide the input for the Phase II Landers Report to reevaluate the probabilities of large earthquakes along faults in southern California. Prelilminary results of that effort are being presented at the 1993 Fall meeting of the AGU in San Francisco.

Concurrently, we have also been examining the characteristics of the earthquake frequency distribution for particular faults by combining paleoseismological data with historical and instrumental earthquake statistics. Understanding the shape of the b-value curve for individual faults is needed to assess the hazard due to moderate to large earthquakes which are not primary surface rupturing events. Initial observations to date suggest that the San Andreas and Garlock faults, the faults with greatest cumulative offset are characterized by a 'characteristic earthquake' frequency distribution whereas the San Jacinto and Newport-Inglewood faults show a classical Gutenberg-Richter distribution. We are now testing that hypothesis by expanding our examination of faults and seismicity to the regions of northern California, New Zealand, and Japan. A manuscript describing the results is currently in preparation. Currently, we are developing and examining existing methodologies to incorporate the distinct and variable shapes of the earthquake frequency distribution for each of the faults into the calculation of seismic hazard in southern California.

We have also began to examine the consequence of ignoring site amplification in the development of seismic hazard maps for hazard mitigation purposes. Our initial results show that the effect of local site amplification can be dramatic in changing the depiction of seismic hazard in a region. For example, in Figure 1, we compare a calculation of the expected shaking of pseudo-velocity at 1-second period at 10% over a 30-year time period on hard-rock to the case where site amplification as a function of local geology is included. In this case, we have assumed, on the basis of Petersen (1992), a site amplification factor of 2 for Tertiary and Quaternary sediments. The result is preliminary and a number of factors have been ignored (e.g. depth of sediments). Nonetheless, the figure illustrates that it is site amplification that is the remaining factor which will produce first-order changes in our view of seismic hazard. We are thus beginning to examine uncertainties in such an approach and the viability of incorporating such information into hazard maps of larger scale (e.g. 1:100,000). It is at this scale that maps can began to be most beneficial to the community of social services concerned with hazard mitigation.

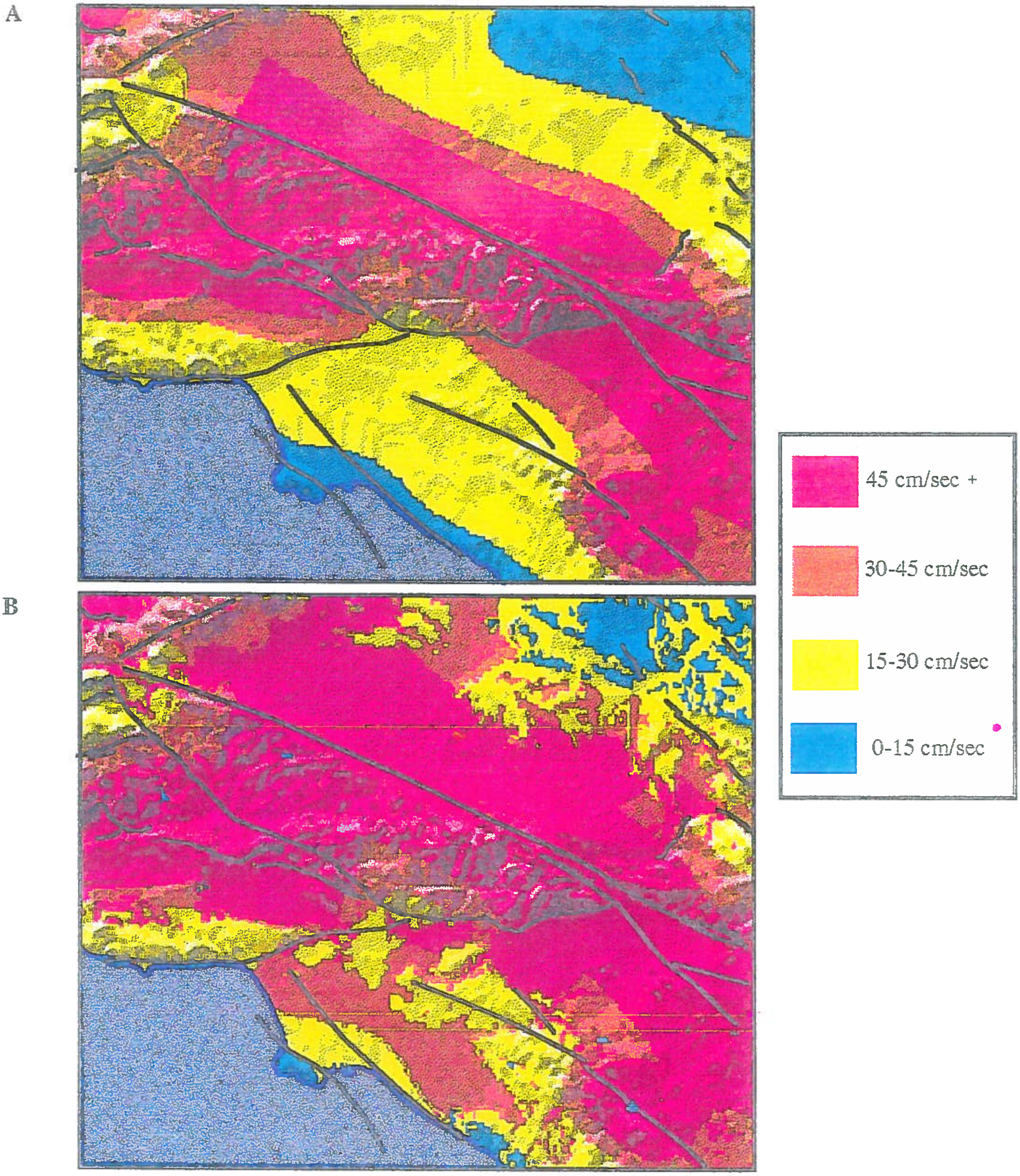


Figure 1. The Los Angeles Basin, showing shaded relief and predicted pseudo-velocity response at 1 s, expected at 10% probability in 30 years on a) hard rock and b) taking into account local site geology. Amplification is assumed on the basis of Petersen (1992) to equal 2 for soft rock and Quaternary alluvium. Map takes into account only major mapped faults and does not include contribution from blind thrusts or moderate size earthquakes occurring off the major faults.

SOUTHERN CALIFORNIA EARTHQUAKE CENTER

1. **Name of PI:** Steven N. Ward
2. **Institution:** University of California, Santa Cruz
3. **Title of Project:** Synthetic Seismicity Models of the San Andreas Fault

Progress Report for 1993

We have been attempting to improve estimates of long-term earthquake recurrence probabilities along the San Andreas Fault by means of synthetic seismicity calculations. The calculations are based on the concept of fault segmentation and incorporate the physics of static dislocation theory. Forecasts constructed from synthetic seismicity are robust in that: they embody regional seismicity information over several units of magnitude; they tie together in a physical manner, a spectrum of fault segment features such as length, strength, characteristic magnitude, mean repeat time and slip rate; they can reasonably account for fault segment interactions; and they are formulated from a catalog which can be extended as long as needed to be statistically significant.

Figure 1 shows the first primary output of the model; a time-space history of seismicity and slip. Seismicity along the San Andreas largely occurs in a convoluted sequence of perhaps a dozen scenarios of characteristic (breaking one segment) and non-characteristic earthquakes (which break several segments at once). Even with distinct strength-defined segments, slip in the various quakes only casually recognizes segment boundaries. It is easy to imagine that overlapping scenarios makes the unraveling of paleoseismic history difficult. Figure 2 shows the second primary output of the model; a time-space history of the stress state. The Figure plots segment-averaged shear stress from Parkfield to Coachella (segments 7-12, Figure 1) over a 4000 year interval. In broad strokes, the segments are loaded over time, fail, and release stress in earthquakes. Sensibly, the stronger segments tend to have a longer interval between major quakes. In closer examination however, things are not simple. Stress recharge consists of two parts; a slow, continuous ramping, plus sudden steps. The ramping reflects the ratcheting in stress from plate tectonics. The steps are stress changes due to fault segment interaction; that is, the shedding of loads from one part of the fault to another by earthquakes. In such an environment, the distribution of quakes in time becomes quite complex.

The degree to which synthetic earthquake sequences are periodic can be gauged from their recurrence statistics. Most simply, these revolve around two numbers, the mean repeat time (T_{ave}) of a certain size quake at a specific site and its coefficient of aperiodicity (ν). The aperiodicity parameter measures the spread in the recurrence interval about T_{ave}. If $\nu = 0$ the sequence would be perfectly periodic. As ν gets larger, periodicity becomes more disrupted (Figure 3). Our fundamental finding is that both T_{ave} and ν are functions of magnitude; T_{ave} increases with magnitude while ν decreases. Large earthquakes retain a vestige of regularity while small ones tend to cluster (Figure 3, *Right*). By allowing both a degree of periodicity for major quakes and a clumping of minor events, the model satisfies common experience in that repeating large quakes at a site are rare, whereas the existence of aftershock sequences belies the clustering of lesser magnitude events.

For the San Andreas models, the cross-over magnitude where gaps become a useful concept is around $M = 7$. Toward lower magnitudes (M=6) ν increases to ≈1.5. For the largest earthquakes (M=7.75), ν drops to ≈0.6. In every case, earthquakes behave more aperiodically than was assumed ($0.21 \leq \nu \leq 0.6$) by WGCEP'88. With weaker earthquake periodicity the effect of gap time recedes, and recurrence probabilities must be revised downward (Table 1, *Right*). For the Parkfield segment for example, the conditional probability of recurrence of a $M \geq 6$ quake within the ten year Parkfield Prediction window beginning in 1983 drops to 32% from Bakun and Lindh's *(16)* estimate of 95%. For the Coachella segment which has not broken in over 300 years, the 30 yr probability of failure drops to 15% from WGCEP's value of 40%. For Mojave, San Bernardino, and Coachella segments combined, the model predicts about a one-in-three and a one-in-eight chance of a M=7+ or M=7.5+ quake in the next 30 years.

Ward, S. N. and S.D.B. Goes, 1993. How regularly do earthquakes recur? A synthetic seismicity model for the San Andreas Fault, *Geophysical Research Letters, 20*, 2131-2134.

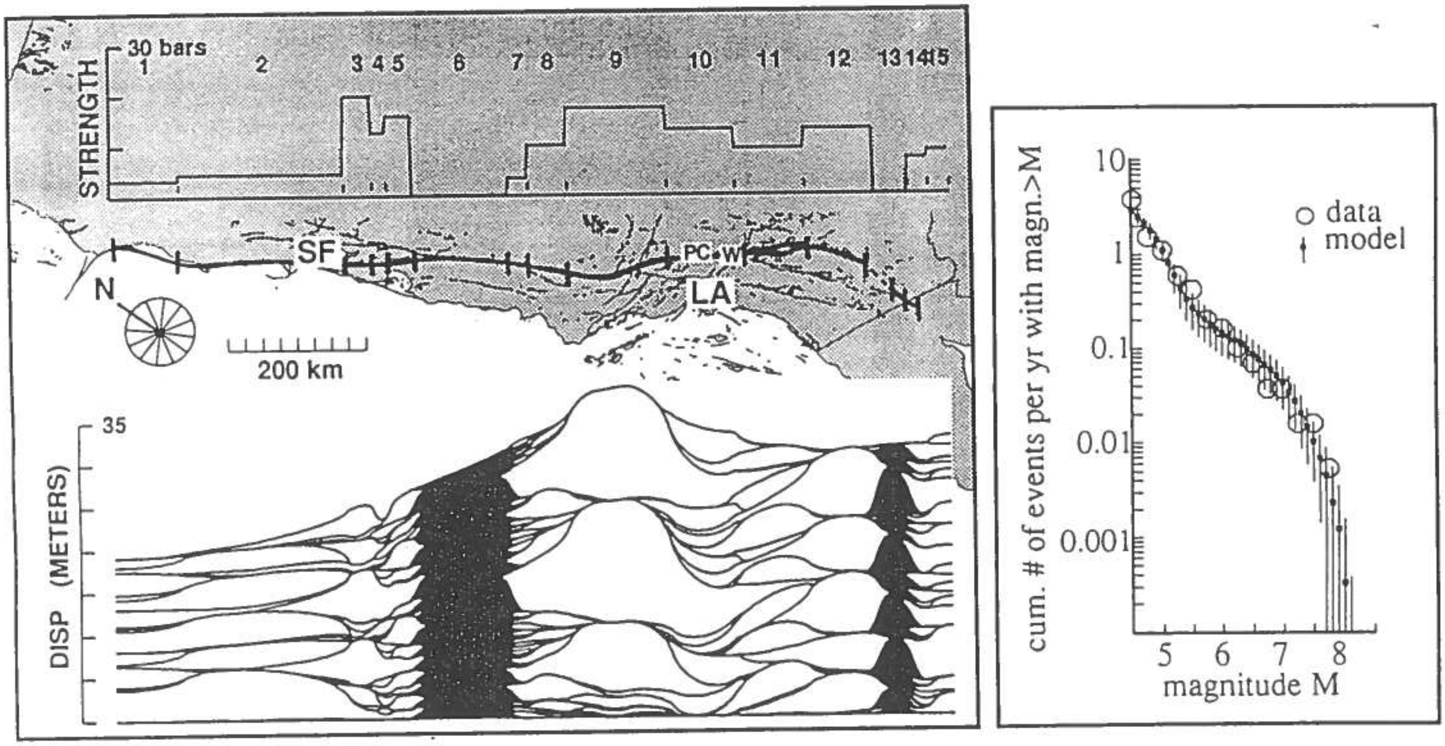


Figure 1. *Left.* Map of California showing the San Andreas Fault (*dark line*) and a typical 1000 year section of synthetic seismicity. Each pillow below the map represents slip in a large quake. The blackened areas are aseismic. This model is based closely on the WGCEP segmentation: length, position and strengths of the 15 segments are drawn along the top. *Right.* An important constraint on the model was that the rate of synthetic seismicity (black squares) must agree with observed seismicity (*open circles*) over several units of magnitude.

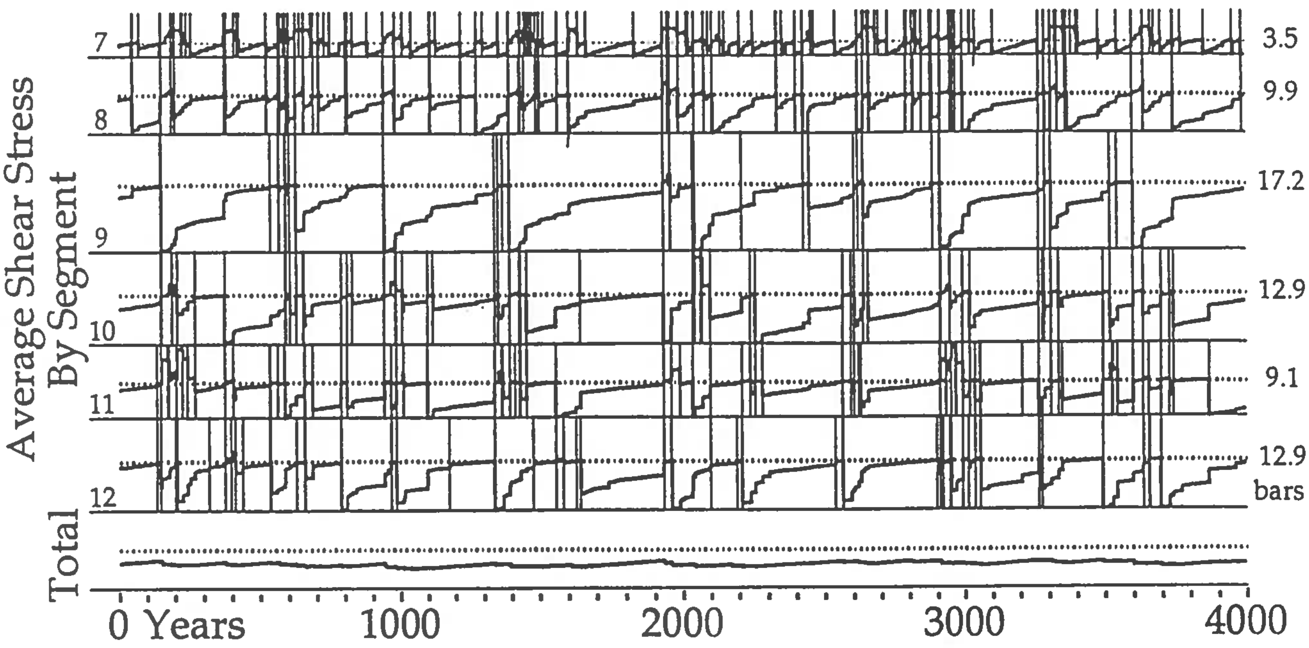
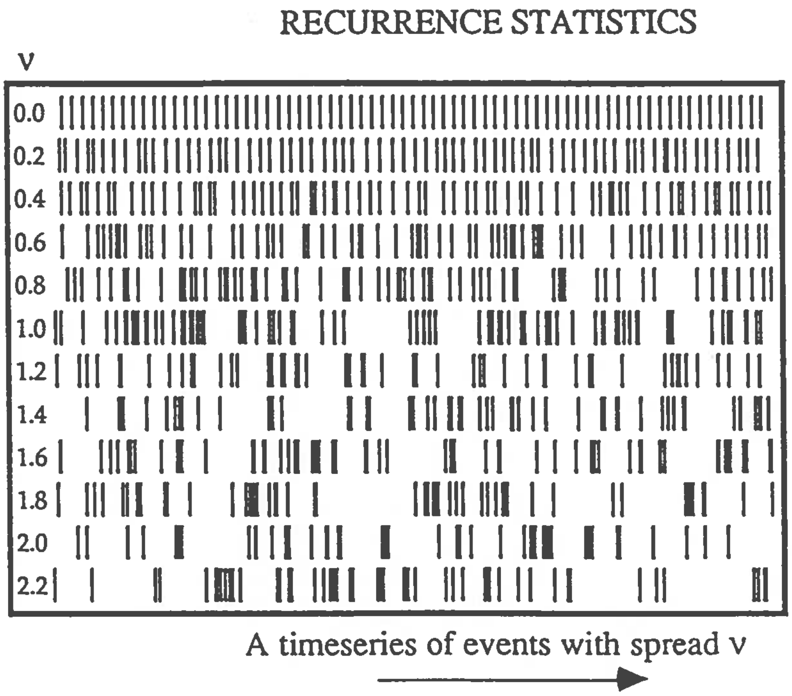


Figure 2. Mean shear stress versus time for Southern California segments Parkfield (#7) to Coachella (# 12) for a typical 4000 year interval. Dashed horizontal lines represent the static strength of the segment. Vertical lines represent segment-breaking earthquakes of magnitude 6.0 or greater. The stress state between quakes is highly irregular due to stress transfer interactions between segments. Note that despite the highly variable stress states of the individual segments, the mean stress over the entire fault (*bottom*) is nearly constant.

PER SEGMENT

	M≥7	
seg	T_{ave}	ν
1	121	1.0
2	119	1.2
3	126	1.0
4	120	0.9
5	172	0.7
6		
7	133	0.8
8	126	0.9
9	191	1.1
10	105	1.2
11	88	1.2
12	137	1.1
13		
14	227	0.7
15	227	0.7



COMBINED STATISTICS FOR WHOLE FAULT

M≥	T_{ave}	ν
6.0	59	1.46
6.5	79	1.28
7.0	137	1.01
7.5	333	0.64

Figure 3. Visualization of the effect of the aperiodicity parameter ν on the recurrence of earthquakes. These 12 "bar code" lines show events drawn from a Weibull distribution of equal T_{ave} and ν increasing from 0.0 to 2.2. Time series with $\nu < 1$ and $\nu > 1$ are termed quasi-periodic and clustered respectively. The tables show how ν depends both on place along the fault (*left*) and on magnitude (*right*).

	Length	Char.	Rate	Recur.	Gap			30yr Cond. Prob.	
Segment	km	Mag.	mm/y	Mag.	Time	T_{ave}	ν	Model	WGCEP
1. Mendocino	100	7.0	18	7.5	82	280	0.49	0.05	<0.1
2. North Coast	240	7.6	18	7.5	82	268	0.53	0.07	<0.1
3. Mid Peninsula	41	7.0	18	7.0	82	126	0.99	0.21	0.2
4. N. Santa Cruz Mts.	20	6.5	18	7.0	82	120	0.92	0.23	0.2
5. S. Santa Cruz Mts.	39	6.9	18	6.5	82	81	1.21	0.28	0.3
6. Creeping Section	130	aseismic	36						
7. Parkfield	30	6.3	36	6.0	22	29	1.11	0.62	>0.9
8. Cholame	55	7.0	36	7.0	131	126	0.88	0.23	0.3
9. Carrizo	145	7.7	36	7.5	131	307	0.58	0.08	0.1
10. Mojave	100	7.4	36	7.5	131	204	0.64	0.15	0.3
11. San Bernardino Mts.	100	7.25	30	7.5	176	201	0.66	0.17	0.2
12. Coachella Valley	100	7.35	30	7.5	308	307	0.50	0.15	0.4
13. Brawley Seismic Z.	50	aseismic	30						
14. N. Imperial Valley	50	6.5	30	6.5	9	57	1.12	0.42	0.5
15. S. Imperial Valley	50	6.5	30	6.5	48	56	1.17	0.38	

Table 1. *Left.* San Andreas Fault segment parameters: length, characteristic magnitude and slip rate (modified from WGCEP). *Right.* Model and WGCEP'88 30-year gap conditional probabilities based on segment-specific recurrence magnitude and gap time. Segment numbers are the same as in Figure 1. Model values of T_{ave} and ν are quoted in columns 6-7.

Progress Report on the Probabilistic Ground Motion Analysis of the Southern California

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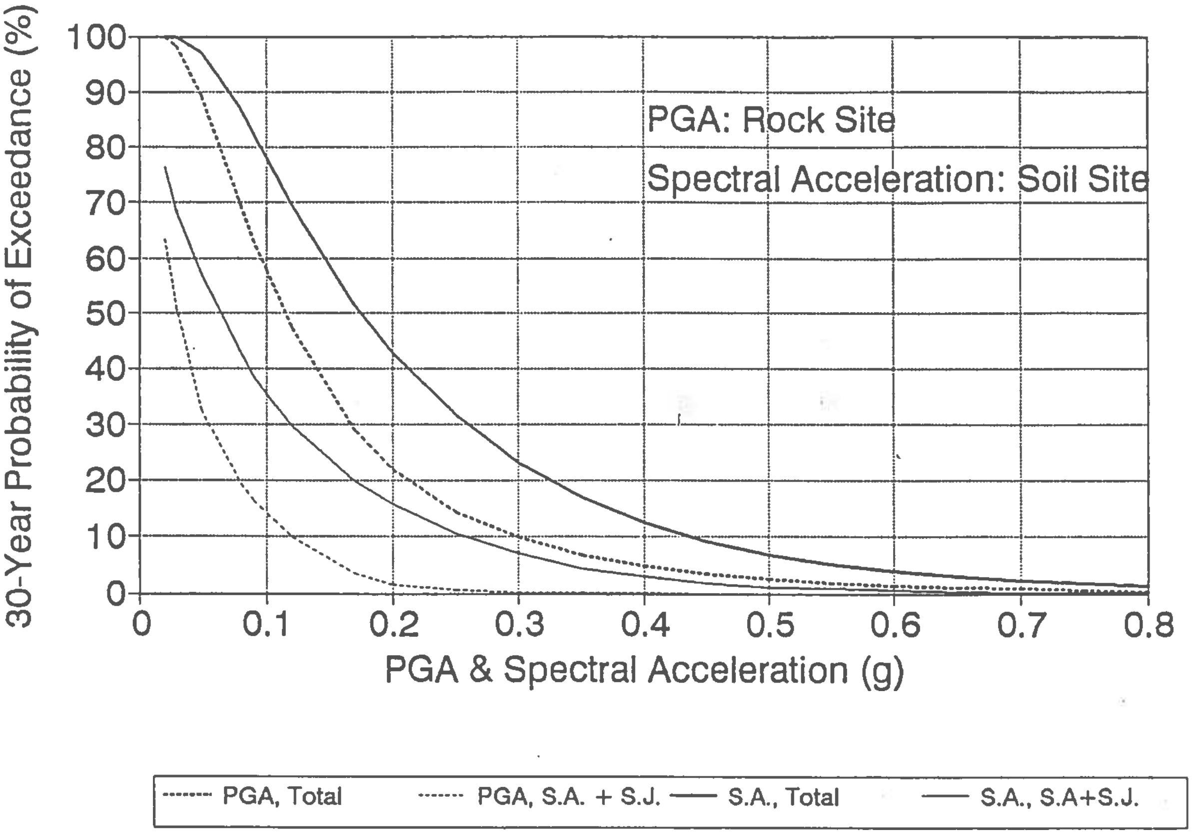
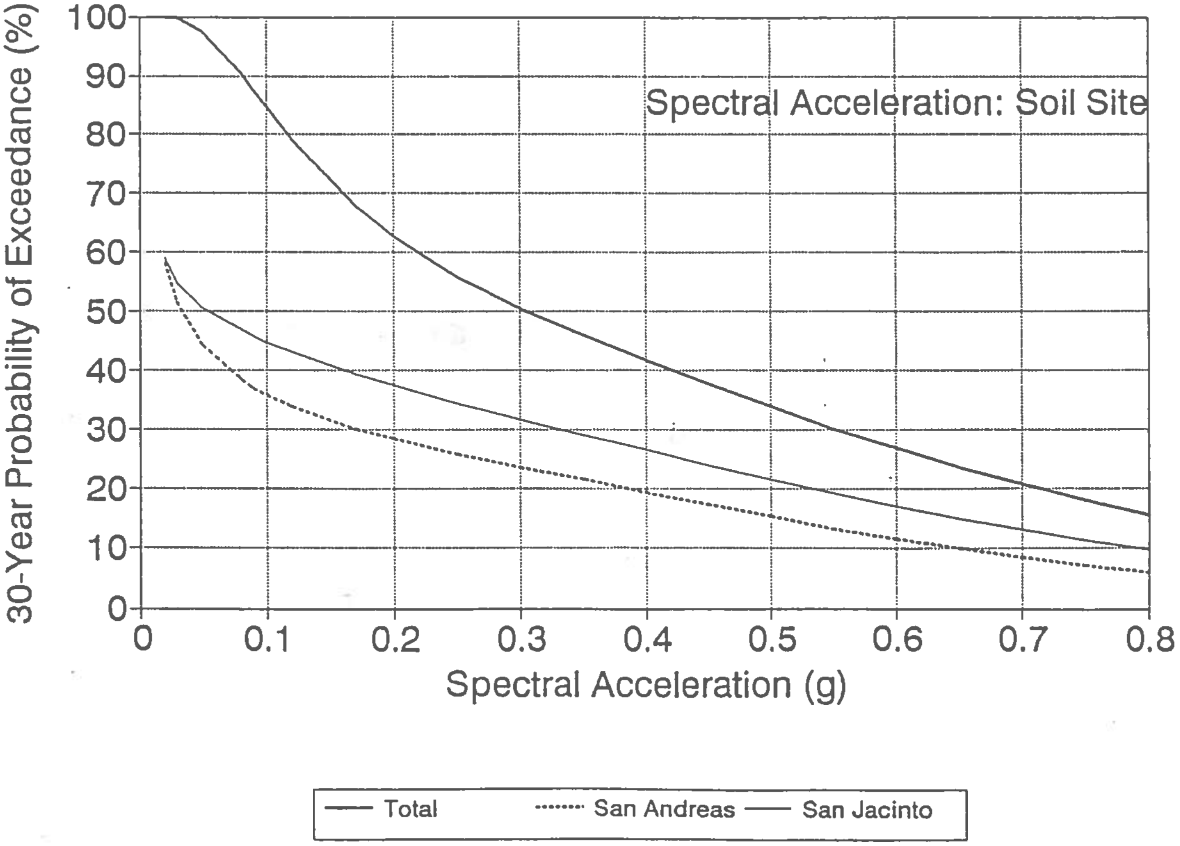
Last year SCEC made a major leap forward on the probabilistic ground motion analysis (PGMA) of the southern California. My participation in that project was to perform parametric studies for the PGMA of the region. The proposed seismicity model for the southern California divides the region into sixty five different seismic zones. A number of these zones are defined narrowly around known faults. However, many others are broad and include a number of active and potentially active faults. The traditional PGMA of areal seismic zones treats earthquakes as point sources. For sites close to areal sources that include known fault systems, the point source assumption could be a matter of concern. Furthermore, the point source assumption does not allow us to model the blind thrust faults. I looked into this problem and developed a model for the PGMA of areal sources using 2-D rupture area for earthquakes. The model, which I call it "2-D Areal", treats earthquakes as line sources with possibility of defining the dipping angles as a function of azimuth. It allows control over the azimuthal distribution of earthquakes as a function of magnitude. Both the line source and point source models for PGMA could be considered as special cases of the 2-D Areal model. Interesting by-products of the model are the seismic moment and strain release distribution as a function of magnitude and azimuth. These information could be useful for constructing regional seismicity models based on the geodetic data. For more information on the 2-D Areal model see the submitted paper to SCEC.

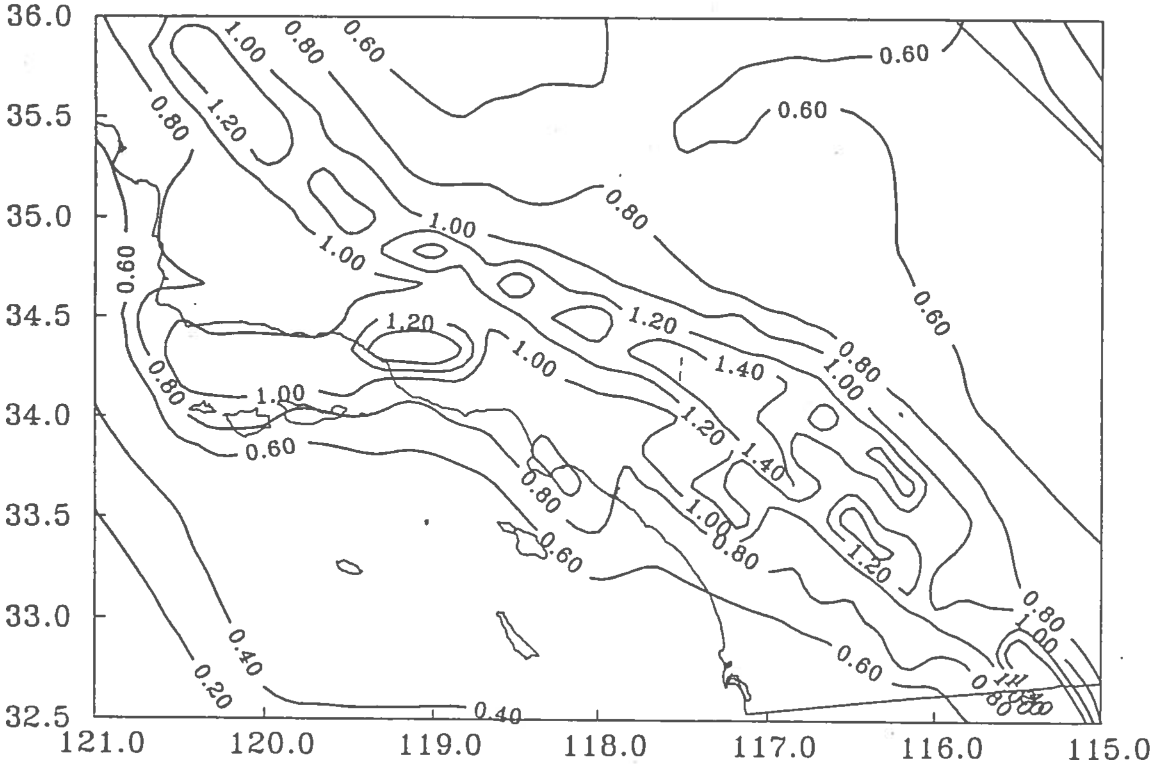
A parametric study of the PGMA at few sites based on the 2-D-Areal and point source models indicate that the point source assumption is valid for cases where the small and moderate size earthquakes are dominant in the PGMA. For narrow zones or zones with peculiar geometry and when the large magnitude earthquakes are dominant in the PGMA, the point source assumption at certain sites would underestimate the probabilistic ground motion values.

The SCEC Working Group following the 1988 Working Group used conditional probability models to estimate the probability of occurrence of large magnitude earthquakes on the San Andreas, San Jacinto, and Elsinore faults. Probabilistic ground motion maps for the PGA based on the Poisson, lognormal, and Weibull conditional probability models for these faults were generated. Probabilistic maps for PGA and spectral acceleration using different attenuation equations and standard deviation of error on the attenuation equations were developed. The results of these semi-parametric studies were used by the Working Group to evaluate and refine the parameters for the seismicity models for the region. The maps presented here show the spectral acceleration values for 0.3 and 1.0 second periods with 10% probability of exceedance in 50 years. As typical examples for the application of the probabilistic analysis, plots of the PGA and spectral acceleration values versus their probability of exceedance in 30-years for the Los Angeles and San Bernandino City Halls are presented.

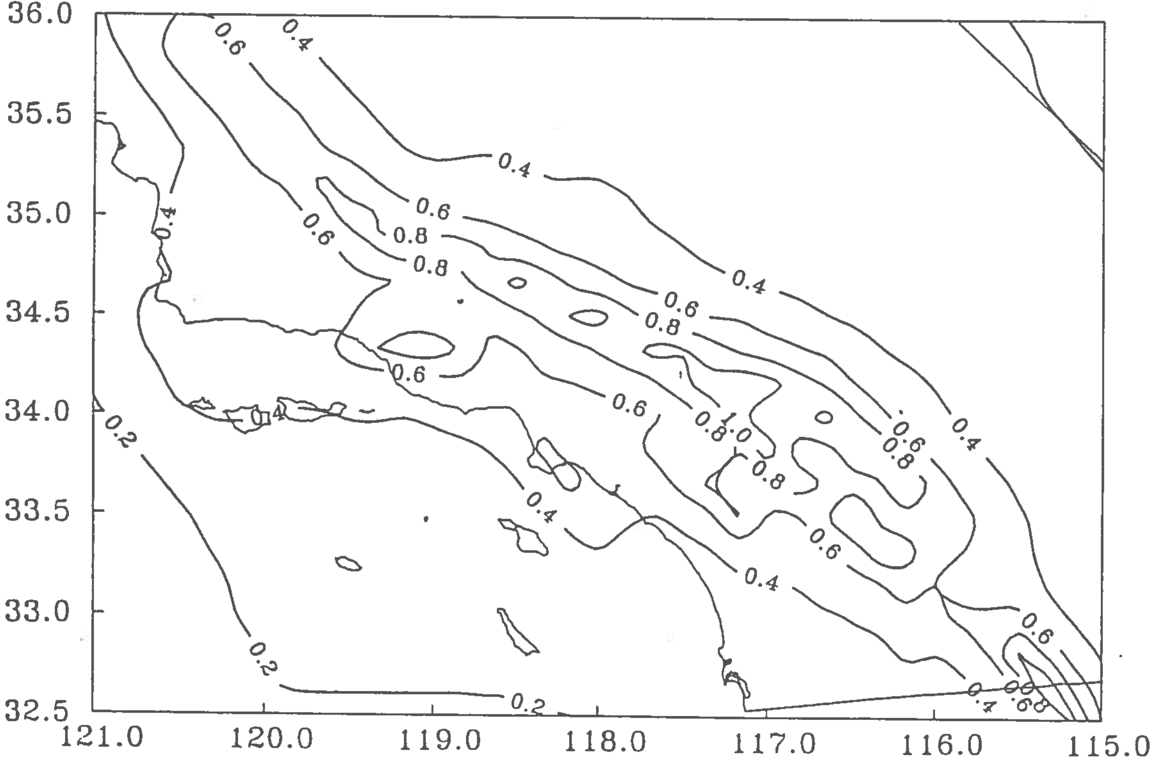

Los Angeles City Hall
PGA & 1 Second Spectral Acceleration


San Bernardino City Hall
1 Second Spectral Acceleration

SA(0.3): 10 Probability of Exceedance in 50 Years (Soil Site)



SA(1.0): 10 Probability of Exceedance in 50 Years (Soil Site)



SITE AMPLIFICATION IN LOS ANGELES BASIN THROUGH MEASUREMENTS OF MICROSEISMS

Research Progress Report on a SCEC Grant
Period: February 1993-November 1993

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Working Group: A
Group Leader: Keiiti Aki
Working Group: B
Group Leader: Steve Day

December 1, 1993

Introduction

This progress report covers research activities supported by the grant for period February 1993 through October 1993. The research activities can be divided into the following groups:

- Analysis of the results from the last year large scale microtremor measurements in the Los Angeles basin where microtremors were recorded at 143 sites in the Los Angeles metropolitan area.
- Three dimensional resonance modeling for Los Angeles sedimentary basin.

In addition a large scale microtremor measurements were performed at Treasure Island in May of 1993 as a part of a project supported by the Navy.

The personnel involved in this research consists of M. Dravinski (PI) and a graduate student G. Ding.

Analysis of Large Scale Microtremor Measurements

The final site map for 1992 microtremor measurements is displayed by Fig. 1. The following tasks have been completed in data processing for microtremor data from the 1992 measurements:

- Velocity spectra were calculated for all the sites including multiple recordings at the reference bedrock site (LC).
- Spectral ratios for each site and the reference bedrock site are calculated for a period range $0.5\,\mathrm{sec} < T < 10\,\mathrm{sec}$.
- Average spectral ratios for each site and the reference site are calculated for the period intervals: 1-2 sec; 2-4 sec; 4-8 sec; 8-10 sec; and 4-4.2 sec.

A typical example of velocity spectra for several stations is depicted by Fig.2. Based on these calculations histograms of predominant period of motion of the basin are determined both from the velocity spectra and from the spectral ratios. The histograms show clear presence of the sources in the predominant periods when the results are based upon the velocity spectra (see Fig. 3). This demonstrate the importance of the spectral ratios in elimination of the source effects in the results.

The following tasks are presently under way in this area of research:

- Correlation of spectral ratio to sediment subsurface structure of the basin.
- Comparison of weak and strong ground motion results.

Microtremor spectral ratio distribution is being compared with the available maps of the subsurface structure of the basin. The idea is to see how does the weak ground motion amplification relates to the depth of the basin.

Following large scale microtremor measurements in August of 1992 earthquake measurements were performed for a week at two sites. One at USC as a typical deep sediment site and one at La Canada which is a bedrock site. Two small earthquakes were recorded at both sites. One occurred on August 14 and the other on August 17, 1992. Based on this records we plan to compare spectral ratios from strong ground motion with those of microtremors.

Three Dimensional Resonance of Los Angeles Basin

In order to gain better understanding of microtremor the measurements resonance analysis of the Los Angeles basin is presently under way. Previous research suggests that for highly irregular geometry of the basin a full three dimensional model is required to study its resonance. For that purpose an eigenvalue problem for resonant motion of the basin is formulated by using finite element approach. The basin has been discretized and the resonant frequencies of different order were computed in the long period range. Figure 4 illustrates the pattern of one of the resonant mode of the basin. So far, the agreement between the theoretical predictions and predominant period of motion observed from microtremor measurement agree well in the long period range $T > 3\,\text{sec}$.

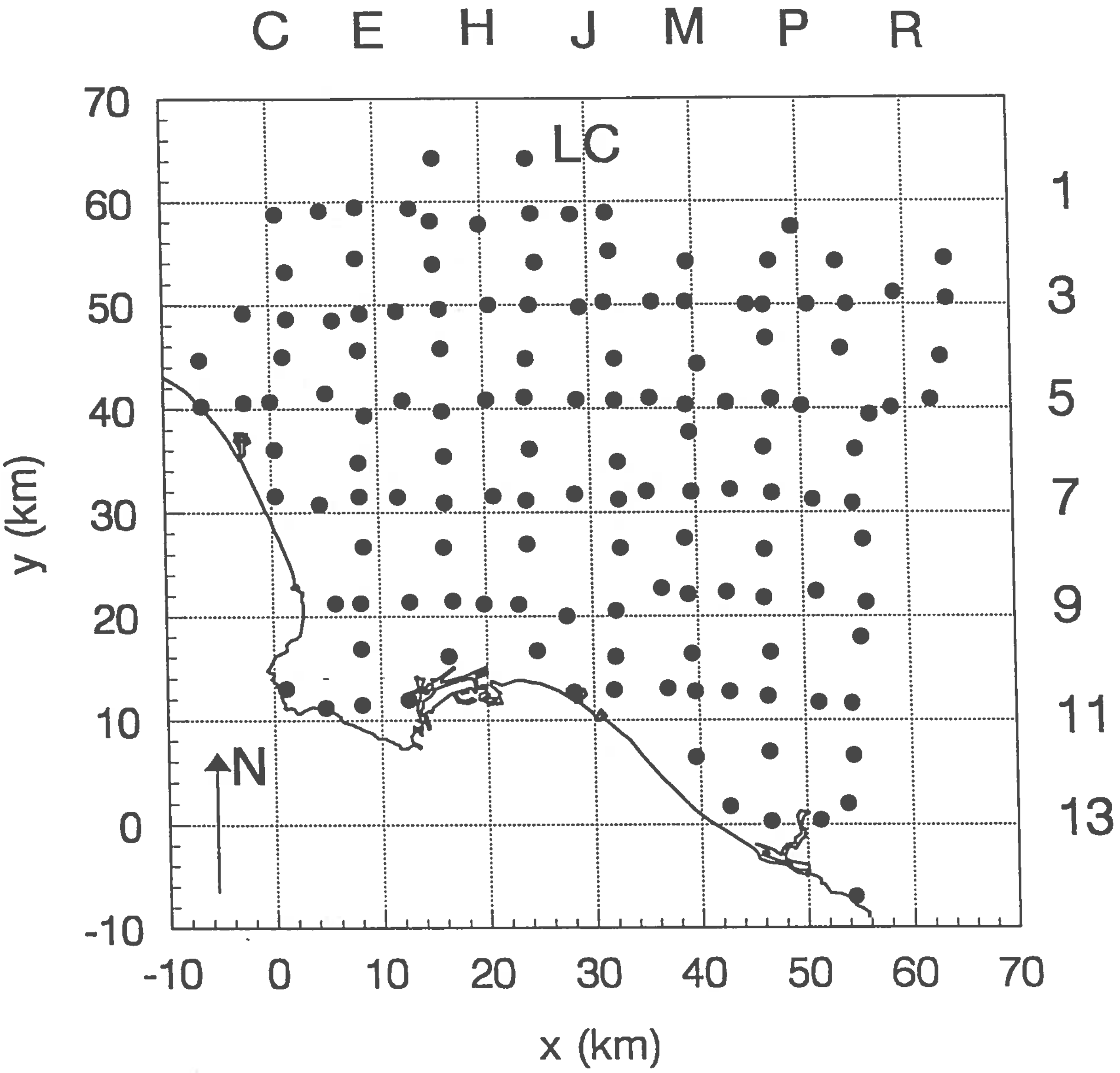


Figure 1: Final sites for long period microtremor measurements in Los Angeles basin. Total of 143 sites plus a reference bedrock site (LC) were considered. The sites are defined in terms of horizontal (1-14) and vertical sections (A-S).

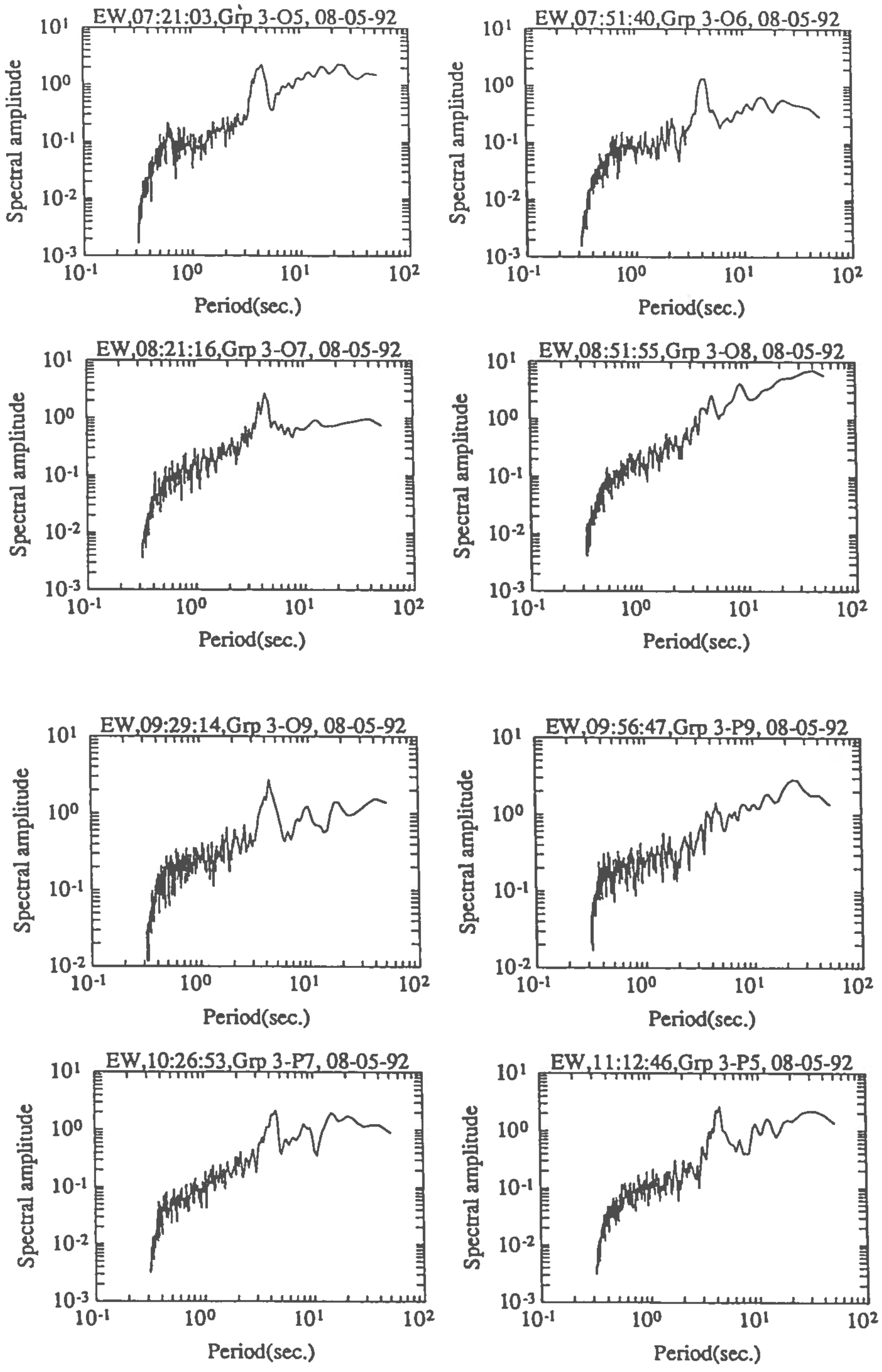
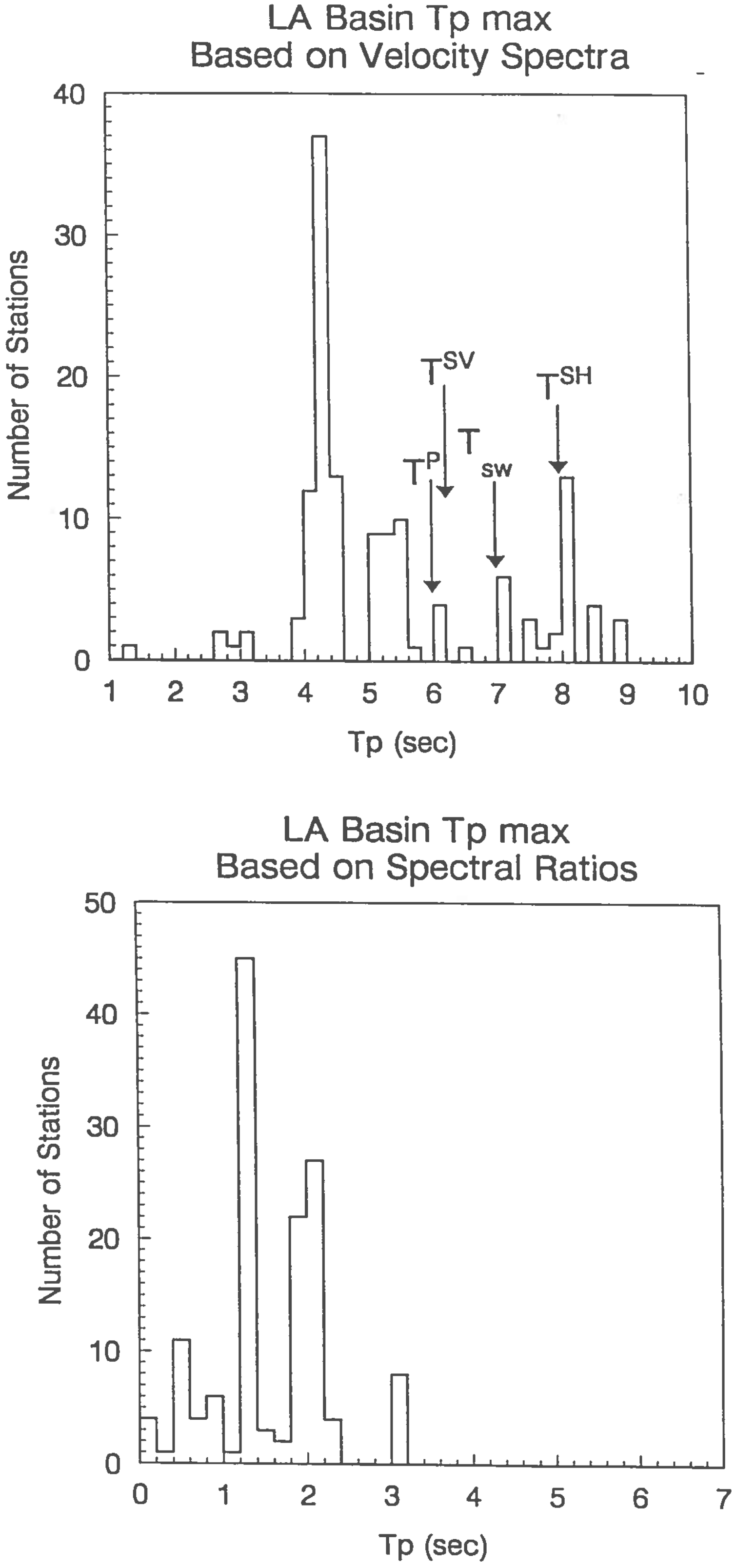


Figure 2: Velocity spectral amplitude (EW) for a set of microtremor sites in Los Angeles basin.


LA Basin Tp max
Based on Velocity Spectra

LA Basin Tp max
Based on Spectral Ratios

Figure 3: Predominant period of motion determined from microtremor spectra (top) and spectral ratios relative to the bedrock site (bottom).

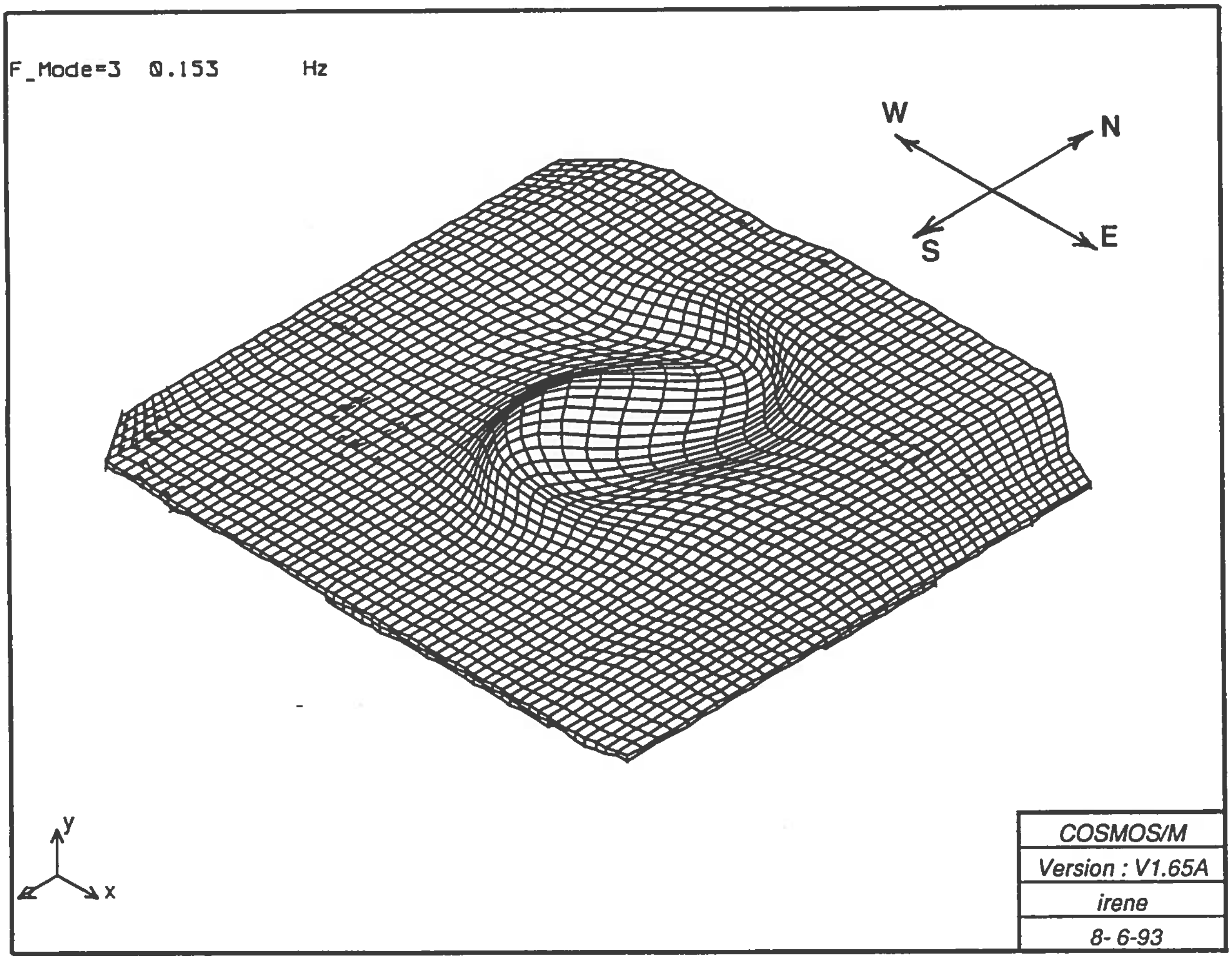


Figure 4: Third vibration mode for the top surface of the Los Angeles basin.

Kagan, Y. Y., (UCLA): SCEC 1993 annual summary report.

During the period from March 1, 1993, to November 24, 1993 I have conducted the following research supported fully or in part by SCEC:

(1) *Study of stress and earthquakes:*

(a) We have investigated the statistical properties of the incremental static stress caused by earthquakes worldwide [3,7]. We compute normal and shear stress on nodal planes for each earthquake in the catalog, as well as stress invariants in the focal zone of each event. These accumulated stress values are calculated at the location of a future earthquake (prestress) and then compared to the stress level measured at the same point after the event (poststress). Comparison of the statistical distributions for pre- and poststress indicates that the normal stress level has little influence on an earthquake occurrence: there is little difference in occurrence rates of earthquakes in compressional vs dilatational stress field. On the other hand, earthquakes do occur preferably in locations where previous earthquakes have increased the shear stress.

(b) California may have the best seismic and geodetic data available, hence we can study earthquake triggering by stress. D. Jackson and I created a catalog of focal mechanisms for strong earthquakes in Southern California extending to 1850. As the initial dataset we use Ellsworth (1990) historical/instrumental earthquake catalog. We modified it by adding: 1) the recent earthquakes from the Harvard catalog, 2) the focal mechanism solutions and spatially distributed seismic moment from other available publications, and 3) finally, for earthquakes in the 19th century, we used the fault trace information and slip distribution for the largest earthquakes to infer their distributed moment tensor. Fig. 1 shows the cumulative stress change for the first stress invariant, I_1, (average normal stress) for Southern California from 1850 to the present. The distribution of the stress is dominated by several large earthquakes: 1857 Ft. Tejon, 1872 Owen's valley, 1952 Kern County, and 1992 Landers events. The incremental stress pattern forms a complex mosaic due to the interaction of incremental stress fields of many earthquakes. We will use this catalog to infer the stress loading responsible for earthquake occurrence in California, as well as for triggering of earthquakes by stress.

(2) *Statistical analysis of seismicity:*

(a) I have reviewed statistical tests used to prove the characteristic earthquake hypothesis [1]. Based on the results of other researchers as well as my own tests, I show that the evidence of the characteristic earthquake hypothesis can be explained either by statistical bias, or statistical artifact. Since other distributions of earthquake size provide a simpler explanation for available information, the hypothesis cannot be regarded as proven. Nishenko (1989) published a map and a report evaluating the future Circum-Pacific earthquake potential, using one of the versions of the characteristic earthquake hypothesis. We compare this prediction with the actual seismicity record as found in two earthquake catalogs: the PDE (1993) list and the Harvard catalog. Only two earthquakes rigorously satisfy the prediction criteria in both of these databases (see more in [8]) The sum of characteristic earthquake probabilities for five years in Nishenko (1991) is 9.0, pro-rated to September 1, 1993, is 8.4. The probability that only two or less earthquakes will occur, if the predicted rate is 8.4, is very low, about 0.2%. Thus the characteristic hypothesis can be rejected at a high confidence level.

(b) D. Jackson and I have shown [2] that the test results for the catalog proposed by Nishenko and Sykes (1993), are similar to our previous (1991) result – the gap hypothesis predicts large earthquake occurrence no better than the hull hypothesis of the Poisson occurrence. Our analysis of the Nishenko's (1989) prediction also yields the same conclusion: although the smoothed Poisson rate estimate performs slightly better than the gap forecast, the difference between them is not statistically significant [8].

(c) D. Jackson and I estimate long-term worldwide earthquake probabilities by extrapolating catalogs of seismic moment solutions [4,9]. We base the forecast on correlations of earthquake focal mechanisms. The forecast is expressed as a map showing predicted rate densities for earthquake occurrence and for focal mechanism orientation. Focal mechanisms are used first to smooth seismicity maps to obtain expected hazard maps, and then to forecast mechanisms for future earthquakes. We test these forecasts: using the first half of a catalog to smooth the seismicity level, and the second half of the catalog is used to validate and optimize the prediction.

(d) We can ask whether the magnitude distribution changes in time in California. Fig. 2 displays three sets of magnitude-frequency relations normalized to the yearly earthquake rate. The catalogs involved are the modified Ellsworth (1990) for 1850-1993, the Caltech 1932-1993 catalog, and the Harvard catalog. The Gutenberg-Richter relation with $b = 1$ is also shown in the plot. Generally, these distributions demonstrate the stability of seismic energy release over the last 140 years. If we assume that the value of β in California is the same as for the whole world, using eq. 14 in [1], we obtain $m_{max} = 8.0$–8.9 i.e., the values which are close to those obtained for the world-wide seismicity (see [1]).

Published or prepared papers:

1. Kagan, Y. Y., 1993. Statistics of characteristic earthquakes, *Bull. Seismol. Soc. Amer.*, **83**, 7-24.
2. Jackson, D. D., and Y. Y. Kagan, 1993. Reply [to Nishenko & Sykes], *J. Geophys. Res.*, **98**, 9917-9920.
3. Kagan, Y. Y., 1993. Incremental stress and earthquakes, *Geophys. J. Int.*, accepted.
4. Kagan, Y. Y., and D. D. Jackson, 1993. Long-term probabilistic forecasting of earthquakes, *J. Geophys. Res.*, submitted.
5. Kagan, Y. Y., 1993. Comment on "Application of the concentration parameter of seismoactive faults to Southern California" by A. Zavyalov and R. E. Habermann, *PAGEOPH*, submitted.
6. Kagan, Y. Y., 1993. Observational evidence for earthquakes as a nonlinear dynamic process, submitted to *Physica D.*
7. Kagan, Y. Y., and D. D. Jackson, 1993. Incremental stress and earthquakes, *Seismological Research Letters*, **64**, p. 33.
8. Kagan, Y. Y., and D. D. Jackson, 1993. New seismic gap hypothesis: Five years after, *Trans. Amer. Geophys. Union (EOS), Suppl.*, **74(43)**, p. 440.
9. Jackson, D. D., and Y. Y. Kagan, 1993. Long-term probabilistic forecasting of earthquakes, *Trans. Amer. Geophys. Union (EOS), Suppl.*, **74(43)**, p. 440.

Fig. 1. Incremental stress in Southern California. The modified Ellsworth catalog 1850-1993 is used. Stress is evaluated at a surface. Stress invariant I_1 (average normal stress) is shown.

Fig. 2. Magnitude-frequency plot for Southern California. Solid line corresponds to the Caltech catalog (since 1932), pluses are for the Ellsworth (1990) catalog (we use the data since 1850), and stars are for the Harvard catalog (since 1977).

Incremental stress (invariant I_1) in S. California 1850-1993

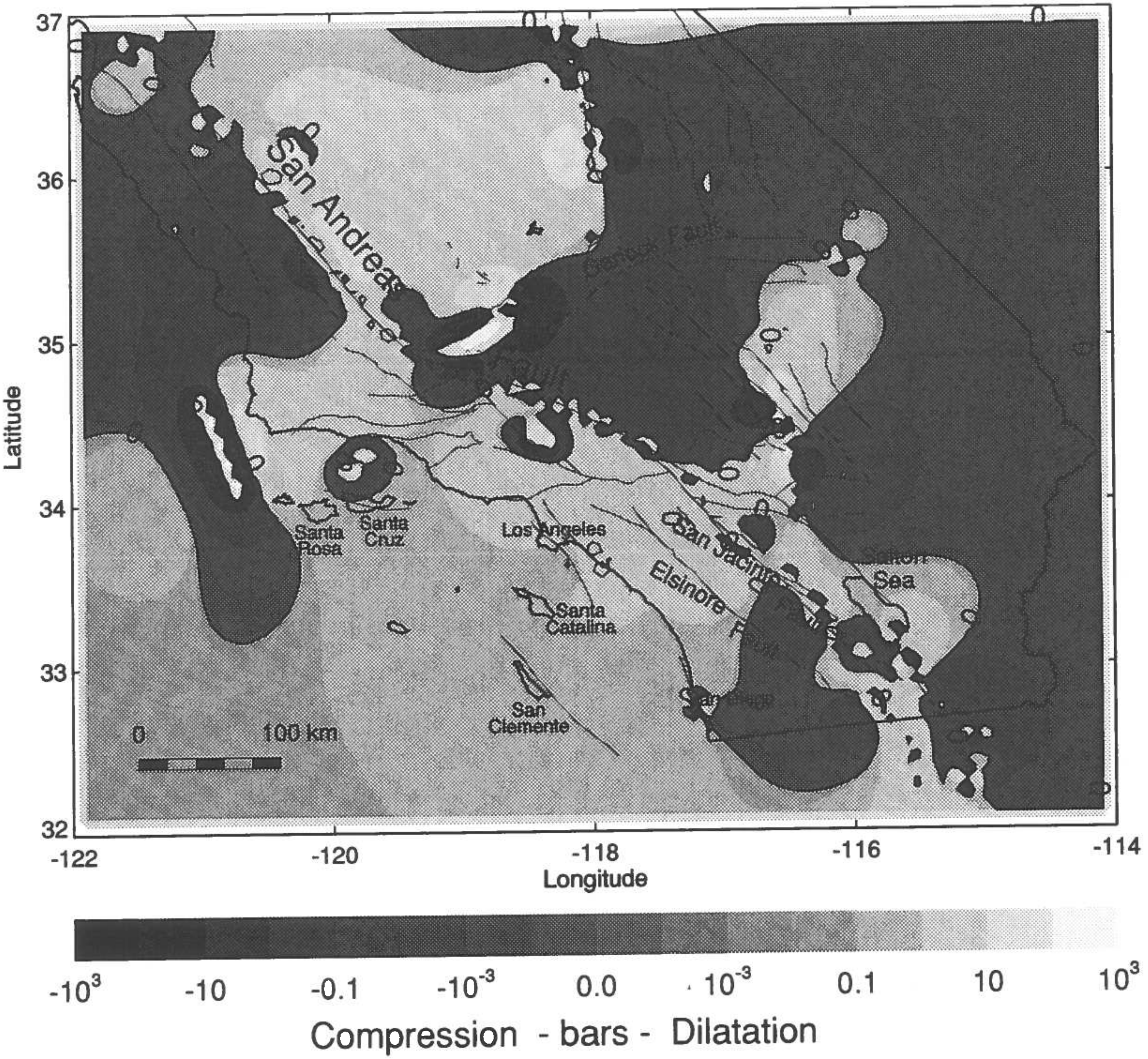
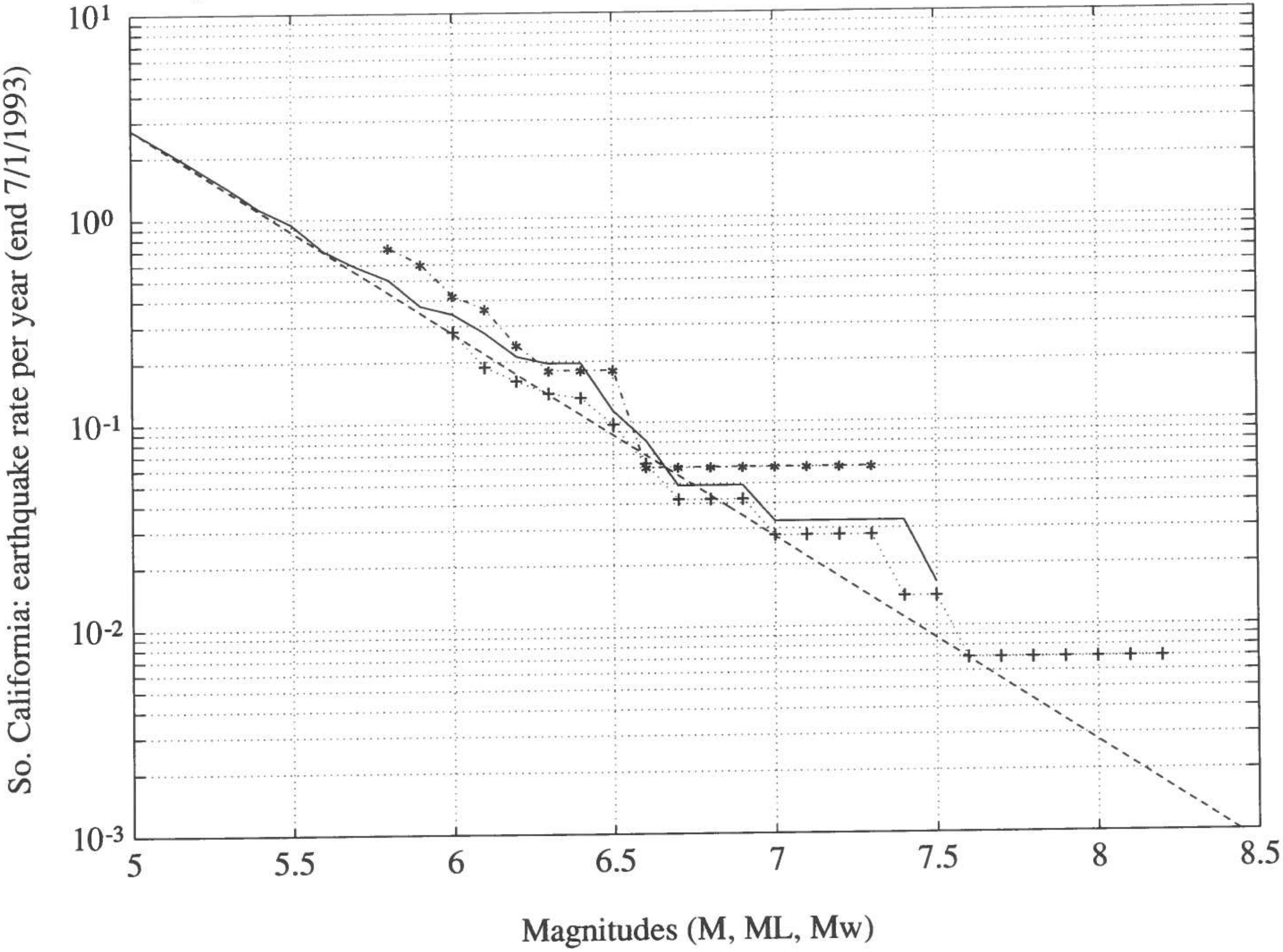


Fig. 2. Ells., CIT (both with H&J corr), and Harvard: + M, - ML, * Mw; b = 1.0



Southern California Earthquake Center
Activity Report, December, 1993.

Jean-Bernard Minster, Principal Investigator, and Nadya P. Williams
Institute of Geophysics and Planetary Physics, A-025
Scripps Institution of Oceanography, UCSD, La Jolla, Ca, 92037-0225

A systematic approach to assess intermediate-term earthquake prediction algorithms based on seismicity patterns

During this report period, the Principal Investigator served on the SCEC Board of Directors, the Steering Committee, and as Vice-Chair on the *Education and Outreach* Policy Advisory Board; he was also Task Leader/reporter for SCEC Task 4: *Intermediate-Term Earthquake Prediction.* In support of the activities of Working Group A (*Master Model)* we have continued our research on ways to assess intermediate-term prediction algorithms of the type introduced by Russian seismologists, as reported below.

"M8" and comparable earthquake prediction algorithm have been developed by Russian seismologists as a means to achieve intermediate term prediction of large events, makes use of a "de-clustered" catalog of mainshocks to find large scale seismicity patterns thought to precede large earthquakes in a given region (e.g. *Gabrielov et al.*, 1986; *Keilis-Borok et al.*, 1990; *Updyke et al.,* 1989; *Healy et. al*, 1992; *Kossobokov et al.*, 1992). When such a pattern is detected, a "Time of Increased Probability" (TIP) is declared, for a period of five years. A similar algorithm named "CN" is described in some detail by *Keilis-Borok et al.* (1988). Our purpose (*Minster and Williams*, 1992) has been to seek a quantitative measure of the stability and robustness of the results with respect to fluctuations and biases in the input data.

These algorithms usually involve rather elementary catalog manipulations, but can be difficult to describe in simple terms. A problem common to almost all these algorithms is that almost everywhere, instrumental data cover too short a time span to allow a standard approach to statistical assessment. We propose a computer-intensive approach which yields a quantitative measure of the confidence one can attach to the output of such programs. In such an assessment the algorithm should not be modified, but user-selectable parameters might be adjusted—e.g. time period for analysis, target region, etc. These define a parameter space in which we explore selected neighborhoods by repeated execution of the program after applying random perturbations to nominal parameter selections. In order to formulate testable null-hypotheses, we have designed a method for randomization of the entire catalog or portions thereof, which permits us to define a time- and space-dependent TIP likelihood function using a bootstrap technique. Application of the algorithm to the "true" catalog then leads to a quantitative measure of the confidence one can attach to a TIP, through a likelihood ratio test. We have tested the "M8" algorithm on the 1963-1993 western US catalog, which contains several large events (M>7.0), including both the 1989 M7.1 Loma Prieta and 1992 M7.5 Landers earthquakes. This algorithm formed the basis for the prediction of the Loma Prieta earthquake by *Keilis-Borok et al.* (1991). It is currently the object of a systematic test conducted by *Healy et al.* (1992). We find that the algorithm is indeed sensitive to large apparent seismicity fluctuations. We also find that published predictions of the Loma Prieta event depend on the spatio-temporal characteristics of a very small (<10%) fraction of the catalog. The algorithm is very successful in the case of Loma Prieta, but the likelihood of success for some other strong events, in particular Landers, does not appear to be statistically significant.

Figure 1 shows the evolution of the TIP likelihood as a function of time between 1982 and 1993, when the target magnitude is M_0=7.0. The catalog used for this history is the DNAG catalog for the period 1963-1986, supplemented by the PDE catalog for the period 1986-1993, after removal of nuclear explosions. Aftershock were removed according to the prescriptions proposed by *Keilis-Borok et al.* (1980). The likelihood increases steadily near the center of the state until the Loma Prieta event, upon which the TIPs in effect are re-labeled as successful predictions. However, at no time does the likelihood become significant near the epicenter of the Landers event. This conclusion is unchanged if the target magnitude is increased to M_0=7.5. It should be noted that for M_0=7.5, the Loma Prieta event does not constitute a predicted event, since it has too small a magnitude, so that the TIPs in effect as of 1989 are retained in subsequent periods. Nevertheless, the TIP likelihood remains small near Landers through the entire period spanned by the catalog. It seems therefore that the seismicity pattern preceding the Loma Prieta event does not have an equivalent before the Landers earthquake in southern California. (This does not necessarily mean that no pattern at all precedes Landers, of course.)

Our approach relies on a very large number of runs. In order to verify whether our results are robust with region, the same type of calculations should be conducted elsewhere in the world. Issues which remain unresolved include (1) the sensitivity of the output to the aftershock removal procedure, and (2) whether similar patterns—controlled by a small fraction of the seismicity— are seen in other seismic areas, such as the Mexican and Aleutian trenches, Japan, and New Zealand. If the outcome is positive, we believe that this should be a strong incentive to seek to identify an underlying physical phenomenon. This work is targeted to yield a direct contribution to the Master Model.

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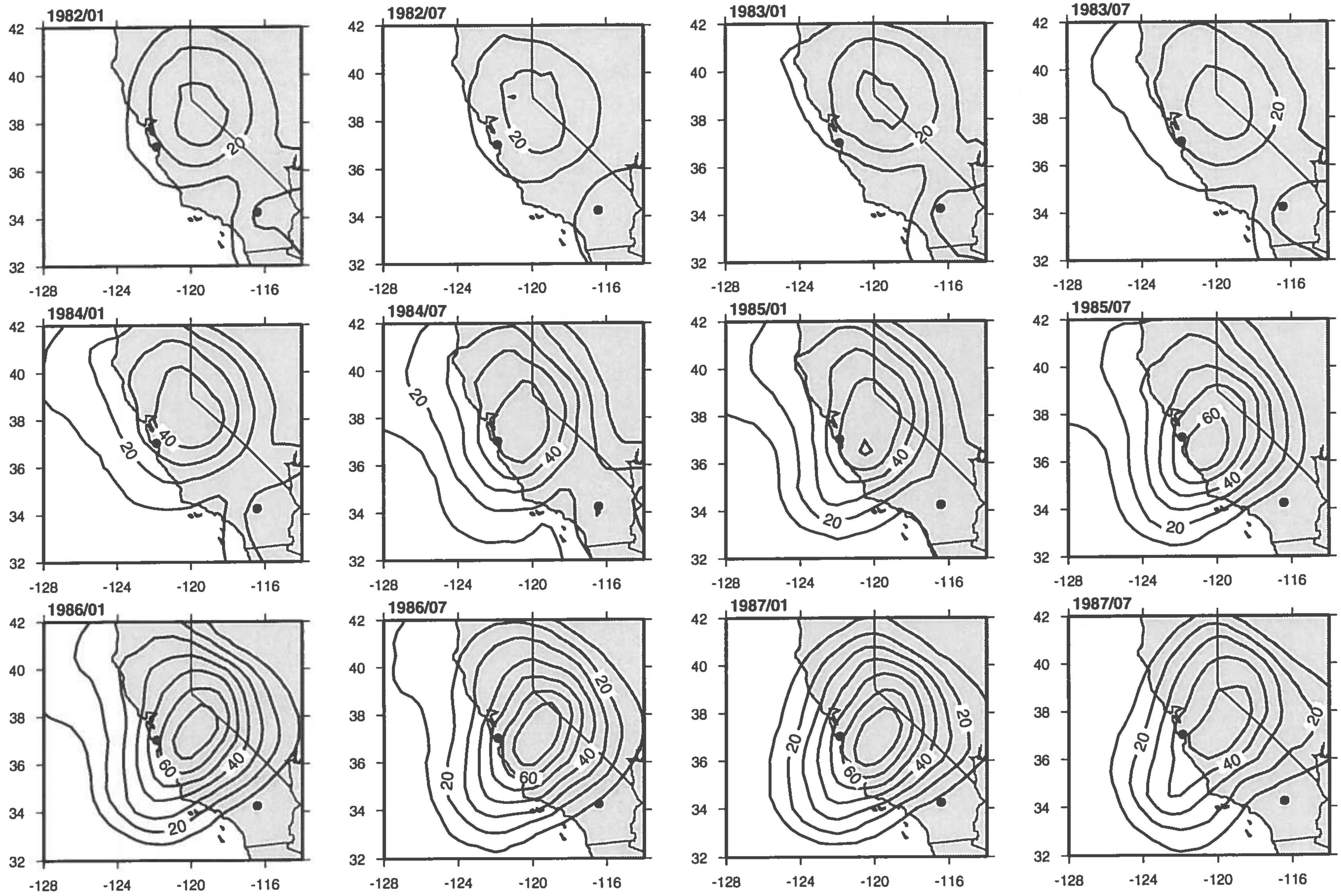
Updyke et al., *Proc. NEPEC June 6-7, 188, Reston VA*, USGS Open-file report 89-144, 1989.

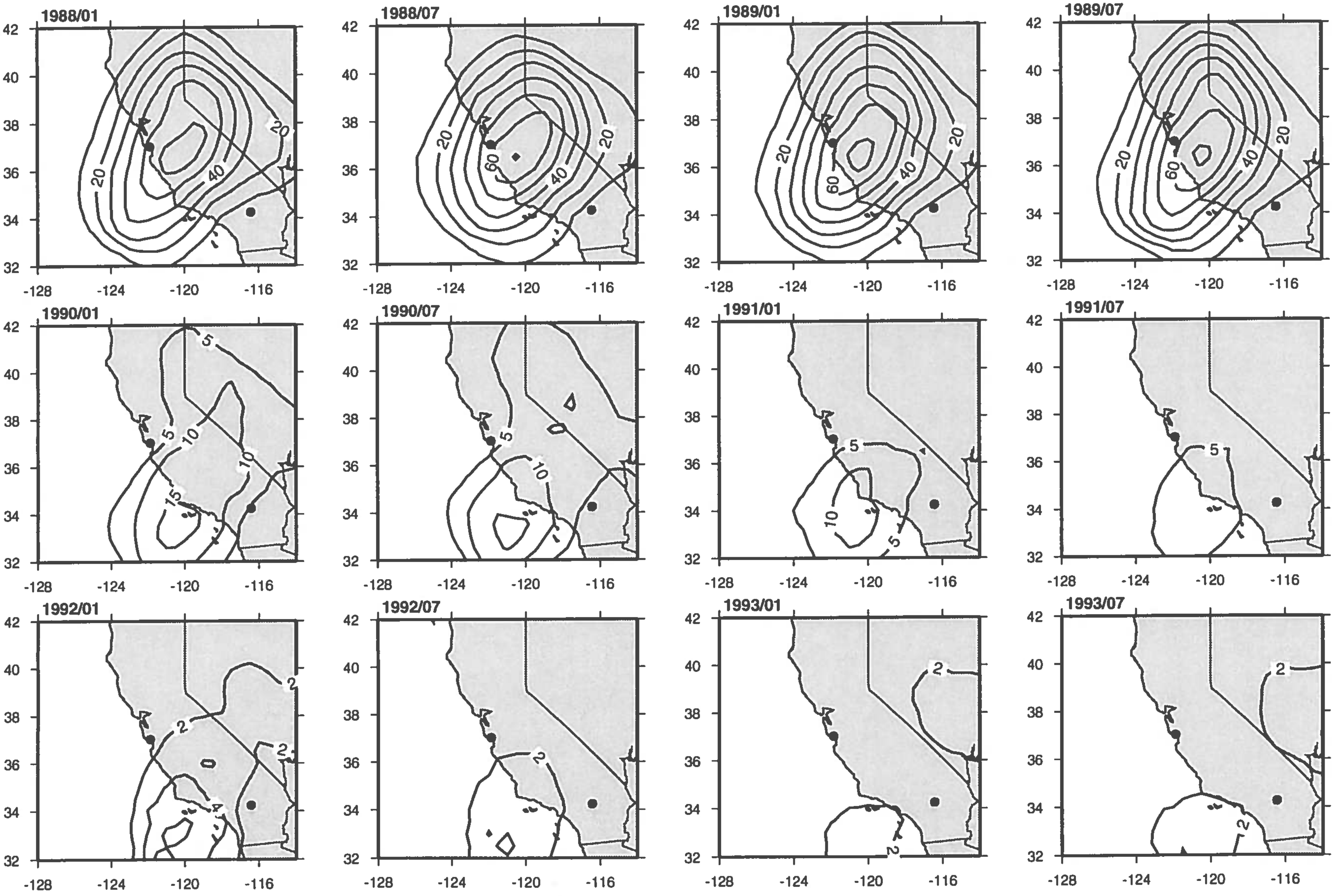
Figure Caption

The figure shows the evolution with time of the TIP likelihood (for M_0=7.0) contoured over the western U.S., updated every 6 months between 1982 and 1993. Each successive frame is calculated using only the seismicity preceding the corresponding date. Two important features are noteworthy: (1) the peak in TIP likelihood preceding 1989 is thought to be significant at the 95 percent confidence level; these TIPs are canceled upon successful prediction of the Loma Prieta event. (2) at no time does the likelihood become significant in the vicinity of the 1992 Landers earthquake. These conclusions are robust with respect to the choice of M_0 (i.e. in particular for M_0=7.5).

1982 - 1987 evolution of TIP likelihood in California



1988 - 1993 evolution of TIP likelihood in California



S. Katz and K. Aki

INTERMEDIATE TERM EARTHQUAKE PREDICTION BASED ON THE USE OF ADAPTIVE NEURAL NETS

The key element of methodology for intermediate earthquake prediction discussed here is forecasting of values of a danger function defined as a maximum amplitude of the earthquakes within moving time-window (time-magnitude forecasting) or within time-space window (time-space-magnitude) forecasting. The prediction methodology is based on the use of a specialized neural net, that continuously changes its structure in time. The neural net is structures in such a way that it is capable to produce stable results even in the case of small training sets. The ability of the neural net to complete a robust restructuring allows to adapt to changing in time and space seismo-tectonic conditions.

The input of the neural net may be presented as a multi-dimensional time series with coordinates taken in the form of seismicity attributes calculated in a moving time or time-space window. This makes this methodology open to inclusion of a number of additional parameters without significant changes on the technique of synthesis of the neural net.

Calculation of the danger function of a series of sub-regions covering a large area allows for time-area prediction with time of a large earthquake being predicted and a dangerous area on a two dimensional map being identified.

Success rate and rate of false alarms for Southern California

Statistics on success rate and rate of false alarms for two thresholds - M5.0 and M5.5 levels is shown in the Tables 1 and 2. The results presented in these Tables were collected using catalog data for Southern California region and for the time period starting from 1981 to 1982. Prediction was made for the whole Southern California region and the neural net was trained using data in a sliding in time time-window $(t-\Delta, t)$. The aim of the training was to predict values of the Danger function at the time $t+\tau$ where τ was 1 month.

Table 1. Rate of correct predictions and false alarms for the earthquakes with magnitudes larger than M5.0

Prediction Truth	Event present	No event	Total
Event present	8 (correct detection)	3 (missed)	11
No event	30 (false alarm)	101 (correct rejection)	131
Total	38	104	141

According to the Table 1, the percentage of the correct prediction (Ppd) and percentage of false alarm and missed events (Pm) for the earthquakes with a magnitude larger than M5.0 respectively are

Ppd=73%; Pfa=23%; Pm=27%

Table 2. Rate of correct predictions and false alarms for the earthquakes with magnitudes larger than M5.5

Prediction Truth	Event present	No event	Total
Event present	2 (correct detection)	4 (missed)	6
No event	23 (false alarm)	113 (correct rejection)	136
Total	27	115	142

According to the Table 1, the percentage of the correct prediction (Ppd) and percentage of false alarm and missed events (Pm) for the earthquakes with a magnitude larger than M5.0 respectively are

Ppd=67%; Pfa=23%; Pm=66%

Large increase in the rate of missed events is due to the formal character of procedure of the event detection and due to the fact that neural net tends to give lower predicted magnitudes comparing to the actual magnitude of earthquakes. In the case of the threshold 5.5 it put 3 events with magnitude in the range (5.5 -6) in the range (5 < M < 5.).
The rate of false alarm and the rate of correct decisions is shown in the Tables 1 and 2 generally are in agreement with results of extensive testing of this neural net on large data-sets of medical data. There, the rate of correct decisions in the range 15%- 25% was obtained.

Influence of the length of the time-window on the value of the predicted magnitude

Figure 1 illustrates dependence of the predicted magnitude for Landers earthquake from the length of the training window. The difference between averaged predicted magnitude and the actual magnitude of the Landers earthquake was about M0.2.

Prediction of time of spatial location of earthquakes' epicenter.

This work is in its initial stage. We give here short description of experiments with Southern California catalog data. The goal was to predict values of a 3D danger function $D(t_i, x_j, y_k)$, where t_i is time, x_j and y_k are coordinates of a center of a spatial 2D window used for calculation of the danger function and for training of the neural net. The training regions were taken as mutually orthogonal one degree bands crossing the whole Southern California region: $S_j=\{x \subset (x_j+\Delta x, x_j-\Delta x)\}$ and $S_k=\{y \subset (y_k+\Delta y, y_k-\Delta y)\}$. Using data from these bands two first level estimates $D(i+1,j)$ and $D(i+1,k)$ were calculated. Then, the final estimate of the danger function was obtained as $D(i+1, j, k)=\sqrt{D(i+1,j) \cdot D(i+1,k)}$. The prediction results are presented as a sequence of two dimensional maps.

Amplitude of the Earthquake Precursor, Landers 1992

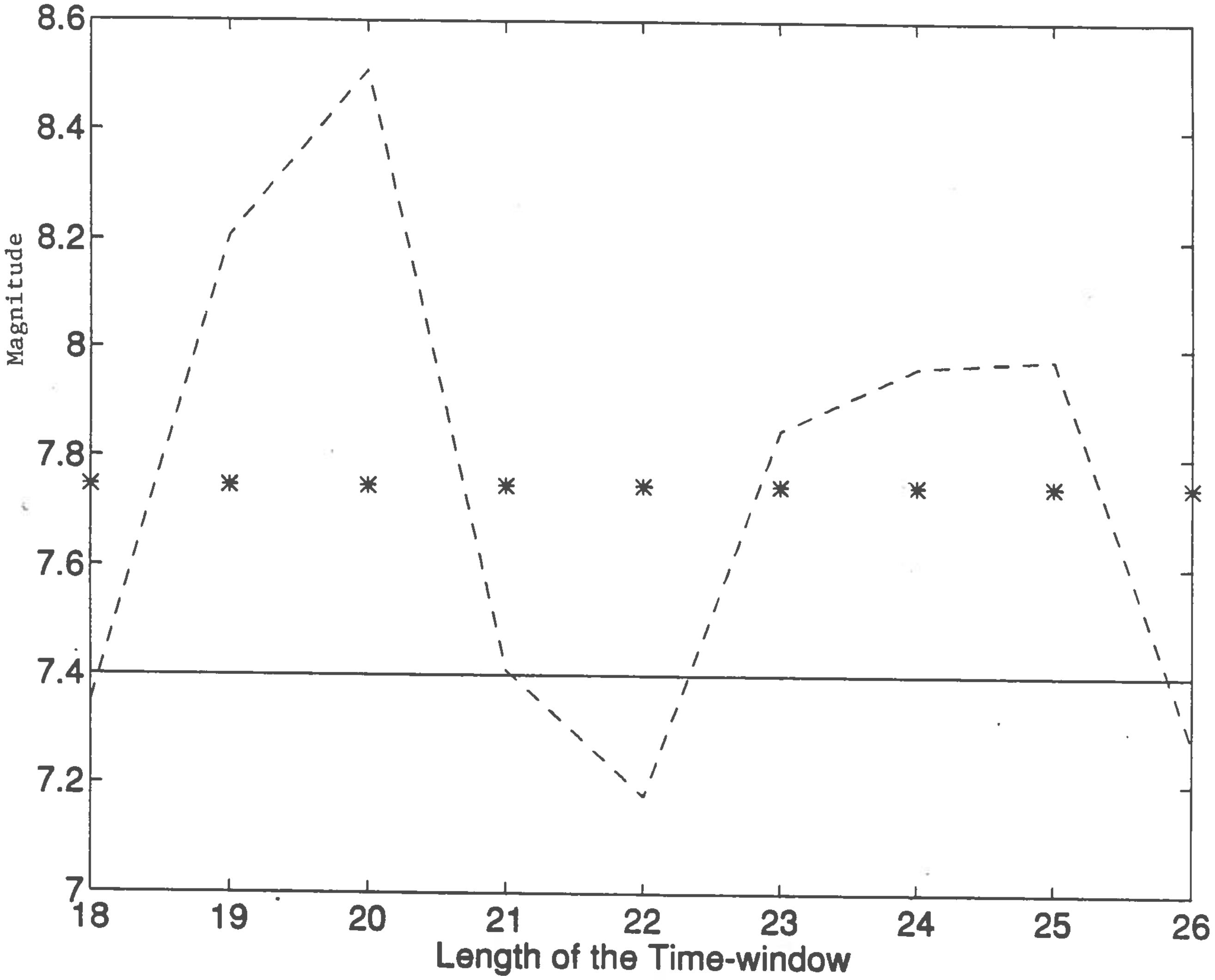


Figure 1

* - Coordinates of the Landers Earthquake

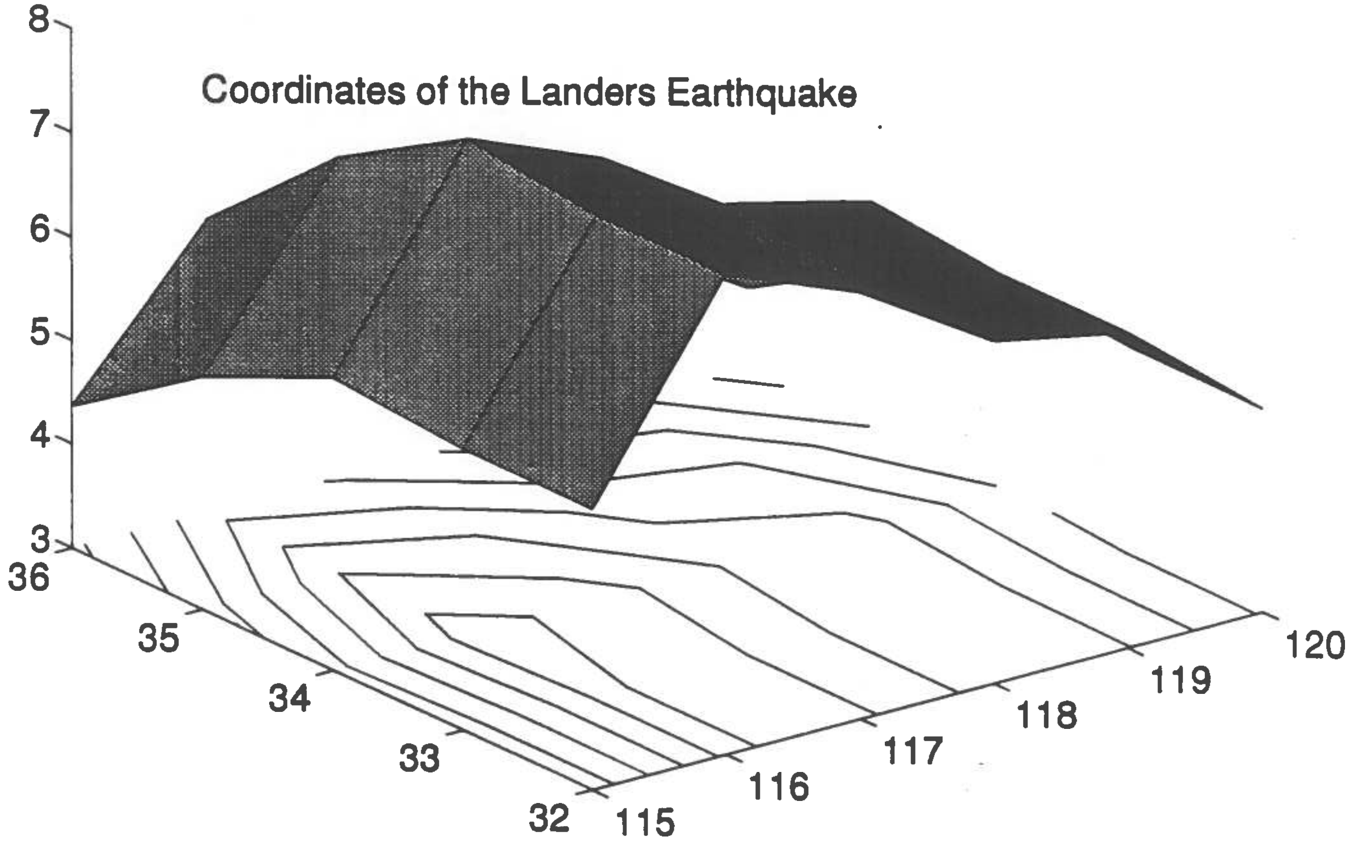


Figure 2

PROGRESS REPORT ON SEARCH FOR SEISMIC PRECURSORS TO CANDIDATE FUTURE LARGE AND GREAT EARTHQUAKES IN SOUTHERN CALIFORNIA

By Lynn R. Sykes

Lamont-Doherty Earth Observatory, Columbia University

In a paper published in Science "Changes in State of Stress on the Southern San Andreas Fault Resulting from the California Earthquake Sequence of April to June 1992" Jaume and Sykes (1992a) modelled stress changes on the southern San Andreas and northern San Jacinto faults caused by the occurrence of the Landers, Joshua Tree and Big Bear earthquakes of 1992. Jaume and Sykes (1992b) presented updated calculations of that type at an invited session of talks at the AGU meeting in Dec. 1992. Fig. 1 shows a recently updated version of similar results for the southern San Andreas fault that includes 1993 estimates of the seismic moments of the three events and revisions in the mechanism of the Big Bear event. The calculated changes in shear stress and in Coulomb Failure Function, CFF, are shown for the San Andreas extending from Cajon Creek near San Bernadino (0 km) to Bombay Beach (190 km) at the southern end of the fault. A 50-km section of the San Andreas fault in the San Gorgonio Pass area (35 to 85 km on Fig. 1) was moved significantly closer to failure by stress changes induced by the 1992 earthquake sequence. Stress changes on other segments of the San Andreas fault were smaller, with the Coachella Valley segment being moved closer to failure and the Mojave and northernmost San Bernadino segments (less than 35 km in Fig. 1) being moved away from failure.

We also considered changes in pore fluid pressure caused by changes in normal stress across the San Andreas at the time of the 1992 sequence. Initially about 60% of the decrease in total normal stress is taken up by a drop in fluid pressure in the fault zone at depth and only 40% goes into a drop in effective normal stress. The initial change in CFF is modelled in Fig. 1 by a low value, 0.3, of the effective coefficent of friction, μ. As fluid pressure along the San Andreas fault returns to its pre-Landers value with time, the effective normal stress decreases further and CFF increases to the data points in Fig. 1 denoted by $\mu = 0.6$. We conclude that the San Andreas fault in San Gorgonio Pass moved closer to failure at the time of the 1992 sequence by a maximum ΔCFF = 0.5 MPa (5bars) whereas with time and increasing fluid pressure ΔCFF should increase by an additional 3 bars to a total of about 8 bars (0.8 MPa).

Two results are very important--1) the San Andreas fault moved significantly closer to failure in 1992 and should move even closer to failure as fluid pressures re-equilibrate with time. The time constant for fluid diffusion is poorly known but appears to be in the range of 1 to 10 years based on earthquakes like Koyna that were triggered by fluid pressure being communicated to the hypocenter along a fault zone following the filling of a large reservoir. We believe the Landers sequence increases the probability of a great earthquake along the southern San Andreas fault since the repeat time of Landers earthquakes is much longer than of great events along the San Andreas. Landers should not be thought of as being part of the normal build up to great events along the San Andreas.

Jaume and Sykes have been working on moderate-size earthquakes in the San Francisco Bay area under a separate grant from USGS. Most of the moderate-size shocks ($M > 5$) appear to be modulated in their timing and mechanism type by the buildup and relief of stress in large to great shocks like those of 1989, 1906 and 1868. Activity built up before those large events in those areas calculated to have positive values of ΔCFF and decreased in those areas afterwards. Similarly, activity increased afterwards in areas calculated to have been moved closer to failure as a result of the occcurrence of those large shocks. The latter activity persisted for about 20 years, perhaps an indication of the temporal role of fluid pressures induced by changes in normal stress across neighboring faults at the time of large events. We conclude that intermediate to long term seismic precursors are best thought of not as scalar quantities, like number of events, but in a tensor sense--activity increases in some places and decreases in others prior to large shocks and in areas predicted from values of ΔCFF for dislocation models of the large events. The reverse happens in those two types of areas after a large event. Jishu Deng, a graduate student, has started work on a similar project for southern California.

Sykes, Scholz, Buck, Lerner-Lam and Menke from Lamont along with Humphreys from U. Oregon have worked on a proposal for a new SCEC task on the state of stress in southern California. The object is to take finished products from other SCEC groups--such as those on crustal deformation, seismicity, moment tensors of earthquakes and rates of fault motion--to produce an updated database accessible to all SCEC members showing calculations of the state of stress and changes in stress as a function of time in southern California.

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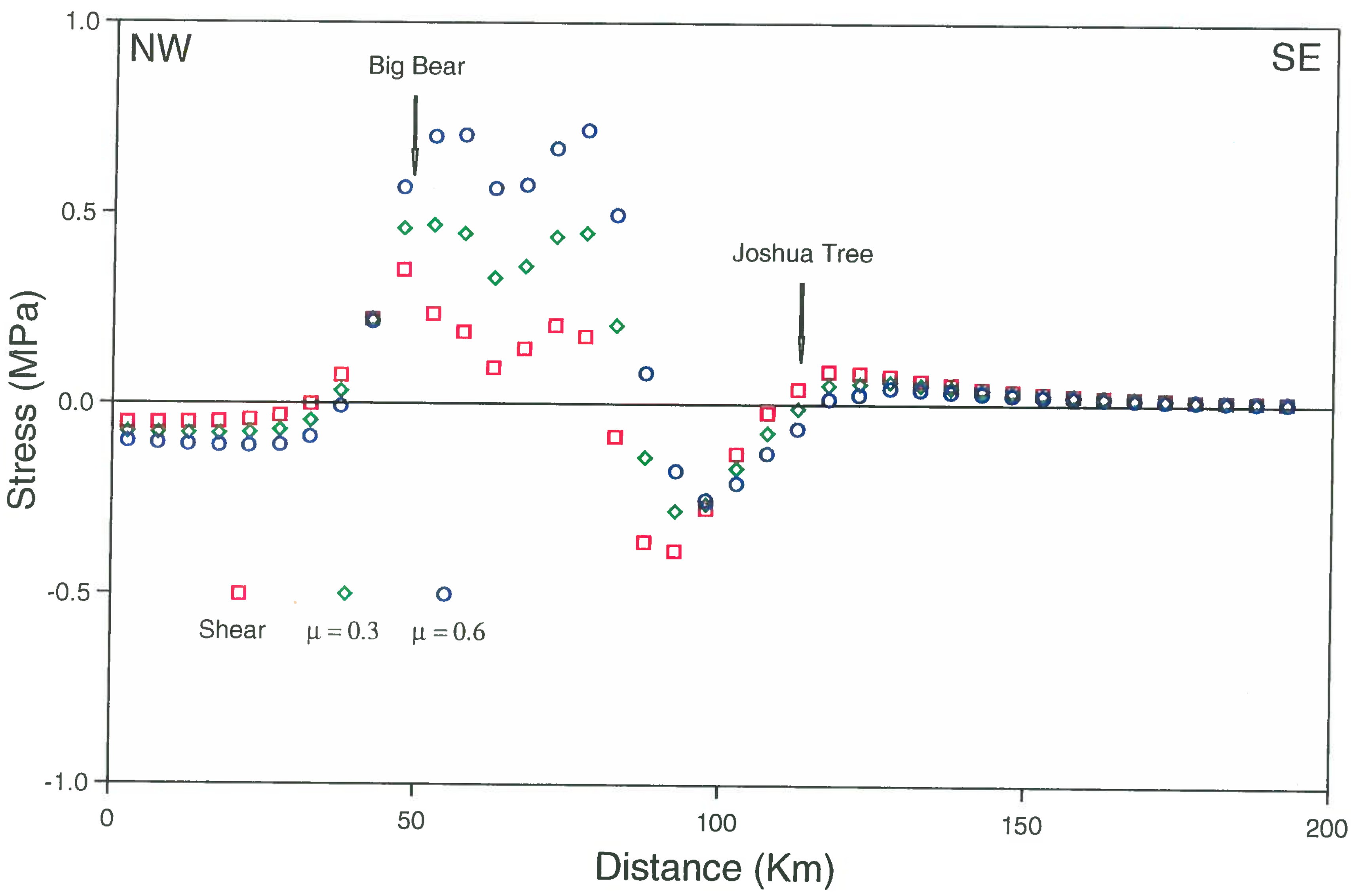
Jaume, S.C. and L.R. Sykes, Changes in state of stress on the southern San Andreas fault resulting from the California earthquake sequence of April to June 1992, EOS Trans. Amer. Geophys. Union, 73, Fall Meeting Supplement, p. 358, (abstract), 1992b.

Caption for Figure 1

Fig. 1. Change in shear stress (square) and in Coulomb failure function, ΔCFF, as a function of distance along southern San Andreas fault. Positive values of ΔCFF promote right-lateral slip along a vertical strike-slip fault. ΔCFF shown for two values of effective coefficient of friction, μ.


NW
SE
Big Bear
Joshua Tree
Shear
μ = 0.3
μ = 0.6
Stress (MPa)
1.0
0.5
0.0
-0.5
-1.0
Distance (Km)
0
50
100
150
200

Prepare Inner Borderland Fault Maps at a Scale of 1:100,000 for Publication as Geological Society of America Map and Chart Series

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Large-scale maps of late Cenozoic faulting and related geologic structure in the inner California Continental Borderland have been prepared for publication in the GSA Map and Chart Series. These maps include recontoured bathymetry of the offshore region from 31° 10' N to 32° 50' N latitude, and faulting associated with four major inner borderland fault zones: 1) San Clemente-San Isidro fault zone; 2) San Diego Trough-Bahía Soledad fault zone; 3) Coronado Bank-Agua Blanca fault zone; 4) Rose Canyon-Descanso-Estero fault zone. In addition, relevant geologic cross-sections and a map of the seafloor geomorphology (Fig. 1), representative of late Cenozoic depositional processes and fault geomorphology, were prepared. A document describing the fault maps, discussing the relevant regional geology and tectonic background, and showing representative high-resolution seismic reflection profiles and interpretations is being written for publication with the map sheets.

A map of seafloor geomorphology (Fig. 1), based on acoustic character in high-resolution subbottom profiles and bathymetry, shows regions of active submarine fan deposition, submarine canyons and channels, acoustic basement ridges and peaks, and flat-topped banks and shelf areas beveled during lowered sea level. Revisions, including a bathymetric base map, have been made for the geomorphology map according to reviewer's comments.

Work accomplished to date includes: 1) prepared bathymetric base for geomorphology map; 2) compiled lithologic sections for areas surrounding the offshore map area based on geologic studies on islands, the mainland, and well-sampled offshore areas of the U.S. borderland (Fig. 2); 3) revised the draft manuscript describing the maps and the geologic/tectonic history of the region; 4) scanned the geomorphology map into AutoCAD/DXF format for incorporation into the SCEC Arc/Info GIS. Work remaining to be completed: 1) redrafting of bathymetric and fault maps according to reviewer's comments; 2) resubmission of revised manuscript and maps for final review by GSA; 3) final drafting of maps for publication by GSA; 4) photograph maps to make negatives used by GSA for map publication; 5) proofreading of final manuscript prior to publication.

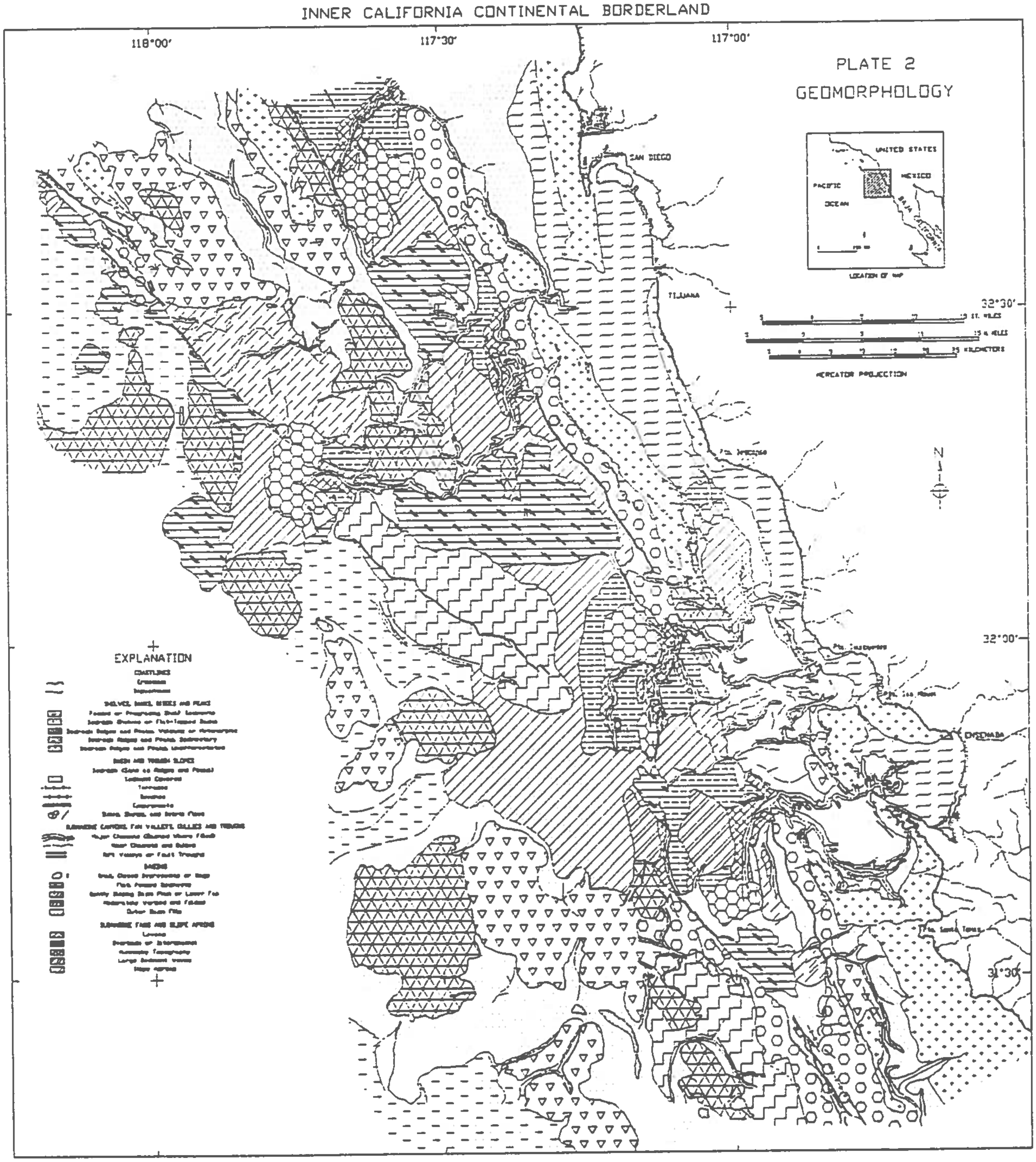
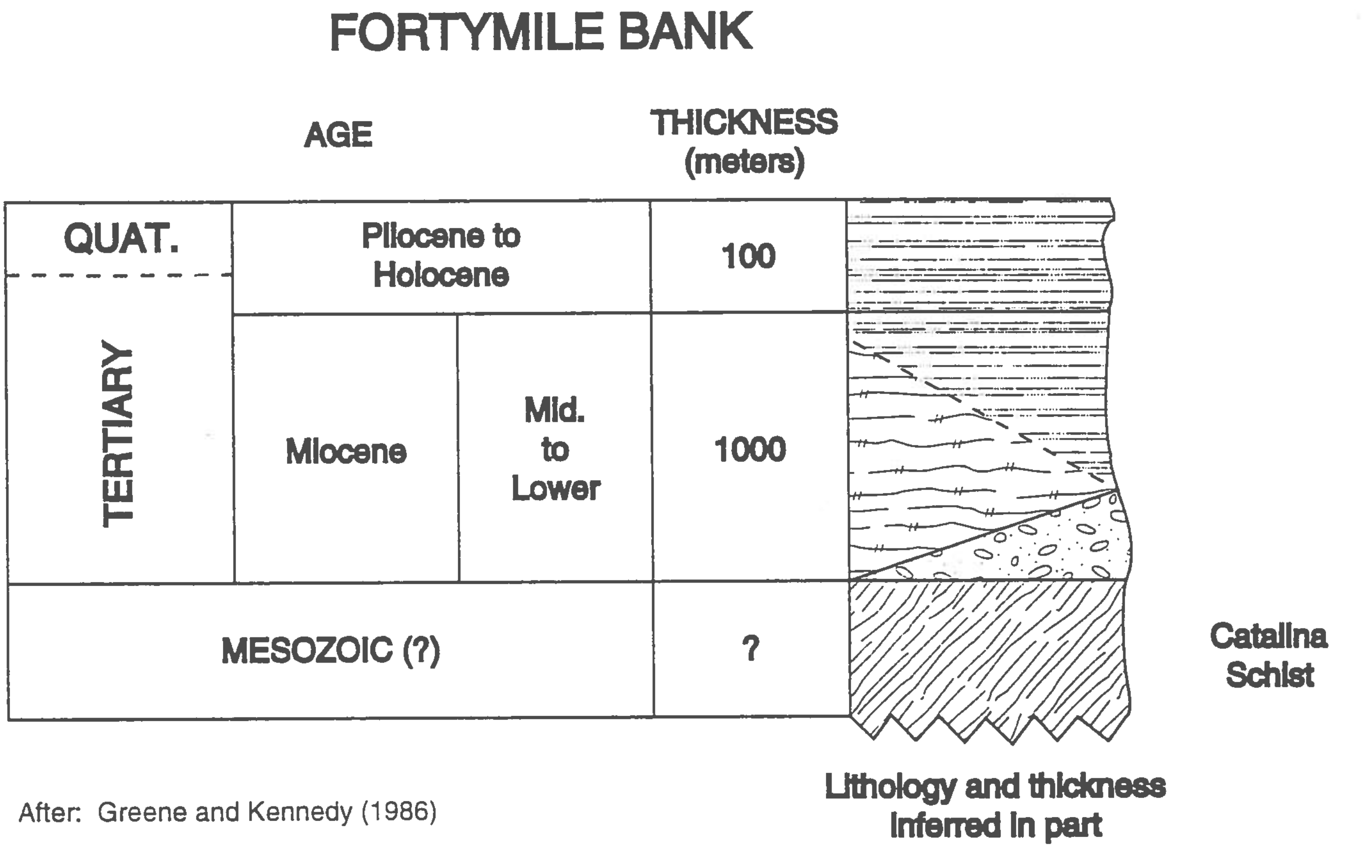


Figure 1. Map of geomorphology and near surface acoustic lithology of the Inner California Continental Borderland west of northern Baja California, Mexico.



After: Greene and Kennedy (1986)

Figure 2. Representative lithologic section from the Inner California Continental Borderland (after Greene and Kennedy, 1986).

Group B: Strong Ground Motion Prediction

Group Leader: Steve Day

PROGRAM OF THE STRONG MOTION WORKING GROUP

Overview:

The primary focus of the Strong Motion Working Group is on the prediction of strong motion time histories and spectra, addressing elements of SCEC Tasks 1, 2, and 3. Specific contributions to SCEC Tasks are the following:

(1) Construction of site amplification factors for southern California, for incorporation into probabilistic seismic hazard analysis maps (Task 1C). The Working Group is developing a first generation of products for incorporation into SCEC seismic hazard maps, based on analysis of existing weak motion and strong motion data.

(2) Strong motion estimation for plausible earthquake scenarios, emphasizing the Los Angeles Basin (Task 2). We are developing improved methods for empirical prediction of strong motion parameters, and applying them to southern California. We are also developing and validating models for computer simulation of strong ground motion time histories. Computer simulations based on seismic source and wave propagation models are critical for assessing the effects on L. A. Basin of very large magnitude San Andreas earthquakes and large magnitude earthquakes on faults within or adjacent to L. A. Basin.

(3) Basic research on those aspects of fault dynamics and wave propagation which are critical to advancing ground motion prediction methodologies. These include research on the propagation and healing of earthquake ruptures (Task 3A)and research on effects of nonlinear wave propagation in near surface rock and soil (Task 1C).

Accomplishments:

(1) Derivation of weak motion amplification factors using coda waves recorded at the southern California Seismic Network, and correlation of these amplification factors with surface geology

(2) Theoretical analysis of the influence of nonlinearity on site amplifications to identify where strong motion site effects can be expected to depart from weak motion estimates.

(3) Construction of first generation strong motion site amplification maps for L. A. Basin, from analysis of available strong motion recordings.

(4) Development of non-parametric regression method for application to construction of probabilistic seismic hazard maps.

(5) Development and validation of source model for computer simulation of ground motion from large earthquakes, based on subevent summation.

(6) Development of numerical model of L. A. Basin seismic velocity structure from synthesis of existing geotechnical, geological, and seismological observations, for use in computer simulations of basin response to earthquake scenarios.

(7) Implementation of innovative numerical methods for three-dimensional simulation of the long-period response of L. A. Basin to earthquake scenarios, including Gaussian beam, boundary element, and adaptive-mesh finite difference methods.

Three-Dimensional Simulation of Long Period Ground Motion in L. S. Basin (PIs: S. M. Day, J. G. Anderson, and K. McLaughlin)

SDSU and SCUBED Progress Report: S. M. Day, H. Magistrale, and K. McLaughlin

This project is part of a joint effort to compute ground motions for central Los Angeles from several plausible earthquakes. We address low frequency (less than 1 Hz) ground motion computations, and apply 3D finite difference computations to account for the geometrically complex, sediment-filled Los Angeles Basin.

Three-dimensional finite difference simulations of long period ground motion in the sediment-filled L. A. basin require a seismic velocity model whose spatial resolution is comparable to the wavelengths of interest. Such simulations also require a gridding scheme capable of handling the small zone size required to approach 1 Hz resolution. We have addressed both of these issues during the past year, and begun doing validation studies with the resulting model and computational scheme. We have constructed a seismic velocity model of the basin using existing geologic information, together with results of seismic travel time studies. These data were combined with an age-depth-seismic velocity relationship and used the model in a finite difference code equipped with a recursive grid refinement algorithm to simulate, as a test case, the ground motions of the 1987 Whittier Narrows earthquake.

Construction of the 3D velocity model. There exists a great deal of information about the stratigraphy and structure of the Los Angeles basin from oil exploration activities and other geophysical studies. Wright (1991) summarizes much of this information, and, in particular, presents depth contours of two stratigraphic horizons of known age. Yerkes et al. (1965) presents depth to basement contours. Age of the material at the ground surface is taken from California Division of Mines and Geology geologic maps.

Knowledge of the age and depth of key horizons led us to the use of age-depth-velocity relation of Faust (1951):

$$v = (kda)^{**}1/6$$

where v is P-wave velocity, d is depth of maximum burial, a is age, and k is a constant. Maximum depth of burial is found from the stratigraphic depth contours corrected for the amount of uplift during the Pasadenan deformation given by Wright (1991). The constant k was modified from Faust's value by calibration against velocity models determined from seismic travel time data by Teng et al. (1973), Hauksson (1987), and Magistrale et al. (1992).

The age and depth of burial at each point in the volume of interest is interpolated from the four known horizons (surface, 2 stratigraphic, basement), and then the seismic velocity is determined from Faust's equation. Outside and below the basin, velocities are assigned according to the regional model of Hadley and Kanamori (1977). S wave velocities are calculated from the P wave velocities using the relation of Nafe et al. (1970). Densities are found from the P wave velocities using the relation of Nafe and Drake (1960). The foregoing algorithm has been programmed and used to generate a digital representation of the 3D seismic structure of the basin and surrounding region, some 2D sections of which are depicted in Figures 1 and 2.

Development and validation of the recursive grid method. The 3D finite difference method was extended to incorporate recursive grid refinement. This scheme represents the seismic structure using a nested set of successively finer grids. The scheme is particularly advantageous when large velocity constrasts are present, as in the L.A. Basin study. The 1987 M 5.9 Whittier Narrows earthquake was selected for the first validation study because it has a well studied source with a simple rupture, is within the basin, and it generated many strong motion records. A test case has been run using relatively coarse zoning, with 4 levels of recursive grid refinement. That calculation is currently being analyzed, after which we will add the additional levels of grid refinement required to approach 0.5 to 1.0 Hz resolution

References:

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Nafe, J. E. and C. L. Drake (1960). Physical properties of marine sediments, in The Sea, 3, M. N. Hill, editor, p. 794-815, Interscience, New York, New York.

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Yerkes, R. F., T. H. McCulloh, J. E. Schoellhamer, and J. G. Vedder (1965). Geology of the Los Angeles basin, California - an introduction, U.S. Geol. Surv. Profess. Paper 420–A, 1-57.

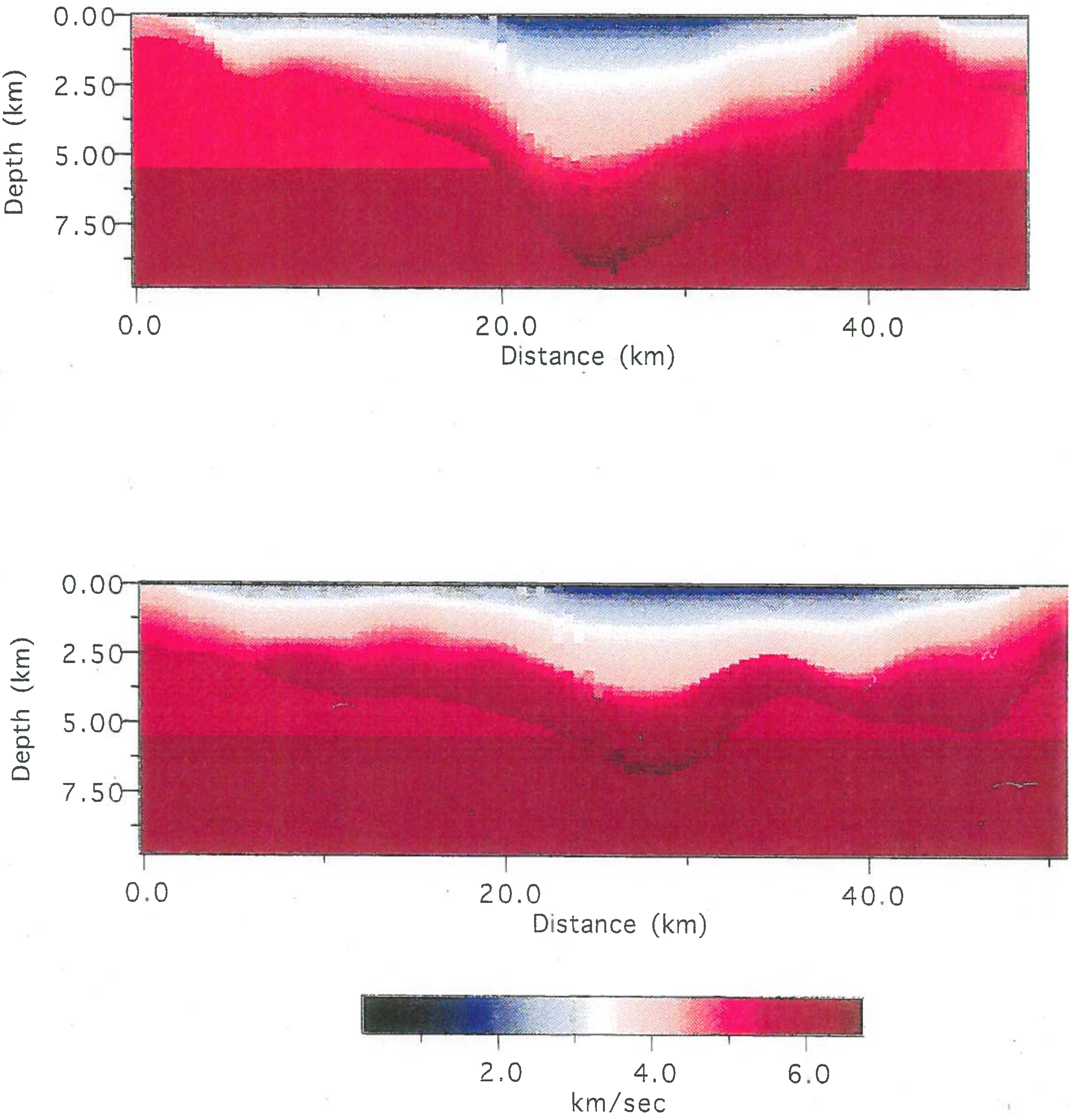

Figure 1. Crosssections of the 3D P wave velocity model for the L. A. Basin. Top crosssection corresponds to crosssection EE' from Wright et al. (1991), which runs across the deepest part of the basin, from Palos Verdes to the San Gabriel Valley. Bottom crossection corresponds to GG' from Wright et al., running from San Pedro to the Chino Hills.

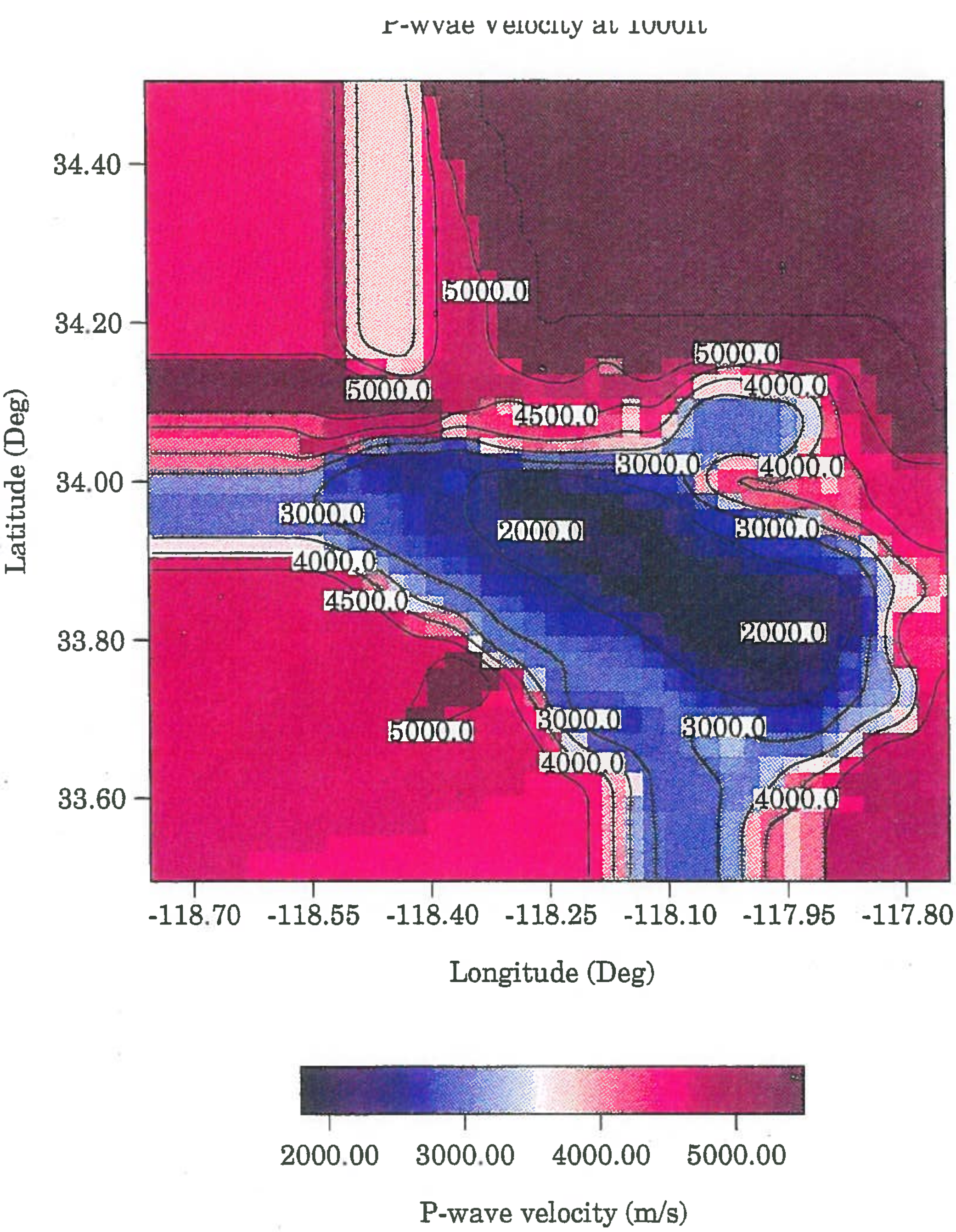

Figure 2. Horizontal section through the L. A. Basin velocity model at a depth of 1000 feet.

Southern California Earthquake Center
Technical Report, Dec 1, 1993

Three Dimensional Simulation of Long Period Ground Motion in L. A. Basin

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This project had as its intent to compute ground motions for central Los Angeles from several plausible earthquakes.

This project is closely coordinated with another SCEC project funded to Anderson, Zeng, and Su at the University of Nevada, *High Frequency Strong-Motion Prediction by Regression and Simulation*. The Dec. 1, 1993 Techical Report for that project describes development of a composite source model which seems to successfully merge low, intermediate, and high frequencies and to effortlessly produce quite realistic synthetic seismograms (Zeng et al, 1993; Yu et al, 1993).

As part of the UNR contribution to this project, we have applied the composite source model to develop synthetic seismograms for central Los Angeles from an earthquake on the San Andreas fault using flat-layered earth structures. We used two structures. One is a regional velocity model which leaves out the Los Angeles basin. The other structure extends a Los Angeles basin velocity model all the way to the San Andreas fault. Figure 1 shows a map of southern California, showing the part of the San Andreas fault that is assumed to rupture. Figure 2 shows very preliminary synthetic seismograms for the regional velocity structure. Figure 3 shows very preliminary synthetic seismograms for the L. A. Basin structure extended to the San Andreas fault.

References

Yu, G., K. N. Khattri, J. G. Anderson, J. N. Brune, Y. Zeng (1993). Strong Ground Motion From the Uttarkashi, Himalaya, India Earthquake: Comparison of Observations With Synthetics Using the Composite Source Model (submitted for publication)

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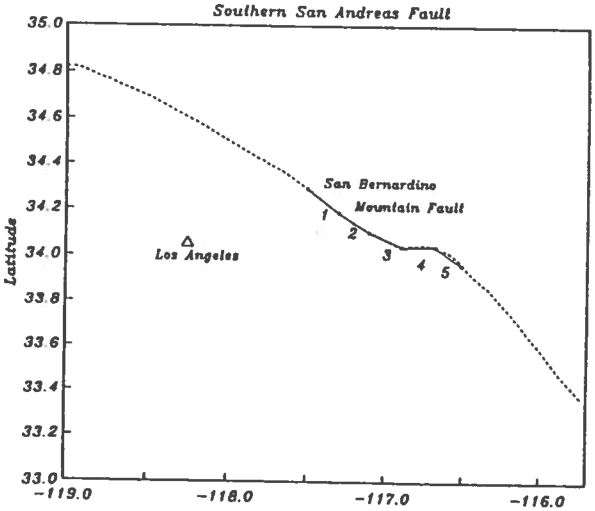

Figure 1. Map of southern California showing portion of San Andreas fault that is assumed to rupture in a $M_W=7.4$ earthquake. Rupture propagates from segment 1 to segment 5.

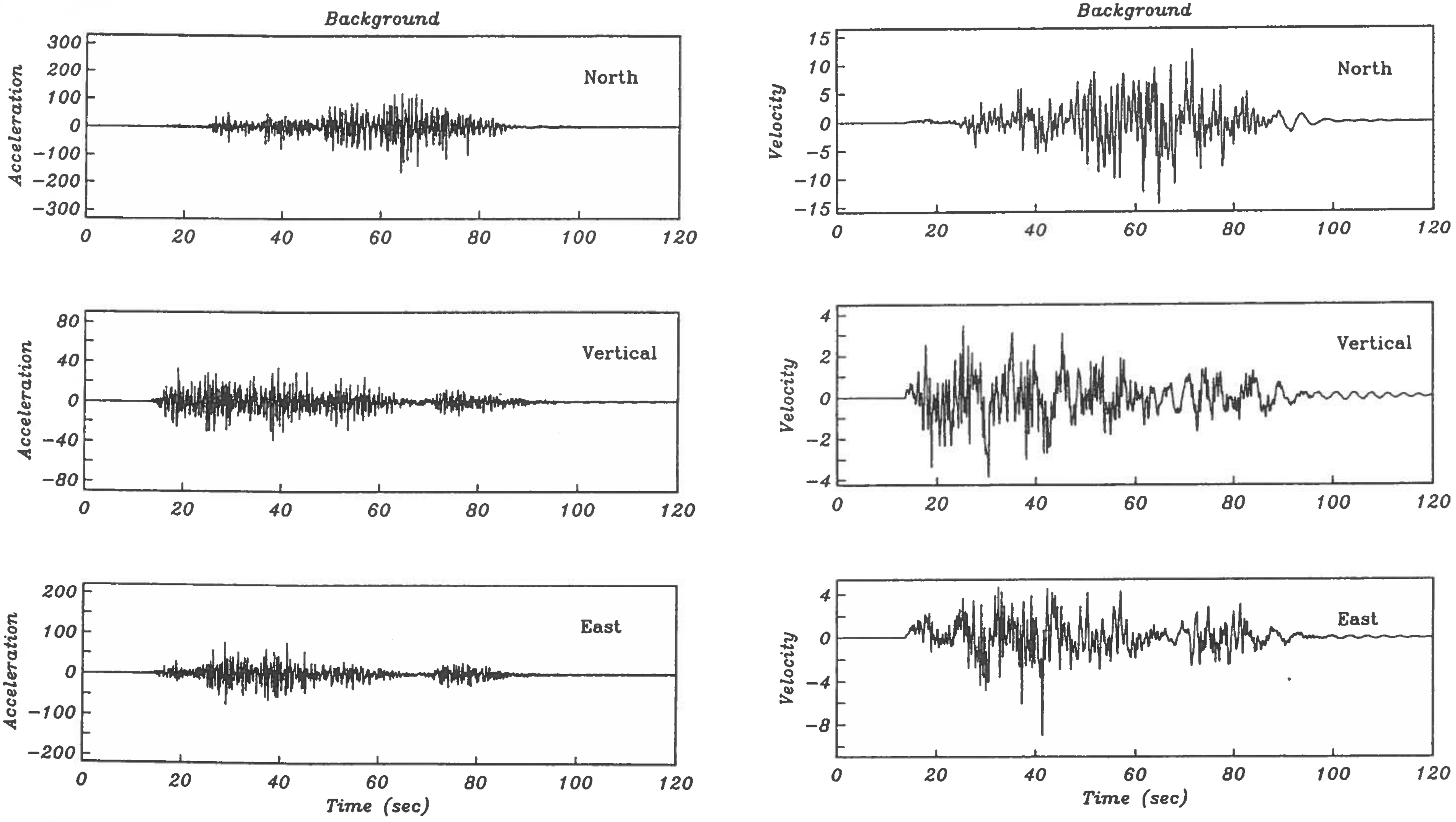

Figure 2. Synthetic acceleration and velocity using a regional velocity structure for southern California, resulting from the earthquake in Figure 1. Synthetics are computed using the composite source model.

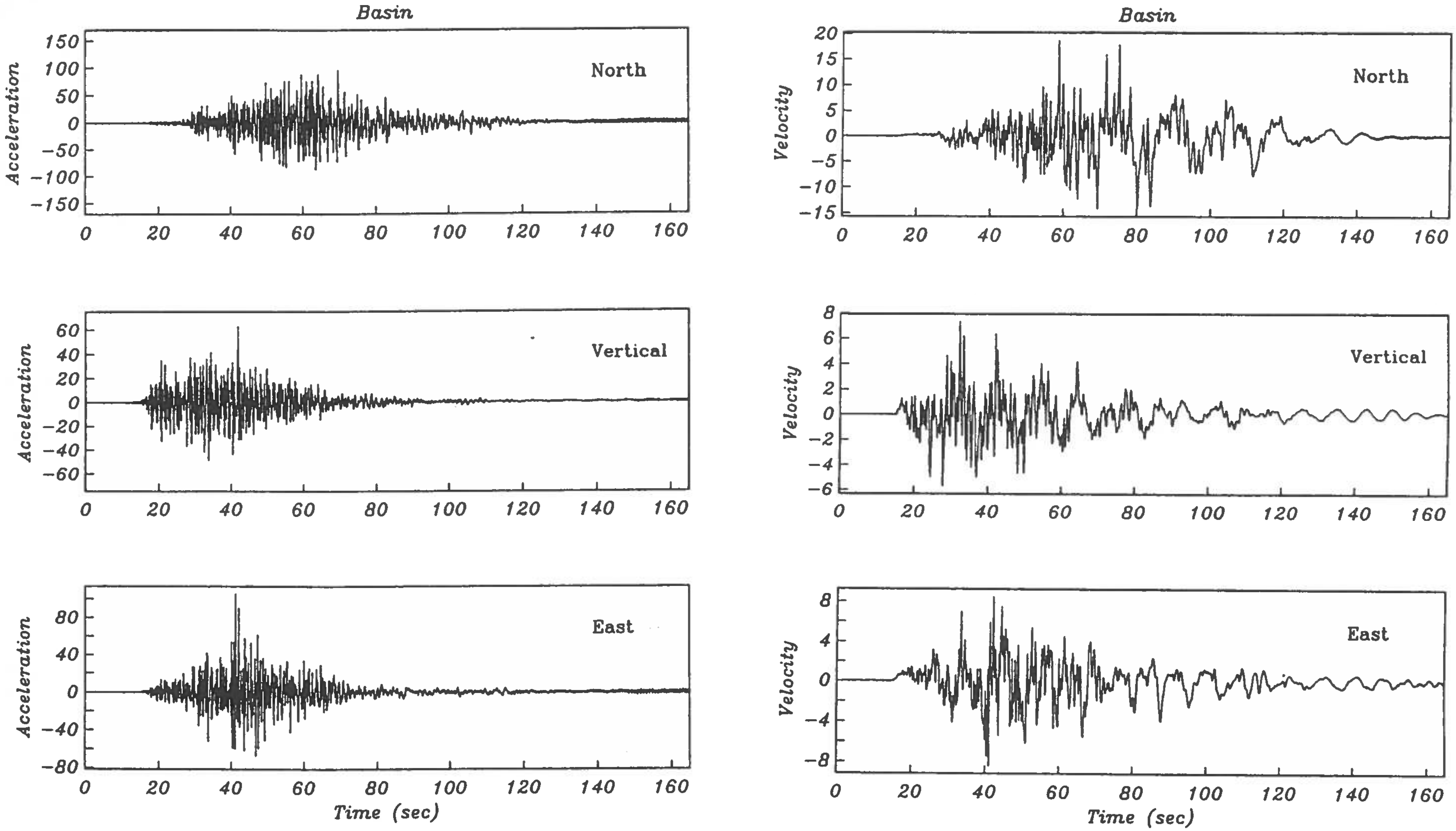

Figure 3. Synthetic acceleration and velocity using a Los Angeles basin velocity structure extended all the way to the San Andreas fault, resulting from the earthquake in Figure 1. Synthetics are computed using the composite source model.

Progress report on
"Simulation of long-period strong ground motion for 3-D models of the Los Angeles basin"

Keiiti Aki and Yoshiaki Hisada
University of Southern California

Target 2, Group B

Combining our original numerical codes for the Gaussian beam method (Kato *et al.*, 1993) and the boundary element method (Hisada *et al.*, 1993), we have been developing a new code for the surface wave Gaussian beam - boundary element method, which runs on the San Diego Supercomputer. So far, we developed fast efficient methods, specially for computing the complete Green's function and the normal mode solution for a 3-D layered half-space based on Hisada (1993) and Chen (1993), respectively, which will be used to compute a huge number of Green's functions and the normal mode solutions in order to construct the near- and far-wavefields inside and outside the 3-D Los Angeles basin. In addition, we have been making improvements in our new code: 1) we consider inclined interfaces between the inside and outside of the basin, instead of the vertical interface used by Hisada *et al.* (1993); 2) we use a shape function of higher-order to interpolate displacements and tractions within boundary elements, instead of the constant element. This would allow us to greatly reduce the total number of boundary elements.

From our experiences with the original codes (Kato *et al.*, 1993; Hisada *et al.*, 1993), we found the following two main problems for computing the complete Green's function and the normal mode solution: 1) the numerical instability caused by the exponential terms in the propagator matrix, which grows with the frequency and/or the wavenumber; 2) the requirement of large CPU time for computing the displacement and stress Green's functions for sources and receivers at close depths. We have overcome the first problem by modifying the generalized reflection/transmission coefficient method (Luco and Apsel, 1983) and applying it to the complete Green's function and the normal mode solution (Hisada, 1993; Chen, 1993; Chen and Hisada, 1993). Because our modified version of the generalized R/T coefficient method is completely free from the growing exponential terms, it can be numerically stable theoretically up to the infinite frequency. As one example to demonstrate our method, Figure 1 shows a layered medium (top), a secular function to determine the phase velocities at 1 Hz for the Rayleigh wave (middle), and the dispersion curves up to 5 Hz for Rayleigh wave (bottom).

We have solved the second problem by developing an analytical method (Hisada, 1993). When source and receiver depths are close or equal, it is difficult to compute Green's functions of the layered half-space, because their integrands, whose integration variable is the horizontal wavenumber, have slowly-decreasing-oscillating and increasing-oscillating properties for the displacement and the stress, respectively. To remedy this problem, we introduce "the equivalent static Green's functions", whose integrands converge to the integrands of Green's functions with increasing wavenumber. By subtracting the integrands of the equivalent static Green's functions from the integrands of corresponding Green's functions, we obtain integrands which converge rapidly to zero and are therefore more efficiently integrated. Since the integrands of equivalent Green's functions are expressed by the products of Bessel functions and simple exponential functions, they are analytically integrable. Therefore, we finally obtain accurate Green's functions by adding together numerical and analytical integrations. As one example, Figure 2 shows the upper limit of the range of integration versus displacements and stresses for a source and a receiver at a same depth, which are computed by both the original method (without using the equivalent static Green's function) and our method for the layered model shown in the figure. Our method shows much faster and more stable convergence than the original method, especially for the stresses.

References

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Chen, X. and Y. Hisada (1993). A supplemental note for "A systematic and efficient method of computing normal modes for multilayered half-space", preparing to submit to Geophys. J. Intern.

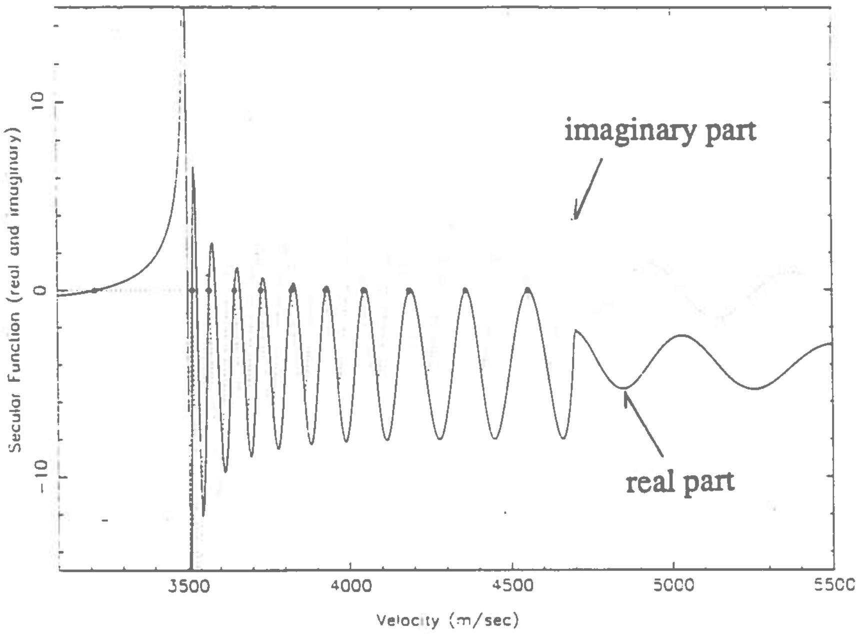
Hisada, Y., K. Aki, and T.-L. Teng (1993). 3-D simulations of the surface wave propagation in the Kanto sedimentary basin, Japan (Part 2: Application of the surface wave Boundary Element method), Bull. Seism. Soc. Am., Vol. 83, No. 6

Hisada, Y. (1993). An efficient method for computing the displacement and stress Green's functions for a 3-D layered half-space and sources and receivers at close depths, submitted to Bull. Seism. Soc. Am.

Kato, K., K. Aki, and T.-L. Teng (1993). 3-D simulations of the surface wave propagation in the Kanto sedimentary basin, Japan (Part 1: Application of the surface wave Gaussian Beam method), Bull. Seism. Soc. Am., Vol. 83, No. 6

Table 1. Multi-layered crustal model

depth to bottom (km)	ρ (g/cm³)	β (km/s)	α (km/s)
18.0	2.80	3.50	6.00
24.0	2.90	3.65	6.30
30.0	3.10	3.90	6.70
∞	3.30	4.70	8.20



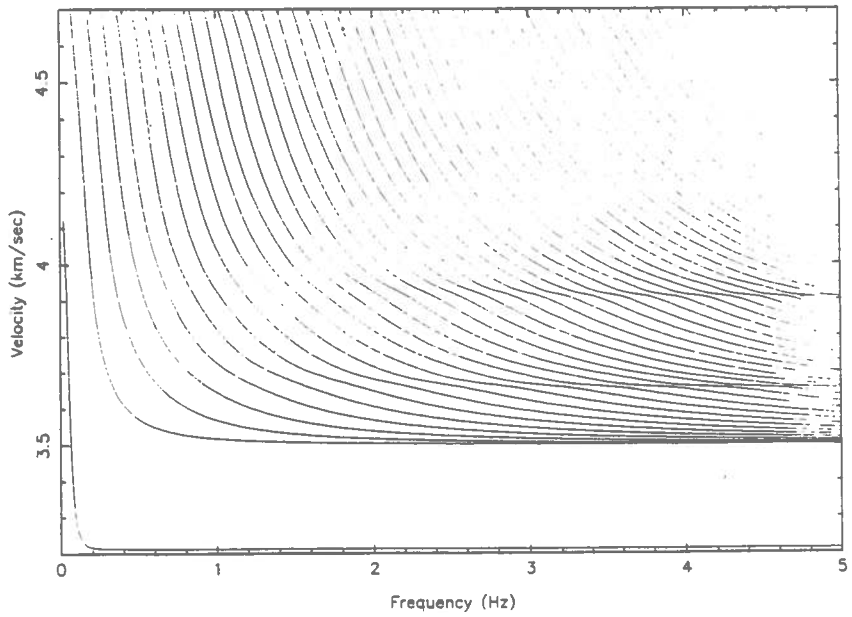


Figure 1. A layered model (top), a secular function for the phase velocities of Rayleigh wave at 1 Hz (middle), and Dispersion curves of Rayleigh waves (bottom), from Chen (1993) and Chen and Hisada (1993).

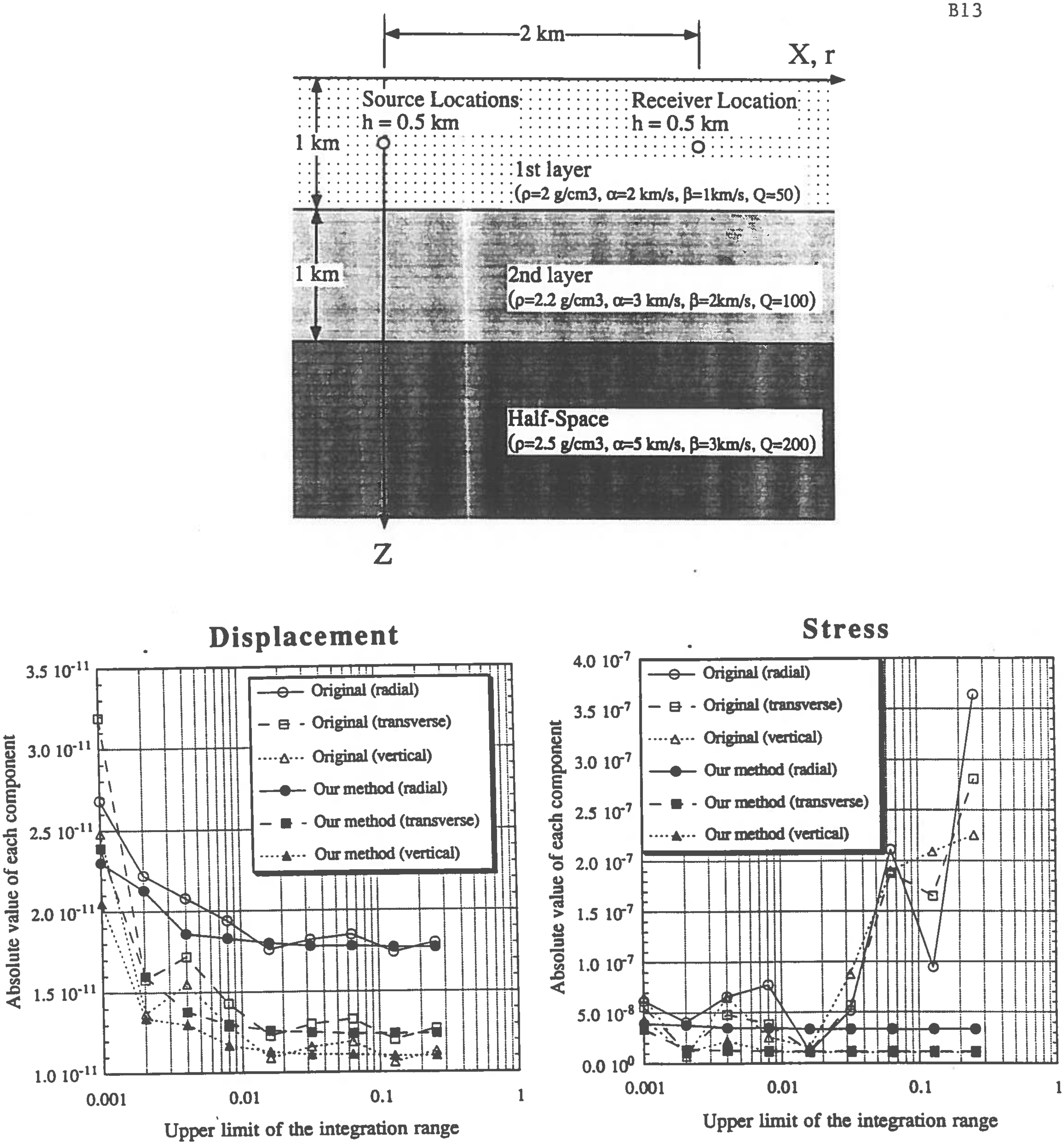


Figure 2. A layered model with a source and a receiver (top), and the upper limit of the integration range versus the absolute value of each component of the displacement and stress Green's functions at ω = 1, which are computed by the original method and our method (bottom). The magnirudes of three components of the source are 1 (Hisada, 1993).

1993 SCEC Annual Report
High-Frequency Strong Motion Predictions for Landers and the Los Angeles Basin

Sandra H. Seale and Ralph J. Archuleta
Institute for Crustal Studies, UCSB

The Landers earthquake provided an excellent opportunity to examine high-frequency radiation from a major earthquake. We have been comparing high-frequency synthetic accelerograms (1-10 Hz band) with data recorded at Lucerne Valley (LUC) and Morongo Valley (MVB). The synthetics are computed using the isochron method (Spudich and Frazer, 1984; Zeng et al., 1993). This method explicitly includes the finiteness of the fault, inhomogeneous slip, rupture velocity, radiation patterns, and wave propagation in a vertically heterogeneous medium.

The initial model of the Landers earthquake incorporated 10 different fault segments that were based on the amount of surface slip. We found that such a faulting model produced synthetics that did not agree with the data. Thus we tried a faulting model that consisted of three segments: Johnson Valley fault (Segment 1), Homestead Valley fault (Segment 2) and a combined Emerson/Camp Rock fault (Segment 3) (Figure 1). The mean rupture velocity on each segment is 3.0 km/s with a random perturbation applied to the time of slip being 0.1 seconds. In Figure 2 the data and synthetics for station LUC are shown at the same scale. The synthetics underestimate the data by about a factor of two. However, the total moment for the three segments is 1.2 x 10^{27} dyne-cm. Simple scaling of the slip on the fault is a possible solution, but there are other factors.

Segment	Length (km)	Azimuth (°) cc from North	Avg. Slip (cm)	Avg. Moment ($\times 10^{26}$ dyne-cm)
Segment 1	20.0	10.4	225	2.5
Segment 2	26.1	26.1	247	3.1
Segment 3	39.6	39.3	303	6.7

Two critical factors that strongly influence the high-frequency radiation are the amount of incoherency in the rupture velocity and the shape of the slip-rate function. One speculative result of this analysis is that the high-frequency radiation is somewhat decoupled from the long-period radiation. Thus simple scaling of the seismic moment does not scale the high-frequency amplitude in the same proportion. We are continuing our investigation of this preliminary result.

References:

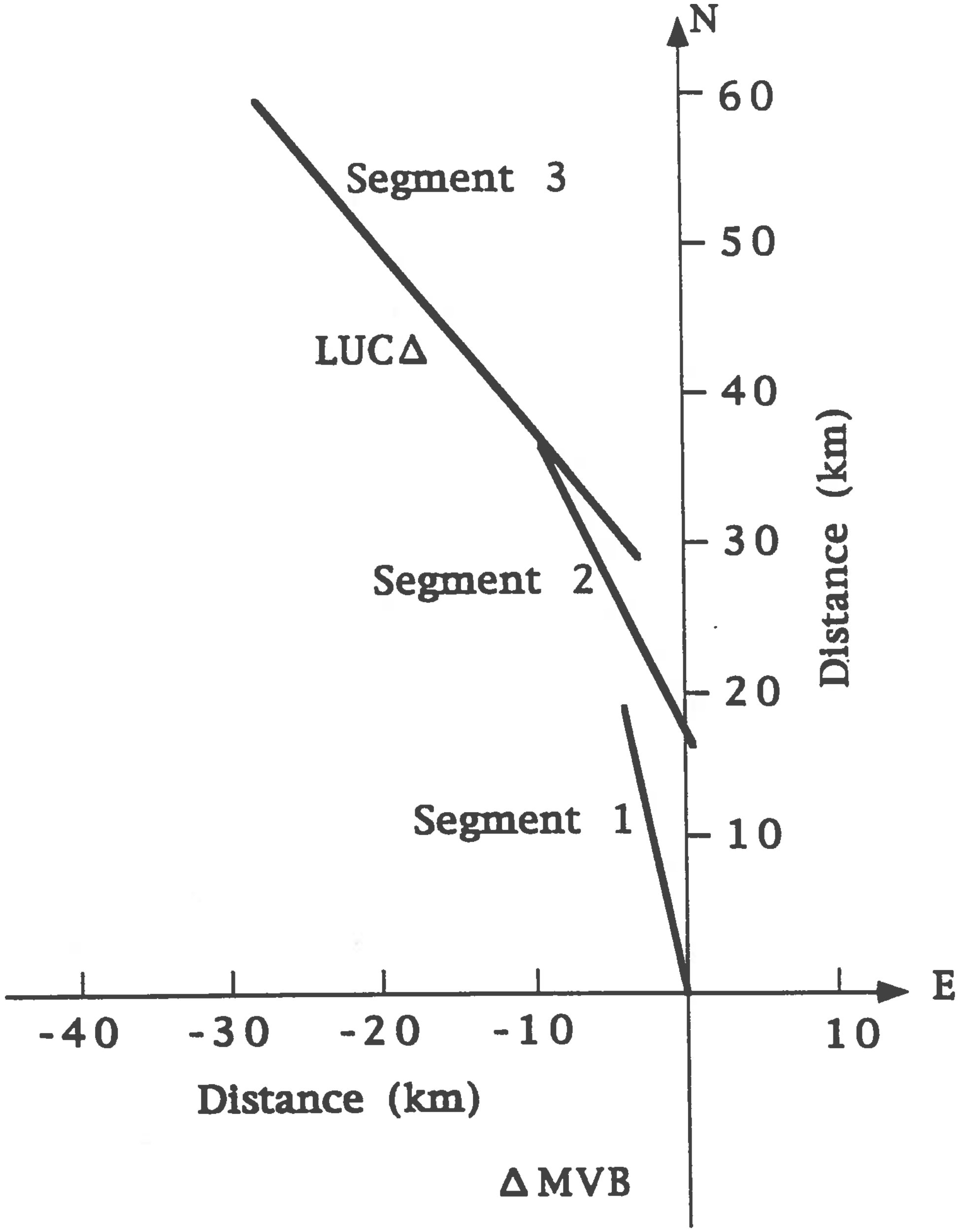
Spudich, P. and L. N. Frazer (1984). Use of ray theory to calculate high-frequency radiation from earthquake sources having spatially variable rupture velocity and stress drop, *Bull. Seism. Soc. Am.*, **74**, 2061-2082.

Zeng, Y., K. Aki, and T-L. Teng (1993). Source inversion of the 1987 Whittier Narrows earthquake, California, using the isochron method, *Bull. Seism. Soc. Am.*, **83**, 358-377.

Figure 1: Plan view of the geometry being used to simulate the Landers earthquake. The three segments are described in the text. Accelerograms from Stations LUC and MVB are compared with synthetics derived from isochron simulations.

Figure 2: In the upper figure the horizontal accelerations at LUC are compared to synthetics derived from the three-segment Landers model. Data are shown as traces labeled *luc.a.n* (north component) and *luc.a.e* (east component). Synthetic accelerograms are shown as *luc.11* and *luc.22*. Synthetic amplitudes are about 1/2 of the data.

In the lower figure the contributions to LUC from the three segments are shown. Not surprisingly Segment 3 has the largest effect on LUC. The differences between components arises from polarizations due to the angle of the fault, i.e., Segments 1&2 strike more nearly North than does Segment 3.


N
60
50
40
30
20
10
Distance (km)
Segment 3
LUC∆
Segment 2
Segment 1
E
-40
-30
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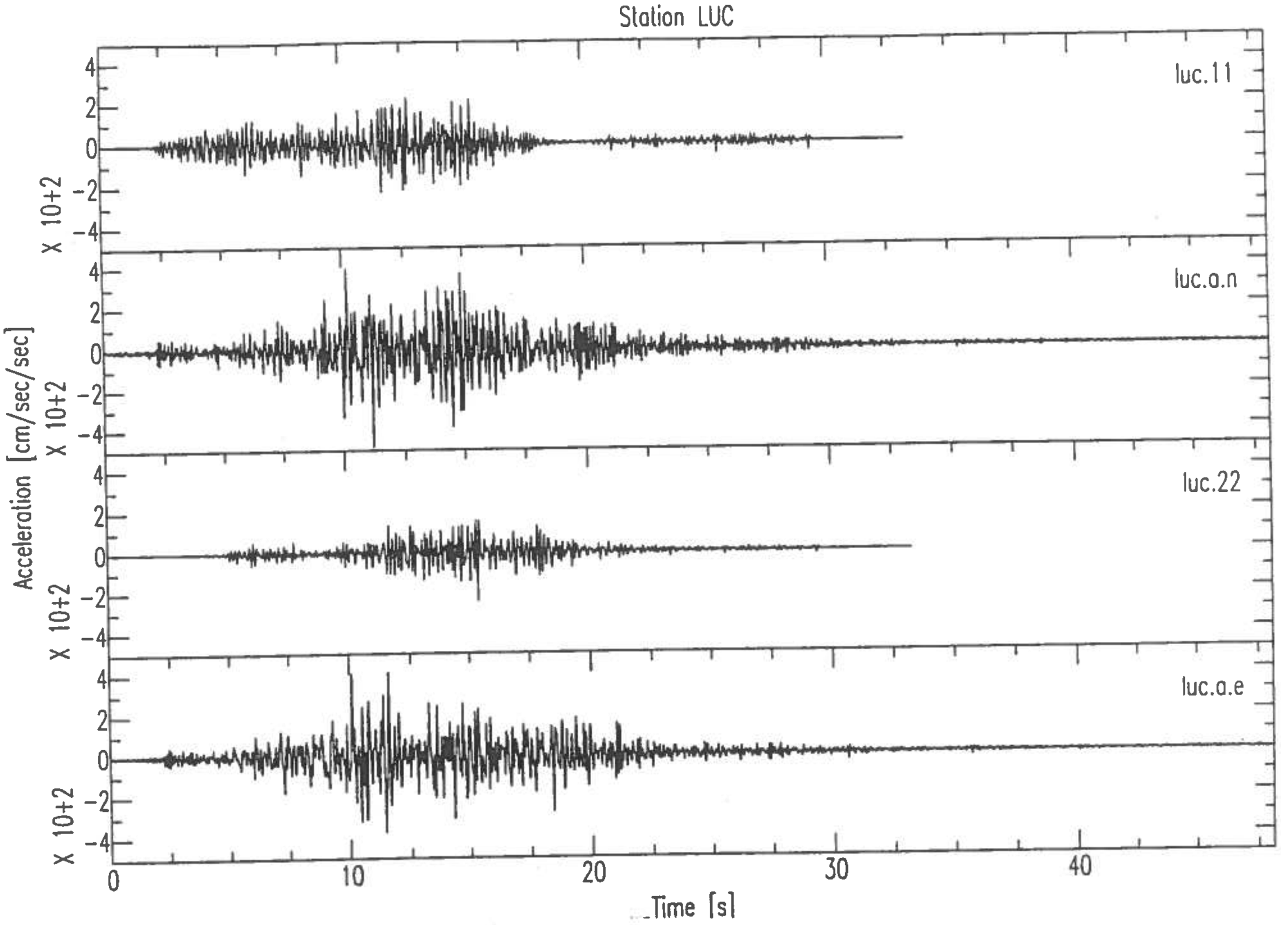
-10
10
Distance (km)
∆MVB


Station LUC
luc.11
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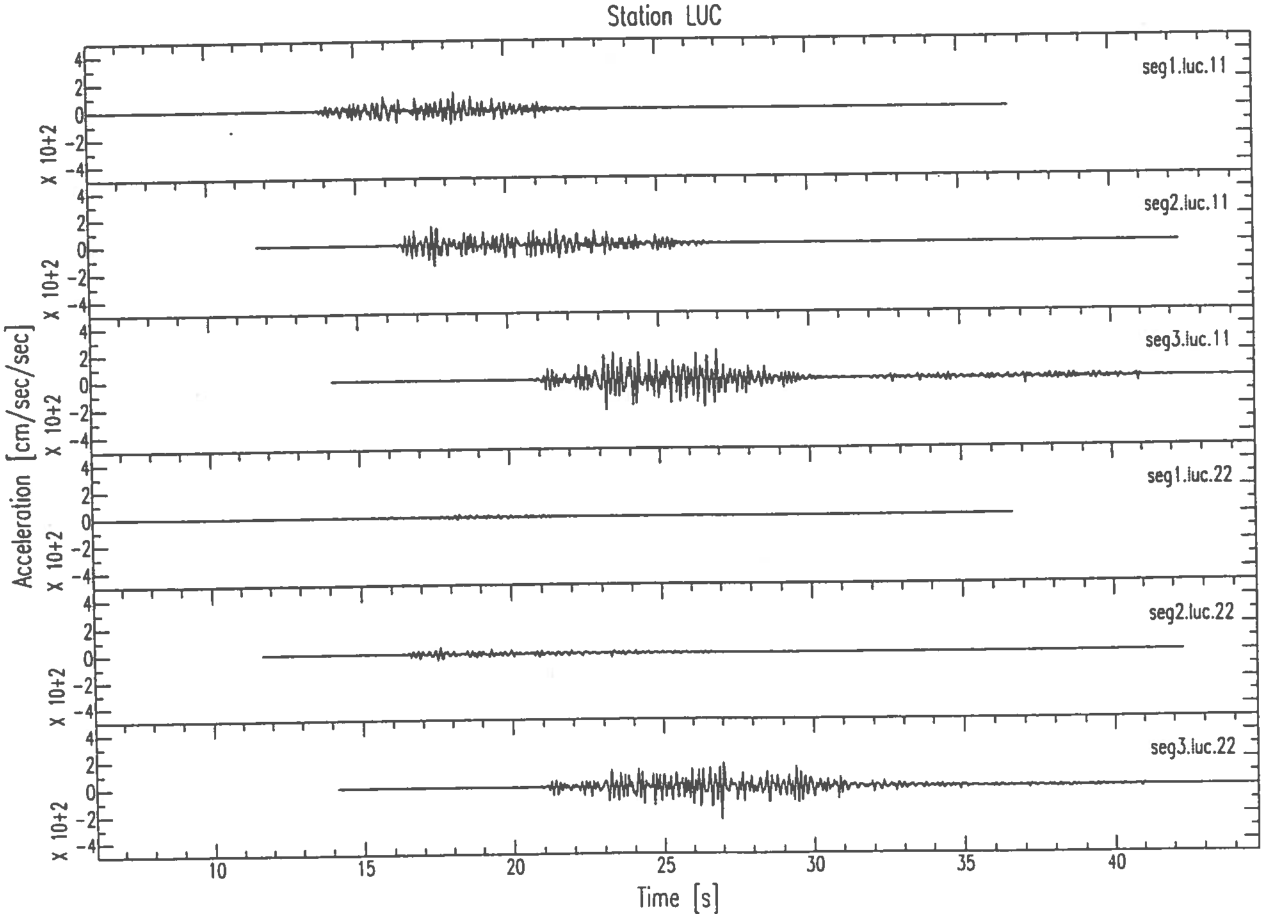
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MAPS OF GROSS SITE AMPLIFICATION FACTORS FOR THE LA BASIN

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INSTITUTE FOR CRUSTAL STUDIES, UC SANTA BARBARA

Site response studies should use both spectral and time-domain approaches. The analyses in the frequency domain (spectral ratio method, cross-spectrum method, etc.) have an obvious limitation of completely disregarding such an important engineering factor as the duration of shaking. At the same time the response spectral ratio method takes more care of duration, but not in a very explicit manner. There is a need to incorporate duration-content information into site-response studies.

Objectives:

- to find a simplified representation of the duration (as a complement to the frequency) contents of a seismic signal;
- to establish a stable and representative measure of the time-domain seismic amplification.

Results:

- amplitude-duration diagram: each value of amplitude A between 0 and A_{max} corresponds to the duration of shaking with amplitude greater than A (number of samples with amplitude greater than A • sampling interval). Amplitude-duration diagram is the inverse function to the cumulative frequency distribution of the signal's amplitudes (Vladimir Schenk, *Phys.Earth Planet. Inter.*, 1985);
- envelope amplification factor: the ratio of the amplitude-duration diagrams at a given site to a reference site. This factor is a very stable measure of amplification (ratio of two amplitude-duration diagrams is remarkably flat between 0.1 and 10 seconds).

Our proposed method provides the amplification factor associated with signal's envelope. A direct comparison of the envelopes of two recordings of ground acceleration at different sites seems impossible. Our idea is to rearrange amplitudes to produce an "equivalent" envelope, preserving absolute duration of shaking above an arbitrary amplitude threshold. Each given value A of the ordinate (observed amplitude) of this equivalent envelope corresponds to the value of the abscissa D, representing the total duration of shaking with amplitude greater than A. For equally spaced time-series this is easily achieved by sorting the initial envelope's amplitudes in a descending order. The resulting duration-amplitude graph represents an inverse function to the cumulative amplitude-frequency distribution (Schenk, 1985). Now we have a tool to study the amplification of envelopes of seismic signals by comparing amplitudes of ground motions with the same duration.

Our studies show that in the range of duration of a prime engineering concern (0.1 - 10 s), the envelope amplification between stations with different site geology is approximately constant (Figure 1). This fact allows us to introduce a time-domain measure of a gross amplification of ground shaking as the average ratio of sorted envelopes between 0.1 and 10 s. The comparison of envelope ratios with response spectral ratios (5% damping) shows that the envelope method is not sensitive to site and/or source resonances, at the same time providing amplification values consistent with those inferred from the response spectral method.

We have used this method to produce a map of gross strong ground motion amplification factors for the Los Angeles Basin (Figure 2).

Figure 1.

Three-component accelerograms of the 1971 San Fernando Earthquake recorded at the Caltech Old Seismological Laboratory, Pasadena (PSL) and the Hollywood Storage Building, P.E. Lot (PEL). We also plot in the left column the total amplitude of a 3D seismic signal (accelerogram) at each time moment *t*:

$$|A(t)| = \sqrt{A_X(t)^2 + A_Y(t)^2 + A_Z(t)^2}\,.$$

Amplitude-duration diagrams for PSL (dotted line) and PEL (dashed line) are shown on the right plot. Their ratio (solid line) indicates an amplification 1.63 between records at PSL (distance to the projection of the rupture on the surface 21.9 km) and PEL for the San Fernando Earthquake (projected distance 24.6 km). Correcting this value for the geometrical spreading factor we get the site amplification 1.83 at PEL relative to PSL.

Figure 2.

Map of strong-motion amplification factors for the LA Basin. We processed 241 three-component records (mainly from two agencies: CDMG and USGS) from the following earthquakes:

- 1933 Long Beach (4 stations)
- 1952 Kern County (6 stations)
- 1968 Borrego Mountain (13 stations)
- 1970 Lytle Creek (20 stations)
- 1971 San Fernando (120 stations)
- 1987 Whittier Narrows (56 stations)
- 1992 Landers (22 stations)

Envelope amplification factors corrected for the hypocentral distances were interpolated using the GMT-SYSTEM. It is understood that the interpolation between sparsely distributed sites is NOT an optimum procedure. The results will be made more reliable by adding additional data points (i.e., from the strong-motion network operated by USC) and/or by applying adequate artificial intelligence methods to extrapolate results to sites with no recorded strong ground motion. The solution of such pattern recognition problem might constitute a separate scientific project.

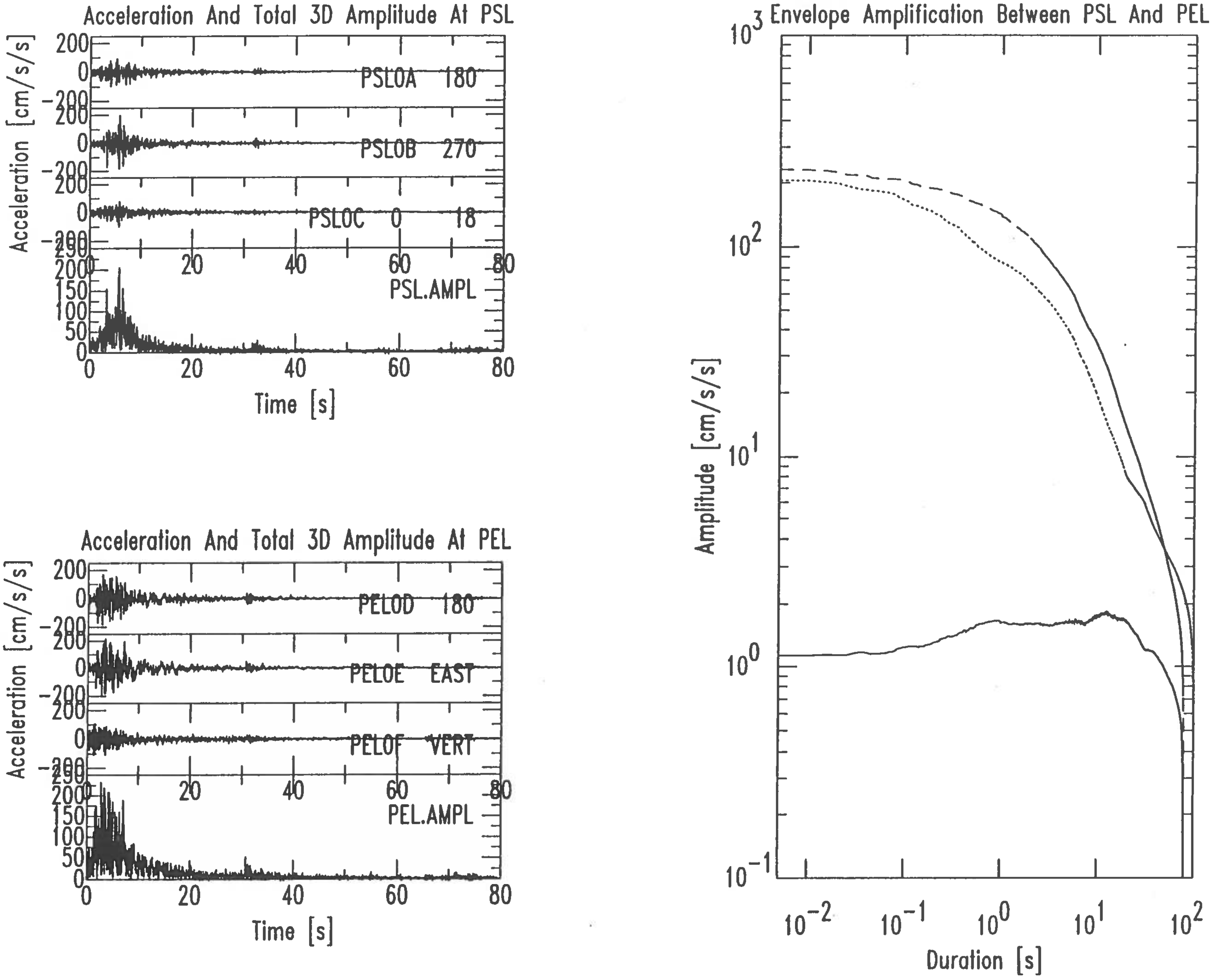
Acceleration And Total 3D Amplitude At PSL
Acceleration [cm/s/s]
200
0
−200
PSL0A 180
PSL0B 270
PSL0C 0 18
PSL.AMPL
150
100
50
0
20
40
60
80
Time [s]
Acceleration And Total 3D Amplitude At PEL
PEL0D 180
PEL0E EAST
PEL0F VERT
PEL.AMPL
Envelope Amplification Between PSL And PEL
Amplitude [cm/s/s]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Duration [s]

Figure 1.

Amplification Contours for the Los Angeles Region-Preliminary Result

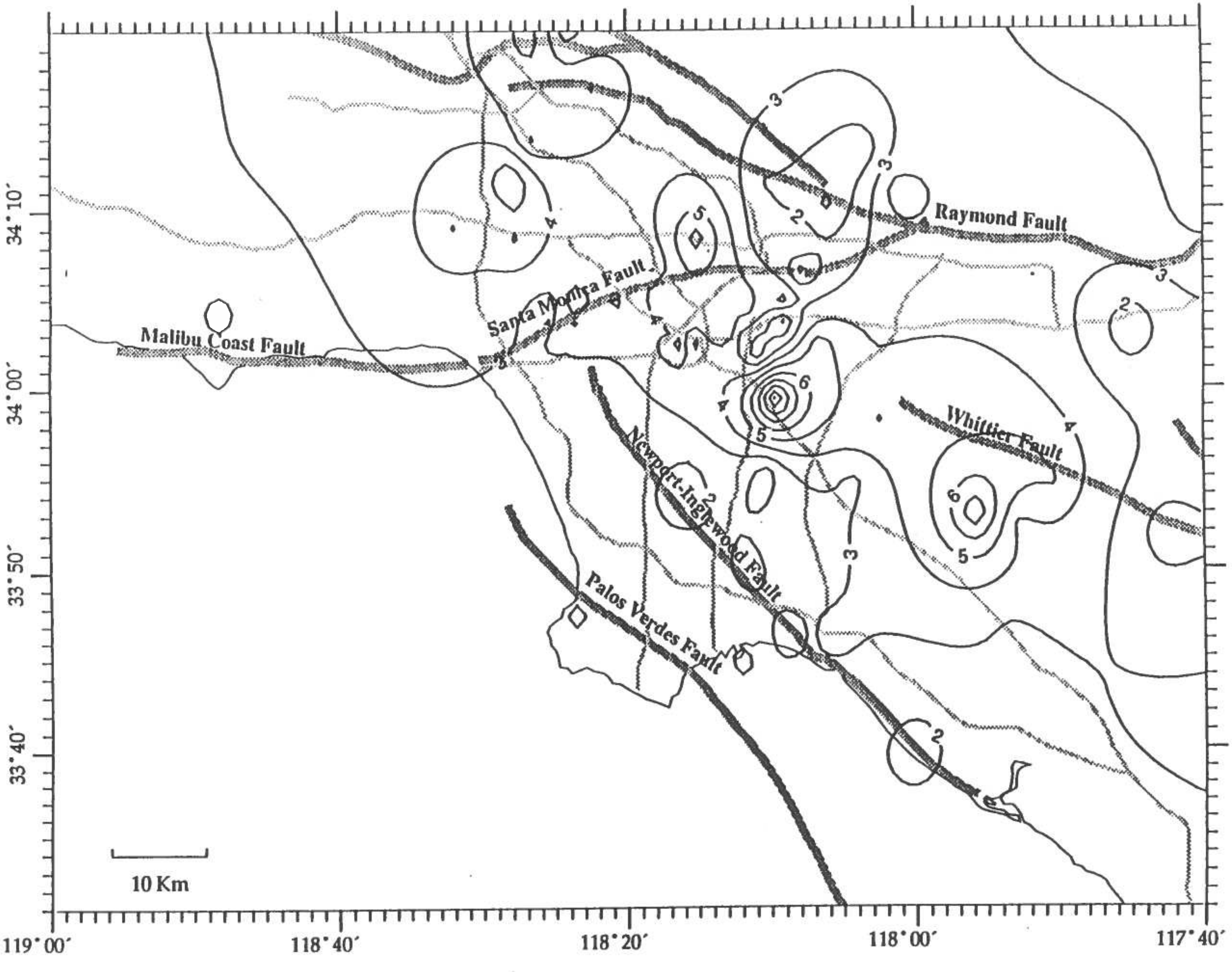

Figure 2.

Southern California Earthquake Center
Technical Report, Dec 1, 1993

High Frequency Strong-Motion Prediction by Regression and Simulation

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This project had as its intent to 1) develop an approach to simulate strong ground motion combininb stochastic and deterministic techniques, 2) develop an approach to smoothly join low frequency and high frequency simulations, 3) evaluate existing regressions. At this point, the project has accomplished most of its objectives.

A composite source model for convolution with synthetic Green's functions for estimating strong ground motions due to a complex rupture process of a large earthquake was developed (Zeng et al, 1993). The random nature of the heterogeneities of the complex fault is simulated in the source model by randomly superimposing a set of subevents on the fault plane. The size distribution of subevents is self-similar. Figure 1 shows an example of the distribution of 10% of the subevents for one realization. Each subevent radiates a displacement pulse with the shape of a Brune's pulse in the far field, at a time determined by a constant rupture velocity propagating from the hypocenter. The Green's function is calculated by the generalized reflection coefficient method for a realistic layered earth structure model. In order to save computing time for calculating a set of Green's functions for each subevent, the fault plane is divided into smaller subfaults, and only one Green's function is calculated for each subfault.

The method is easy to apply because all the input parameters have a clear physical basis. To validate the method, we first simulate strong ground motions for event - station pairs that correspond to conditions of actual records obtained in Mexico by the Guerrero accelerograph array. Figure 2 shows the geometry. The resulting synthetic accelerations, velocities, and displacements (Figure 3,4) have a realistic appearance. Amplitudes, durations, and Fourier spectra are, in general, consistent with the observations within the uncertainties imposed by imperfectly known site effects. They are also reasonably consistent with strong motion regressions. Thus, we believe that this method will be useful for estimating possible strong ground motions produced by future large, complex earthquakes. The success in generating ground motions with a realistic appearance may suggest that the earthquake source is akin to the superposition of failure of asperities with a self similar distribution of sizes.

Second, the method was further calibrated on strong motion records of the Uttarkashi earthquake of October 19, 1991 (MS=7.0). This event occurred in the greater Himalayan region north of the Main Central Thrust, at an estimated depth of 12 km (Figure 5). The fault plane solution indicates a low angle thrust mechanism, striking northwest, consistent with the tectonic pattern of thrusting in the region. Aftershocks define a belt parallel to, and north of, the surface trace of the Main Central Thrust, roughly 10 km wide and 30 km long. The main shock is located at the northeast edge of this zone. The earthquake was recorded on 13 strong motion accelerographs at distances ranging from 25 to

150 km from the epicenter. One station at Bhatwari (peak horizontal acceleration of 272 cm sec^{-2}) is above the aftershock zone. The maximum peak horizontal acceleration was about 313 cm sec^{-2} at Uttarkashi, at an epicentral distance of 36 km.

The amplitudes and frequency content of the strong ground motions are more or less consistent with expectations for an earthquake of this magnitude in California. In Figure 6, synthetics generated using the composite source model and synthetic Green's functions are compared with observations for three stations representing locations above the fault (Bhatwari), and at intermediate distance (Tehri) . At Bhatwari, they are reasonably successful in producing acceleration, velocity, and displacement with a realistic appearance and the correct statistical properties. To produce these, we introduced trial-and-error modifications of the layered-medium velocity model within uncertainties. At the more distant stations, we first used the same velocity structure that worked for the two nearest stations. Figure 7 compares peak accelerations, velocities, and displacements. Differences emphasize the large potential role of unknown site and wave-propagation effects.

The applications revealed certain weaknesses in the approach, which we are working to correct. Occasionally, the method yields near nodal components which do not appear on observations. We are developing a techniques to incorporate seismic scattering theory and some variability of orientation of strike and rake of subfaults into the synthetic seismograms, and preliminary calculations suggest that these will be successful in increasing the realism of the results.

References

Yu, G., K. N. Khattri, J. G. Anderson, J. N. Brune, Y. Zeng (1993). Strong Ground Motion From the Uttarkashi, Himalaya, India Earthquake: Comparison of Observations With Synthetics Using the Composite Source Model (submitted for publication)

Zeng, Y., J. G. Anderson and G. Yu (1993). A Composite Source Model For Computing Realistic Synthetic Strong Ground Motions (submitted for publication)

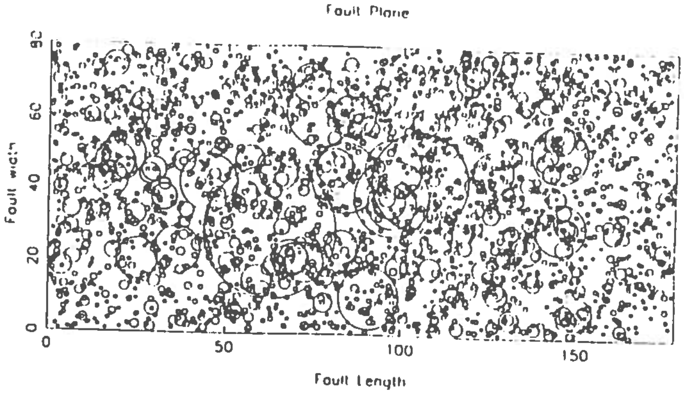


Figure 1. Spatial distribution of 10% of the subevents used for one simulation.

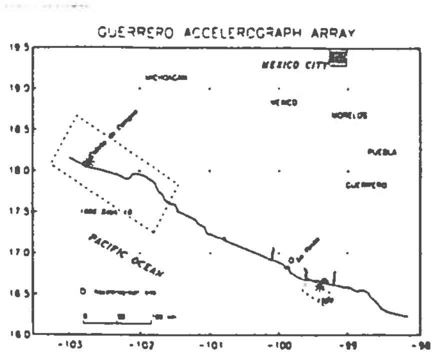


Figure 2. Epicenter, fault size, and station locations for the simulated seismograms from Guerrero, Mexico.

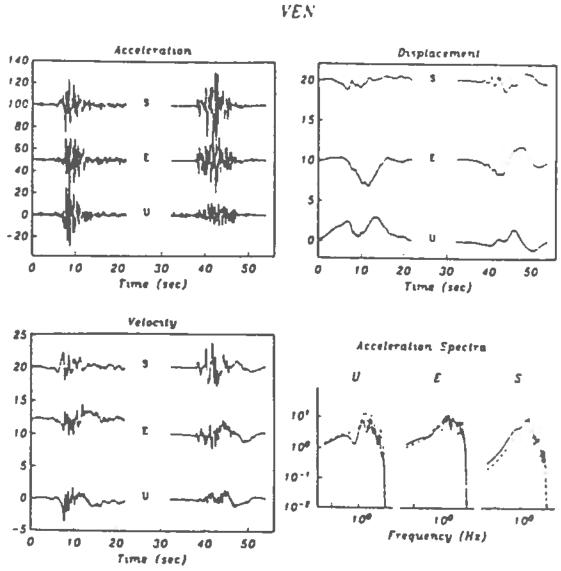


Figure 3. Observed (April 25, 1989, M=6.9) and simulated (right, solid) acceleration, velocity, high-pass filtered displacement, and Fourier amplitude spectra at the station La Venta.

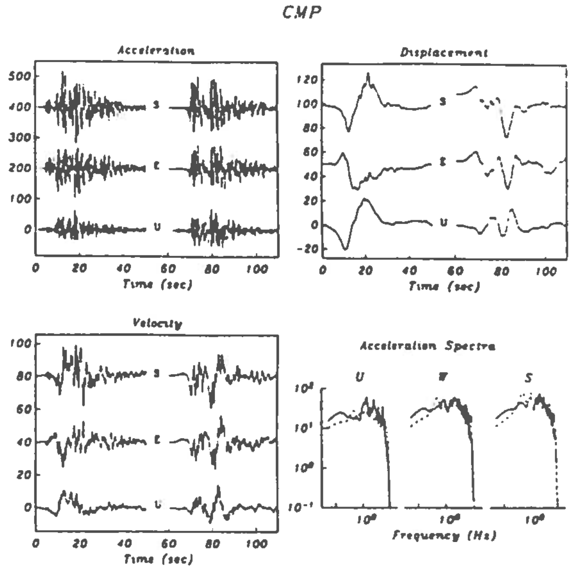


Figure 4. Equivalent of Figure 3 for the September 19, 1985 earthquake recorded at Caleta de Campos.

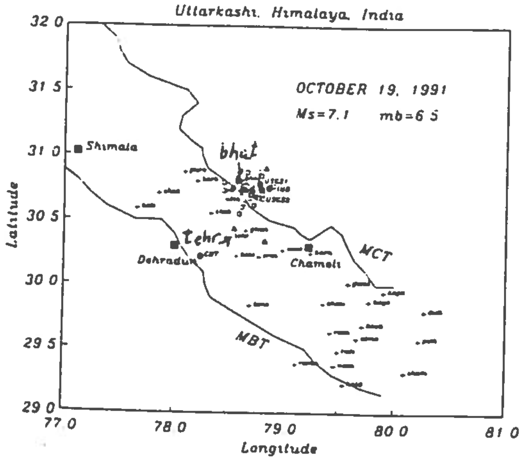


Figure 5. Map showing Uttarkashi main shock (solid circles, various estimates), some aftershocks (open circles), and strong motion sites (plus). Major thrust faults are marked by thick lines.

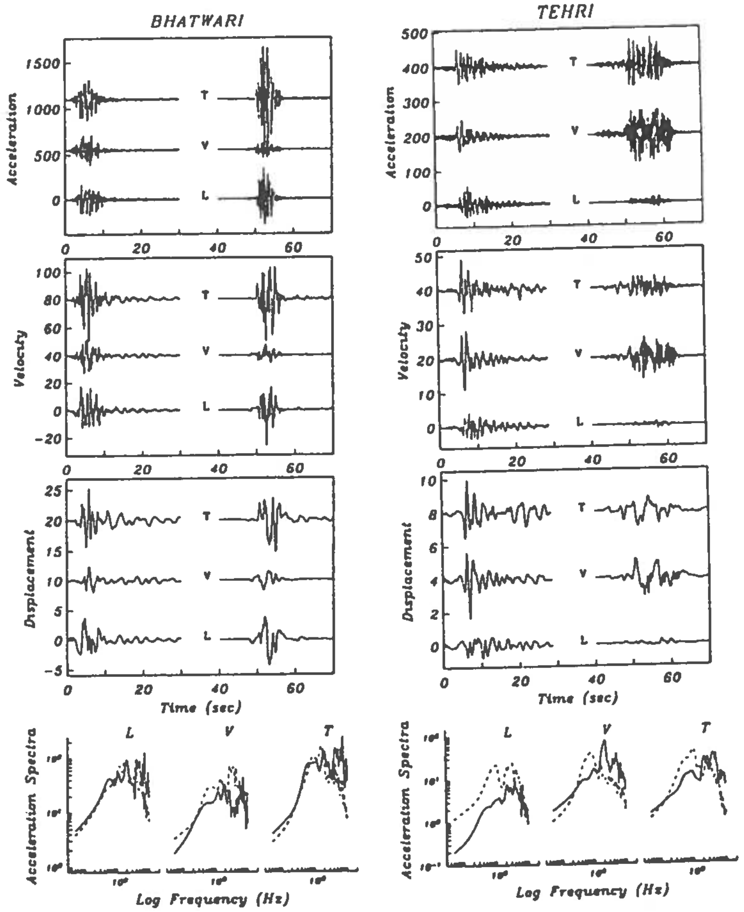


Figure 6. Comparison of observed (left, dashed) and synthetic ground motions at Bhatwari and Tehri.

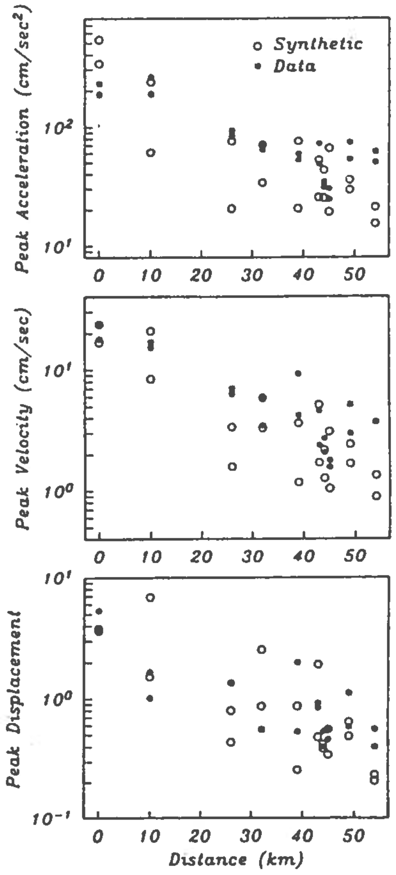


Figure 7. Peak horizontal values of acceleration, velocity, and displacements, as observed (asterick), and as predicted (circle) using the models in Figures 3 and 5.

Group C: Fault Zone Geology

Group Leader: Kerry Sieh

PROGRESS REPORT FOR GROUP C FOR 1993
(EARTHQUAKE GEOLOGY)

Kerry Sieh

Working Group C is proud of its progress during SCEC's first two and a half years, and we look forward to continuing our collaboration with each other and with other Center participants. The Center has fostered exceptionally productive interactions among Group C geologists, industry and government agencies and with the geophysicists and geodesists of the other working groups. Many of these interactions would not have occurred without SCEC funding and organization.

Accomplishments in 1993

Our achievements to date can be grouped into three categories:

1) Earthquake geology of the Los Angeles Basin

During the past year, SCEC geologists have continued to focus much of their attention on the earthquake geology of the Los Angeles metropolitan region. Our understanding of the geometry of active structures within the metropolitan region has improved and we have begun to determine their slip rates and paleoseismic behavior.

Bob Yeats and his colleagues at Oregon State University recently completed modeling of the **Wilshire Arch**, the young, anticlinal structure they discovered between downtown Los Angeles and Beverly Hills. The geometry of this structure, its associated right-lateral faults and the Hollywood basin can be created by right-oblique slip on a north-dipping thrust fault, which terminates about 3 km from the ground surface. The 400-m amplitude and shape of the 0.8 to 1.0 million-year-old structure can be produced by 1700 slip increments of 1 m of vertical and 1.5 m of dextral slip. The slip rate associated with this model, 2.6 - 3.2 mm/yr, represents more than 25% of the shortening across the LA basin seen in GPS measurements. A manuscript that describes these results has been submitted to *Geology*.

In cooperation with Southern California Edison and Leighton and Associates, Eldon Gath has recently excavated the **Alhambra Wash fault**, believed to be the strike-slip structure that caused the largest aftershock of the Whittier Narrows earthquake. Although the fault did not rupture at the ground surface during the 1987 earthquake, Gath has documented 4.5 to 9 m of right-lateral offset on this structure in four surficial ruptures over the past few tens of thousands of years. The rate of dextral slip on the fault is about an order of magnitude lower than the rate of the Whittier fault. He suggests that this is one of the structures that distributes slip at the northern end the Whittier fault. He also suggests that it breaks much less frequently than the Whittier fault (7,500 years versus 1,000 to 1,500 years).

Gath and Tom Rockwell are also close to completion of a manuscript on the neotectonics and paleoseismology of the **Whittier fault.**

John Shaw and John Suppe at Princeton have completed the first phase of their study of the blind thrusts that are producing **growth wedges on both flanks of the LA Basin**. They have concluded that both growth wedges are the result of northeast-dipping thrust ramps and that both of these ramps are part of the same southwest-verging system of ramps and flats. These interpretations suggest that a large, probably seismogenic thrust fault system directly underlies the entire Los Angeles basin, *sensu strictu*. They calculate that an earthquake of at least $M_W6.8$ could be generated by one part of this structure, failing solo. Karl Mueller and Suppe are now searching for paleoseismic sites where the most recent folding events can be documented and dated. They may have found a useful site along the **Compton-Los Alamitos trend.**

On the northern flank of the Los Angeles basin, Jim Dolan and I have continued our investigations of the **Santa Monica** and **Hollywood faults.** Our work on the MetroRail crossing of the Hollywood fault, with Paul Guptill and Grant Miller of Earth Technology Corporation, has shown that the Hollywood fault is active and has moved at least once in the past 17,000 years, but not in the past 2,000 to 4,000 years. If one postulates only moderate earthquakes on this structure, the long late Holocene dormancy the suggests a slip rate of ≤ 0.5 mm/yr. Borings to depths of more than 200 feet showed that the fault is surprisingly steep: it dips about 80° northward. This steep dip and the fact that the last event produced a mountain-facing scarp indicates that it is probably a predominantly left-lateral fault, not a reverse fault. Our paleoseismic investigation of the Santa Monica fault, done in collaboration with Tom Rockwell, demonstrates that the fault has moved at least twice within the past 14,000 years. The latest event occurred more than 2,000 years ago.

All of these data have been important in shaping SCEC's hazard maps for the Phase II report and will greatly influence our future calculations of strong ground-motion for the metropolitan region. Without these fundamental data on the sources of future destructive earthquakes in the Los Angeles region, we would have a woefully inadequate factual basis for any useful models of potential ground shaking, liquefaction, or surface rupture hazards within and near the Los Angeles basin.

We are pleased to have made so much progress in defining the geometries and styles of slip on the major seismic sources in and near Los Angeles. Despite our rapid progress, however, we clearly have more work before us than behind us.

We are intrigued, for example, by the fact that all of our few paleoseismic sites have yielded recurrence intervals measured in thousands rather than hundreds of years. We wonder if these very lengthy intervals are a first hint that these faults relieve large amounts of slip very infrequently, rather than small slippages, very often. We are guardedly optimistic that, with addition work, we may be able to answer the question: Do the faults of the Los Angeles region fail in small, moderate earthquakes on individual fault segments, or do they fail in multi-segment, large earthquakes, like the Landers event. This, it seems to me, is the most important question regarding the Los Angeles metropolitan region that can be addressed by SCEC geologists in the next few years.

2) Landers Post-seismic Geology

In the days, weeks and months following the Landers earthquake of June 28, 1992, a team of twelve SCEC geologists conducted extensive and intensive investigations of the surficial fault ruptures associated with the earthquake. Some of their basic findings are contained in a recent paper by myself and other SCEC scientists, which appeared in *Science* . Within a year of the earthquake, Group C's GIS center had created a database of geological data included the topology of the fault and slip data for approximately 1400 sites along the rupture. The fault topology is now available to any scientist or organization through anonymous FTP. The specific site data will be available within a few months, at which time a lengthy manuscript on the geological aspects of the earthquake will be submitted for publication, accompanied by a large map.

This diversion of Group C from its focus on the Los Angeles basin was very much worthwhile. The Landers earthquake provided a unique and rare opportunity to investigate the nature of earthquake faulting. Not since 1952 has such a large earthquake occurred on land in California; and not in the State's entire historical record has such a complex rupture occurred. Our investigations have profoundly affected the community's understanding of fault segmentation and its importance in the creation of probabilistic seismic hazard maps. Our field mapping has also aided in calculations of the effect of the Landers earthquake on the San Andreas fault. Our mapping has already been utilized in several seismological and GPS- and radar-interferometric geodetic investigations of the earthquake. Sally McGill and Charlie Rubin have used the data to show that paleoseismological investigations of ancient earthquakes must be cautious in interpreting multi-modal peaks in geomorphic offset as evidence for more than one earthquake. Furthermore, the CDMG is currently using our mapping in their creation of new Alquist-Priolo Special Studies Zone maps of the region.

Perhaps most importantly, our archive of fault-rupture and fault-slip data is the most extensive and complete archive of surficial fault rupture ever compiled. We feel we have fulfilled an important obligation to our contemporaries as well as the generations of seismologists that will follow us.

3) Landers Paleoseismology

The unusual pattern of faulting that produced the Landers earthquake raised some very important questions about the physics of earthquakes. Group C geologists recognized that one of these questions could be addressed only if paleoseismological data were recovered from the faults of the Landers earthquake and neighboring structures.

What determines whether or not a fault ruptures in its entirety during a large earthquake and whether or not nearby faults also are induced to rupture? Specifically, why did slip on the Johnson Valley fault transfer onto the Landers fault rather than continue onto the northern stretch of the Johnson Valley fault? We hypothesized that the parts of the Johnson Valley and Emerson faults that did not break during the earthquake had broken more recently in the past than those segments that did break. They were therefore stressed far below their yield stresses at the time of the 1992 earthquake and could not be induced to fail. We now know that, at least in part, this hypothesis is incorrect. Only the and the Lenwood fault, west of the 1992 ruptures, and perhaps the southern Johnson Valley fault had sustained major ruptures in the few thousand years prior to last years earthquake.

Charlie Rubin and I have determined, from an excavation across the 1992 trace of the **Emerson fault**, that the previous rupture of that fault segment occurred about 9,000 years ago! Dave Schwartz and his colleagues at the USGS have determined that the previous rupture of the **Homestead Valley fault** occurred between 6,000 and 10,000 years ago. Scott Lindvall and Tom Rockwell's excavations across the **Landers fault** also revealed only one previous Holocene earthquake. In each of our excavations on these three faults of the 1992 earthquake, the height of the scarp of the last prehistoric event is about the same height as that of the 1992 event. This implies similar values of horizontal slip in the 1992 event and its most recent predecessor. Such large amounts of strike-slip on faults only six to twenty kilometers long suggest that the last prehistoric rupture, like the 1992 event, involved more

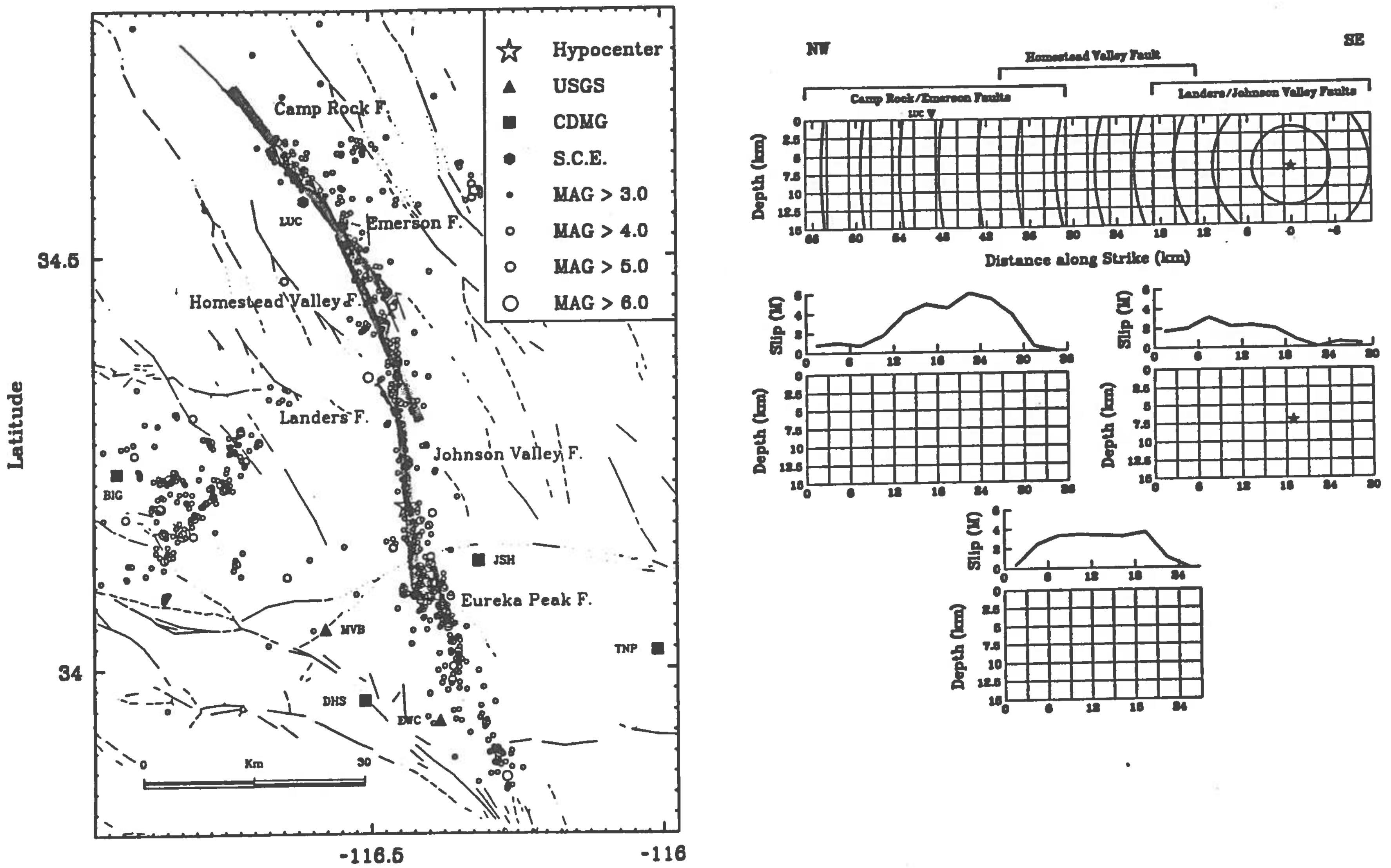


Figure 1. On the left is a map showing the fault surface offset (dark lines) and the surface projection of the three fault segments of the model fault (hatchured lines). Aftershocks are shown as circles with magnitude as given in the legend. Solid symbols mark locations of strong-motion stations. On the right is a fault model cross-section (northwest on left, southeast on right) displaying the subfault discretization of the three model fault planes (bottom 3 faults) which make up the complete Landers fault model (top fault). Presented above each fault segment is the observed surface offset as averaged over each subfault length. The location along strike of station LUC is marked with a triangle and the hypocenter is shown as a star. The circular curves depict the advance of the rupture front at 2 sec intervals for a constant 2.7 km/sec rupture velocity.

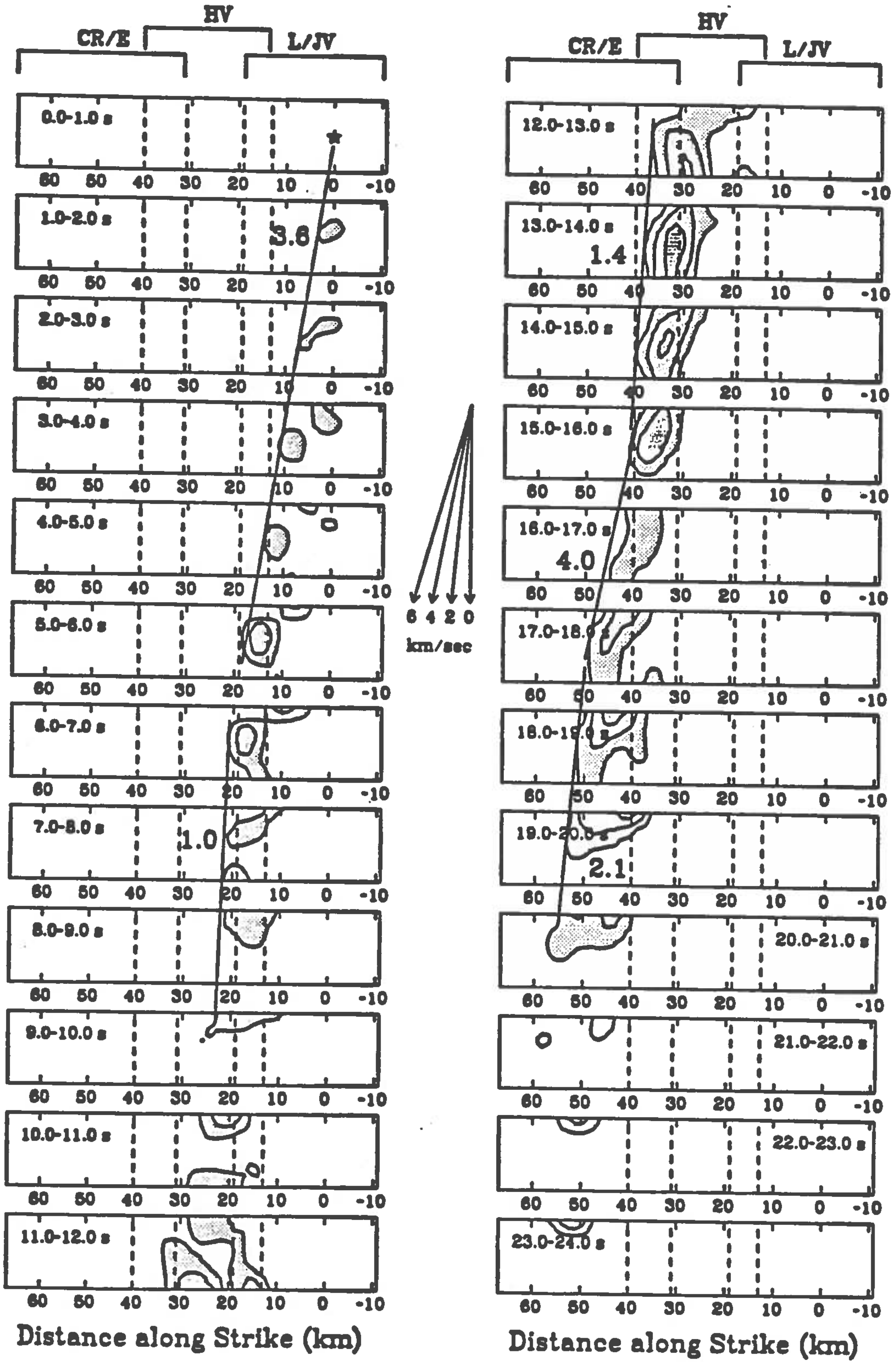


Figure 2. Time progression of the Landers rupture for the combined data model given at intervals of 1 sec as labeled. The contour interval is 0.5 m. For reference, a rupture velocity roset is given with arrows. Lines indicate selected regions of fairly constant rupture velocity. From top to bottom, these lines represent 3.6, 1.0, 1.4, 4.0, and 2.1 km/sec, respectively, as labeled, after Wald and Heaton (1994).

Scaling Law of Aftershock Spectra of Joshua Tree-Landers-Big Bear Earthquakes

Anshu Jin and Kei Aki
University of Southern California
Task 3, Group F
(progress report)

Our subject of study is the relationship between fault zone structure and the seismic spectra generated by earthquakes on the fault. From a rupture mechanics point of view, a fault zone governed by a friction law with given parameters such as the break-down zone size and the magnitude of critical weakening slip should result in a scaling law of seismic spectrum which deviates from the self-similarity. In order to detect such departure from self-similarity we study the relationship between seismic moment and corner frequency for aftershocks of Joshua Tree, Landers, and Big Bear earthquakes. Our study is still on-going and the following is a progress report.

An observed seismic spectrum is a function of source, path, and receiver site. The simplest way of eliminating the path and receiver effects is to take spectral ratio between two earthquakes sharing a common path and receiver. The Joshua Tree-Landers-Big Bear earthquakes created a huge number of aftershocks which offers a unprecedented opportunity to find aftershock pairs which share a common path approximately and the similar source radiation factor judged from the first P arrival waveform on 3 component records).

Joshua Tree aftershocks recorded at Terrascope stations.

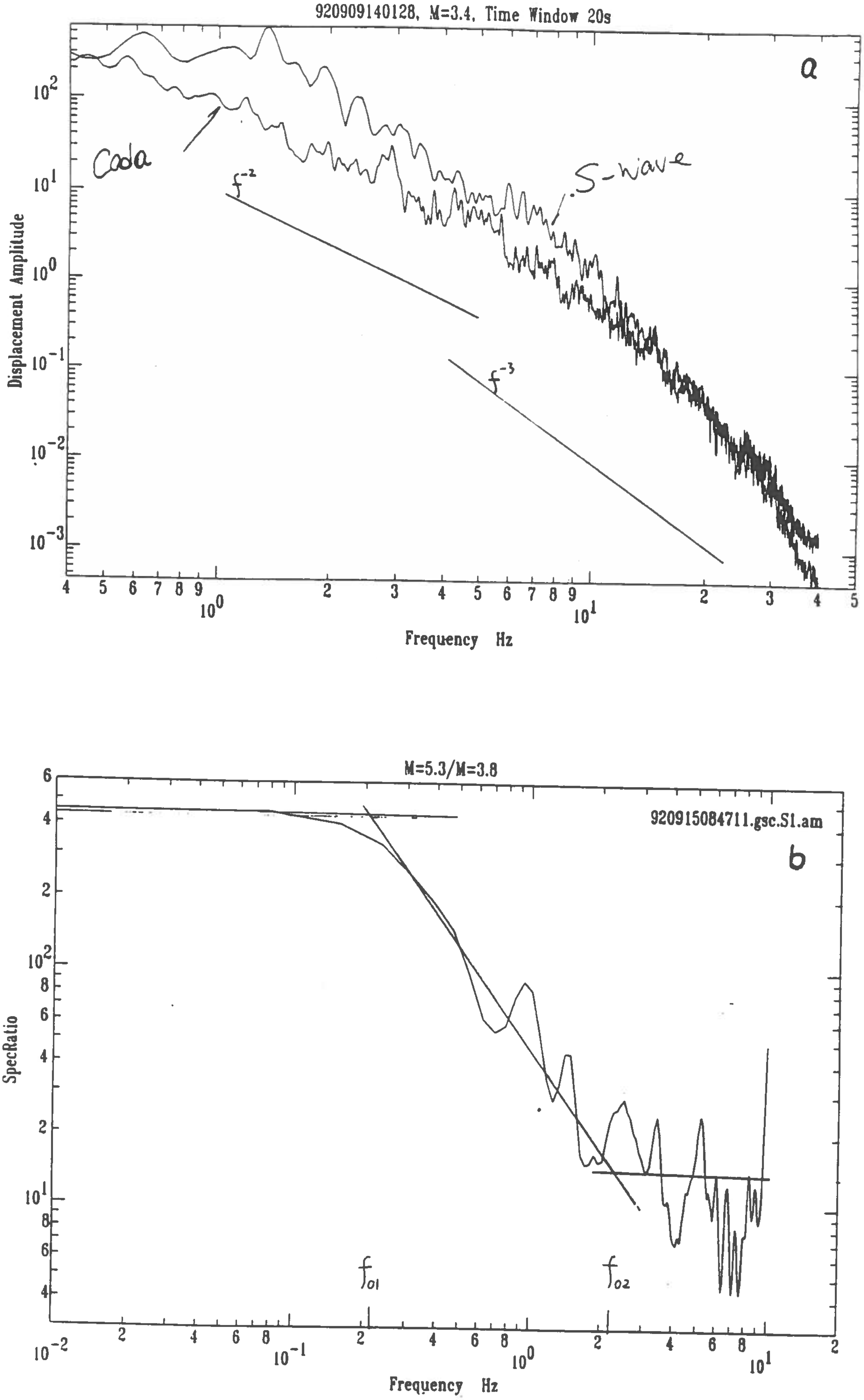
Spectral property Figure 1a shows an example of the S-wave and coda spectra for a M=3.4 event averaged over available Terrascope stations. Since according to Jin et al.(1993), total seismic attenuation, Q_t, in southern California is nearly proportional to frequency, we use$Q=Q_0f$ to correct for attenuation. As shown in Figure 1a, we found that beyond the corner frequency the earlier portion of the spectrum obeys f^{-2} model until about 6 Hz, then turn to decay faster with the frequency dependence of f^{-3}.

Estimation of corner frequencies by spectral ratio If we assume similarity between large and small earthquakes, the spectral ratio between earthquake 1 and 2 sharing the same path, receiver, and source radiation factor will tend to be flat when $\omega<\omega_{10}$, and $\omega>\omega_{20}$, where ω_{10} and ω_{20} are the corner frequencies for events 1 and 2, respectively and $\omega_{10}<\omega_{20}$. Then, the corner frequencies of events 1 and 2 can be determined from the two turning frequencies of spectral ratio curve. Figure 1b shows an example of the observed spectral ratio for a Joshua Tree-aftershock pair with magnitudes 5.3 and 3.8.

During September to November, 1992, we found four Joshua Tree aftershocks with magnitude M>4.5 which can be used as the reference earthquakes, and selected smaller aftershocks to form doublets by the use of relative P times in the following way. Putting the P travel time of event 1 at station i as t_{1i}, and that of event 2 as t_{2i}, then calculate the mean of the difference $|t_{2i}-t_{1i}|$, $\Delta t = \frac{1}{N}\sum_{1}^{N} |t_{2i}-t_{1i}|$. The aftershock pairs with $\Delta t \leq 0.2$s were selected as a doublet which share a common path approximately.

Spectral ratio for each doublet was calculated at each station, then averaged over stations. First ,we read the corner frequency, fc_i^j, from station-averaged spectral ratio, visually, for event i of doublet j as shown in Figure 1b. If event i is involved in m doublets, we determine corner frequency by $fc_i=\frac{1}{m}\sum_{j=1}^{m} fc_i^j$. Totally 33 corner frequencies were estimated for aftershocks with magnitude range 2.7 to 5.3. Figure 2 is a plot of fc vs. M_0, where M_0 is the seismic moment calculated from M_L using $\log M_0 = 1.5M_L + 16.0$ (Thatcher and Hanks,1973). Interestingly, all points with $M_0 > 10^{21}$(M_L~3.5) fall above the Hanks'(1974) empirical curve, and most points with $M_0 < 10^{21}$ fall under that curve. To further substantiate this behavior of the f_c vs. M_0 relation, we need more smaller aftershocks with magnitude down to about 1. Currently we are trying to get the smaller earthquake data from both the IRIS continuously recording Terrascope seismograms for and the REFTEKs records collected by Li et al at USC. Another uncertainty is regarding the estimation of seismic moment, we shall use coda spectra at low frequencies tin stead of M_L.

The same procedure is currently being applied to Landers and Big Bear aftershocks.


920909140128, M=3.4, Time Window 20s
a
Displacement Amplitude
10^2
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10^{-3}
Coda
S-wave
f^{-2}
f^{-3}
4
5
6
7
8
9
10^0
2
3
4
5
6
7
8
9
10^1
2
3
4
5
Frequency Hz
M=5.3/M=3.8
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b
SpecRatio
6
4
2
10^2
8
6
4
2
10^1
8
6
4
f_{01}
f_{02}
10^{-2}
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10^1
2
Frequency Hz

Figure 1

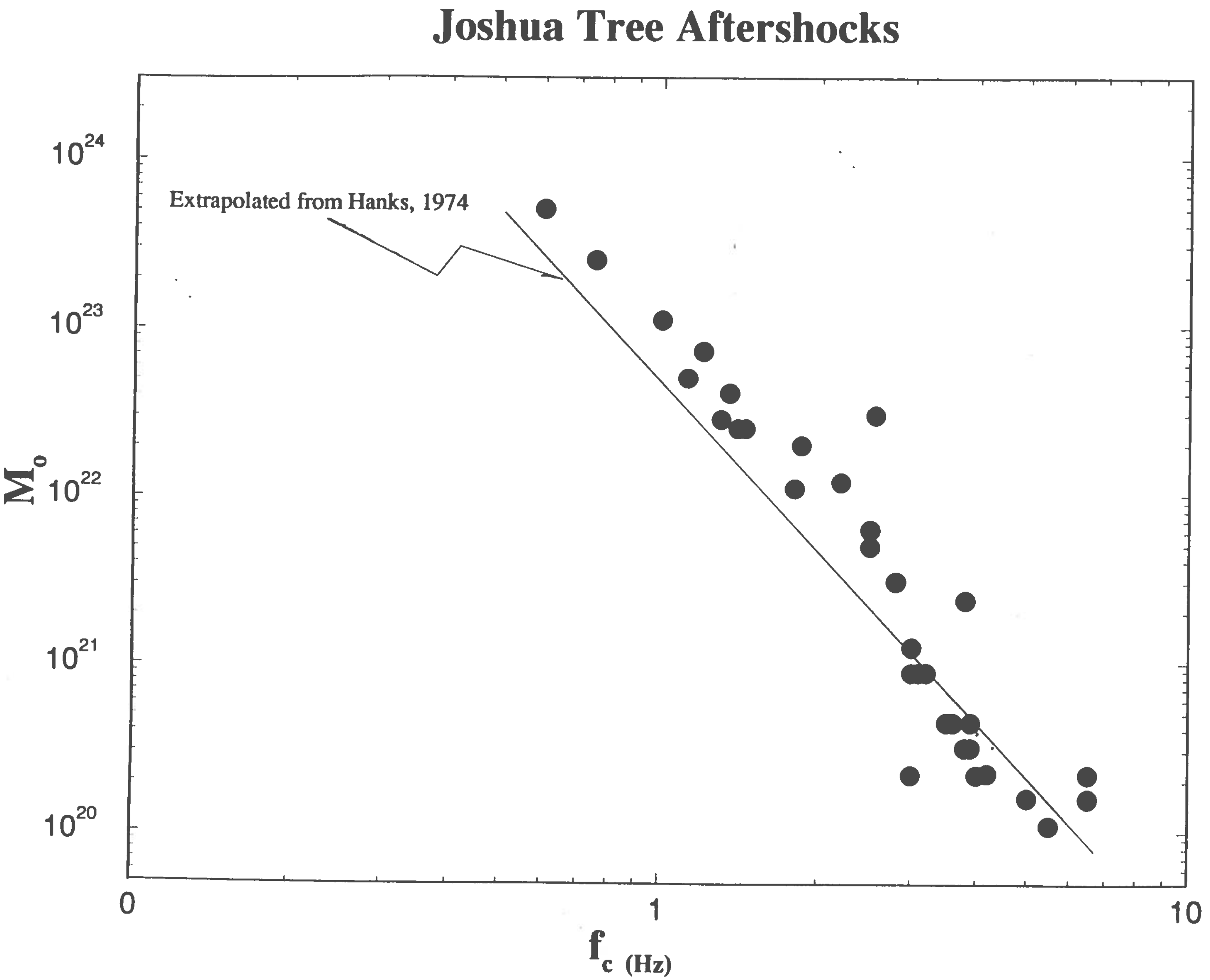
Joshua Tree Aftershocks
Extrapolated from Hanks, 1974
M_o
10^{24}
10^{23}
10^{22}
10^{21}
10^{20}
0
1
10
f_c (Hz)

Figure 2

SCEC Project: Progress Report, 01 Dec. 1993

PI Egill Hauksson
Institution: California Institute of Technology
Title : **Precise Locations and Mechanisms of Aftershocks and Stress State of the 1992 M_w6.1 Joshua Tree, M_w7.3 Landers, and M_w6.2 Big Bear Earthquakes**

INVESTIGATIONS

The (M_w6.1, 7.3, 6.2) 1992 Landers earthquakes that began on 23 April with the M6.1 1992 Joshua Tree preshock are the most substantial earthquake sequence to occur in the last 40 years in California. We have synthesized aftershock data from this sequence recorded by the SCSN to provide a detailed three-dimensional picture of the deformation. The results appear in two papers, one is published in JGR while the other is submitted to BSSA special volume on the Landers earthquake.

RESULTS

The 1992 Landers Earthquake Sequence: Seismological Observations

EGILL HAUKSSON,[1] LUCILE M. JONES,[2] KATE HUTTON,[1] AND DONNA EBERHART-PHILLIPS[2]

(Published in Nov. 1993 issue of Journal of Geophysical Research)

The (M_W6.1, 7.3, 6.2) 1992 Landers earthquakes began on April 23 with the M_W6.1 1992 Joshua Tree preshock and form the most substantial earthquake sequence to occur in California in the last 40 years. This sequence ruptured almost 100 km of both surficial and concealed faults and caused aftershocks over an area 100 km wide by 180 km long (Figure 1). The faulting was predominantly strike slip and three main events in the sequence had unilateral rupture to the north away from the San Andreas fault. The M_W6.1 Joshua Tree preshock at 33°N58' and 116°W19' on 0451 UT April 23 was preceded by a tightly clustered foreshock sequence ($M \leq 4.6$) beginning 2 hours before the mainshock and followed by a large aftershock sequence with more than 6000 aftershocks. The aftershocks extended along a northerly trend from about 10 km north of the San Andreas fault, northwest of Indio, to the east-striking Pinto Mountain fault. The M_W7.3 Landers mainshock occurred at 34°N13' and 116°W26' at 1158 UT, June 28, 1992, and was preceded for 12 hours by 25 small $M \leq 3$ earthquakes at the mainshock epicenter. The distribution of more than 20,000 aftershocks, analyzed in this study, and short-period focal mechanisms illuminate a complex sequence of faulting. The aftershocks extend 60 km to the north of the mainshock epicenter along a system of at least five different surficial faults, and 40 km to the south, crossing the Pinto Mountain fault through the Joshua Tree aftershock zone towards the San Andreas fault near Indio. The rupture initiated in the depth range of 3-6 km, similar to previous M~5 earthquakes in the region, although the maximum depth of aftershocks is about 15 km. The mainshock focal mechanism showed right-lateral strike-slip faulting with a strike of N10°W on an almost vertical fault. The rupture formed an arclike zone well defined by both surficial faulting and aftershocks, with more westerly faulting to the north. This change in strike is accomplished by jumping across dilational jogs connecting surficial faults with strikes rotated progressively to the west. A 20-km-long linear cluster of aftershocks occurred 10-20 km north of Barstow, or 30-40 km north of the end of the mainshock rupture. The most prominent off-fault aftershock cluster occurred 30 km to the west of the Landers mainshock. The largest aftershock was within this cluster, the M_W6.2 Big Bear aftershock occurring at 34°N10' and 116°W49' at 1505 UT June 28. It exhibited left-lateral strike-slip faulting on a northeast striking and steeply dipping plane. The Big Bear aftershocks form a linear trend extending 20 km to the northeast with a scattered distribution to the north. The Landers mainshock occurred near the southernmost extent of the Eastern California Shear Zone, an 80-km-wide, more than 400-km-long zone of deformation. This zone extends into the Death Valley region and accommodates about 10 to 20% of the plate motion between the Pacific and North American plates. The Joshua Tree preshock, its aftershocks, and Landers aftershocks form a previously missing link that connects the Eastern California Shear Zone to the southern San Andreas fault.

State of Stress From Focal Mechanisms Before and After the 1992 Landers Earthquake Sequence

12 Aug. 1993, Submit. to BSSA, Special issue on the 1992 Landers earthquake

The state of stress in the Eastern California Shear Zone (ECSZ) changed significantly because of the occurrence of the M_W6.1 1992 Joshua Tree and the M_W7.3 Landers earthquakes. To quantify this change, focal mechanisms data from the 1975 Galway Lake sequence, the 1979 Homestead Valley sequence, background seismicity 1981-1991, and the 1992 Landers sequence are inverted for the state of stress. In all cases the intermediate principal stress axis (S_2) remained vertical and changes in the state of stress consisted of variations in the trend of maximum and minimum principal stress axis (S_1 and S_3) and small variations in the value of the relative stress magnitudes (ø). In general the stress state in the ECSZ has S_1 trending east of north and ø=0.4-0.6 suggesting that the ECSZ is a moderate stress refractor and the style of faulting is transtensional (Figure 2).

South of the Pinto Mountain fault, in the region of the 1992 Joshua Tree earthquake, the stress state determined from the 1981-1991 background seismicity changed on 23 April and 28 June 1992. In the central zone the S_1 trend rotated from N14°±5°W to N28±5°W on 23 April and back again to N16°±5°W on 28 June. Thus the Landers mainshock in effect recharged some of the shear stress in the region of the M_W6.1 Joshua Tree earthquake.

Comparison of the state of stress before and after 28 June 1992 along the Landers mainshock rupture zone showed that the mainshock changed the stress. The S_1 trend rotated 7°-20° clockwise and became progressively more fault-normal from south to north. Along the Emerson-Camp Rock faults the change was so prominent that the focal mechanisms of aftershocks could not be fit by a single deviatoric stress tensor. The complex P and T axes distribution suggests that most of the uniform component of the applied shear stress along the northern part of the rupture zone may have been released in the mainshock.

The San Bernardino Mountains region of the M_W6.2 Big Bear earthquake has a distinctively different state of stress, as compared to the Landers region, with S_1 trending N3°±5°W. This region did not show any significant change in the state of stress following the 1992 M_W6.2 Big Bear sequence.

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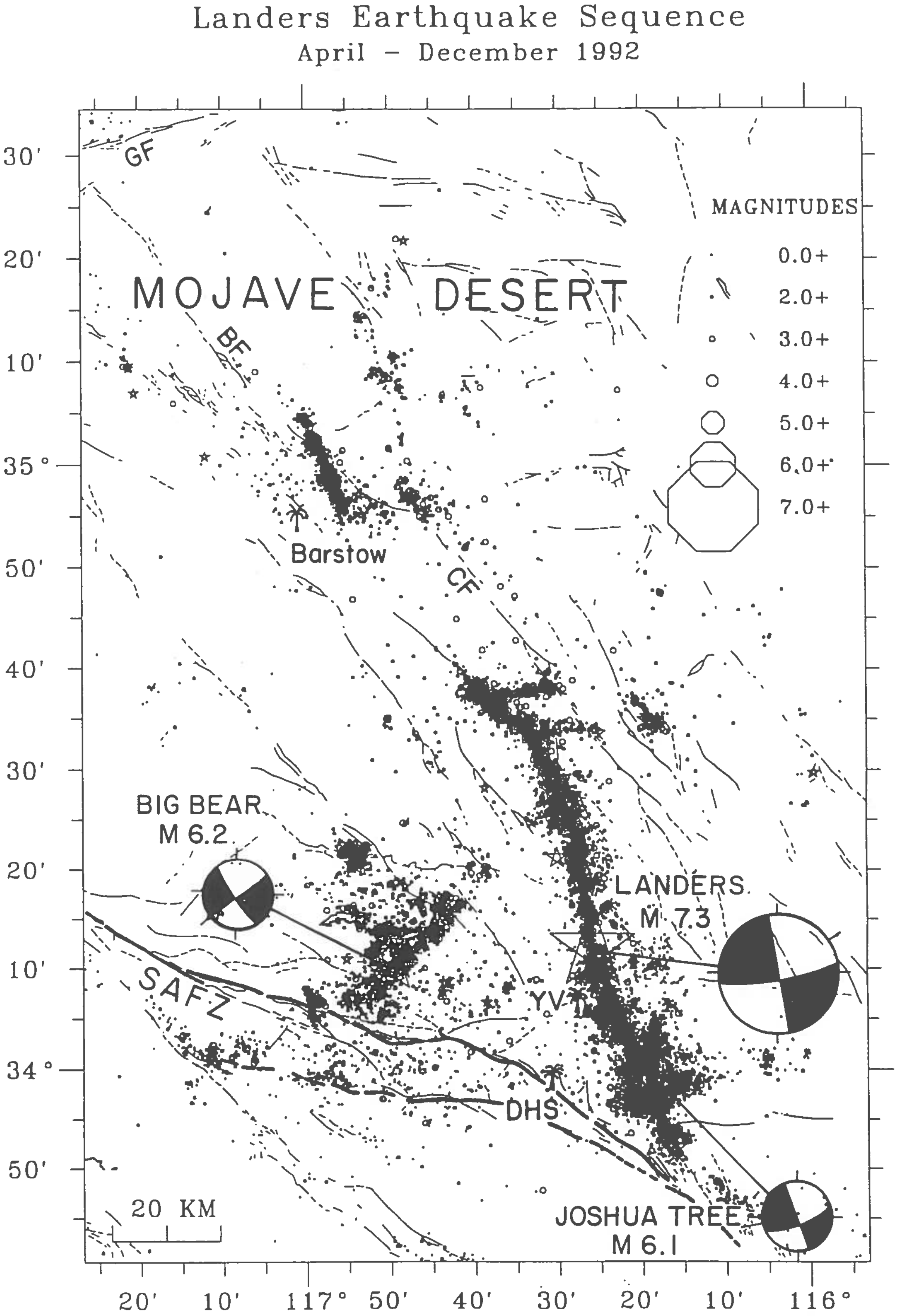

Fig. 1 Landers aftershock region showing all earthquakes recorded by the SCSN from April to December 1992, and major faults (dotted if inferred) from *Jennings* [1975]. Lower-hemisphere, first-motion focal mechanisms, compressional quadrant shaded, of the three main earthquakes are also shown. BF, Blackwater fault, CF, Calico fault, YV, Yucca Valley, GF, Garlock fault, SAFZ, San Andreas fault zone, and DHS, Desert Hot Springs. Earthquakes of $M \geq 4.0$ are shown by stars.

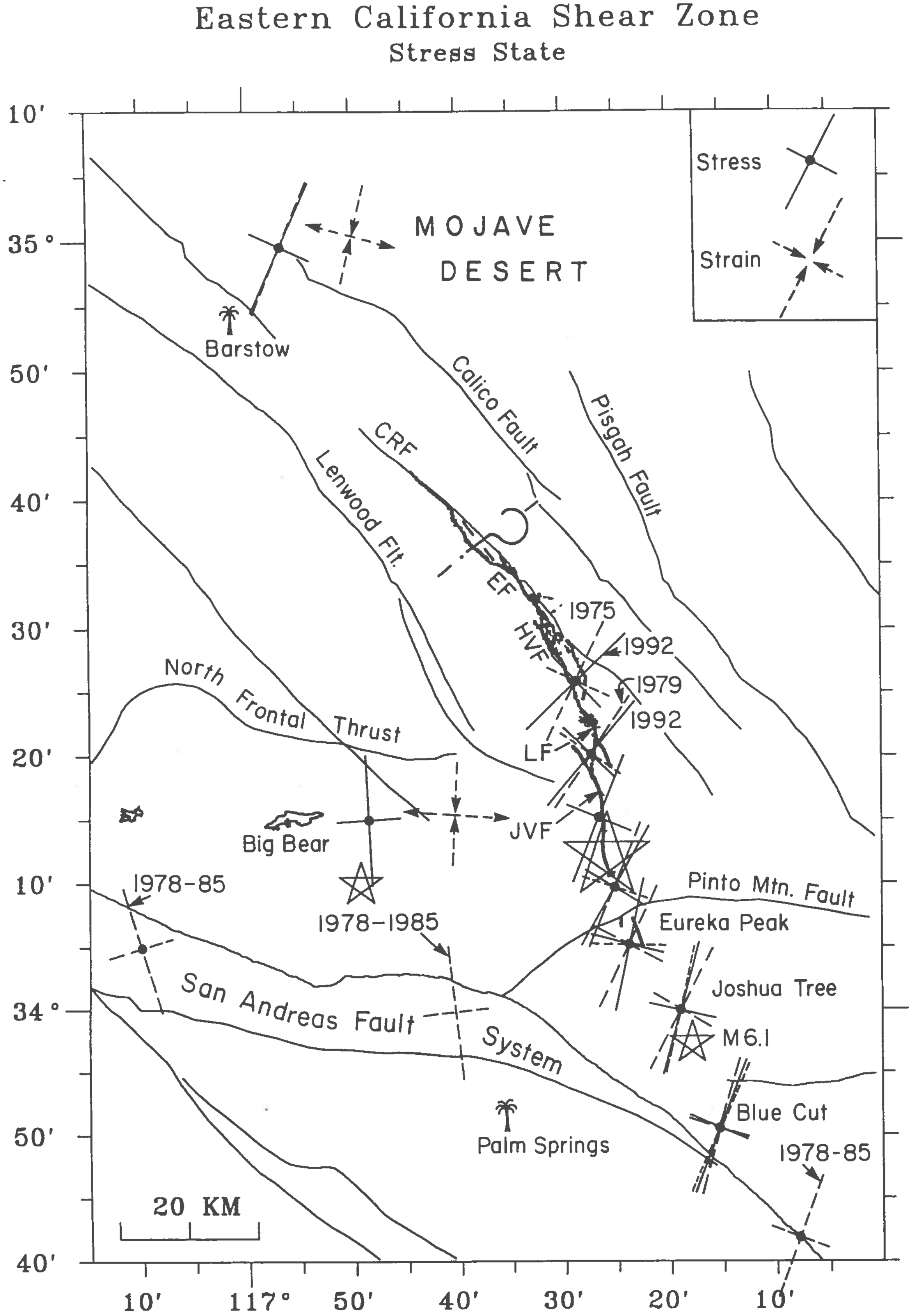

Figure 2. Summary of the S_1 trends in the eastern California shear zone and along the San Andreas fault zone. The S_1 trends labeled 1978-85 are from Jones (1988). The stars indicate the epicenters of the M_w6.1 Joshua Tree, M_w7.3 Landers, and the M_w6.2 Big Bear earthquakes. The geodetic strain data are from Savage *et al.,* (1990). CRF-Camp Rock fault. The different S_1 trends are labeled with the respective year (see also Table 1). The question mark across Emerson Camp Rock faults indicates that the deviatoric stress tensor could not be determined using the method of Michael (1984). In the Joshua Tree area each set of three S_1 trends are shown as 1981-1991 data (short dashes), 23 April to 27 June 1992 (long dashes), and 28 June to 31 December 1992 solid lines.

Anomalous Low Frequency Signals from Local Earthquakes

Principal Investigators:
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Frank Vernon, UCSD

A collaborative study to record aftershocks was undertaken by several institutions following the June 28 Landers and Big Bear earthquakes. The M7.6 Landers earthquake occurred at 04:58 PDT approximately 6 miles north of Yucca Valley along the southern extension of the Johnson Valley fault. The earthquake produced over 70 km of ground rupture, with cumulative right-lateral offsets of 3 to 6.5 m along segments of the Homestead Valley, Emerson Lake, and Camp Rock faults, all of which were involved in the sequence. The primary aftershock activity occurred in a narrow band from 33.6N, -116.2W north to 34.5N, -116.6W, with a separate cluster at 35.0N, -117.0W. The M6.5 Big Bear earthquake occurred at 08:04 PDT approximately 35 km west of the Landers epicenter in the San Bernadino Mountains, involving left-lateral slip on a fault that strikes N45°W and dips 70°SE. The Big Bear aftershocks occur over an area of about 30 km long, extending northeast from 34.1N, -117.0W to 34.4N, -116.6W.

Inspection of the recordings collected by the portable instruments by personnel at UCSD and SDSU revealed approximately 40 recordings with a long period wavetrain following the S wave arrival, which we interpret as a Raleigh wave (R_g). The dispersion of the R_g waves contains information about the shallow shear wave velocity structure. We determined R_g group velocities at several frequencies from radial and vertical waveforms of a M_l aftershock in the Big Bear area recorded at 4 stations (Fig. 1) using the codes of Herrmann (1987). The sensors that recorded the waveforms represent most of the types used on the portable stations: FBA-23s, L22s (a short period velocity sensor), and STS-2s (a broadband velocity sensor). We obtained robust group velocities from each type of sensor.

We found evidence for local variations in the shallow shear wave structure. Typical S wave velocities down to about 4 km depth were 2.5 to 3.5 km/s between the earthquake and the portable sites RIMR and YKNF. S wave velocities were lower, about 1.6 to 2.2 km/s between the earthquake and the sites BRCC and UCVF (Fig. 2). These sites are south of the Pinto Mountain fault, and RIMR and YKNF (and the aftershock) are north of the fault. These S wave velocity variations may be imaging a low velocity area along the Pinto Mountain fault also seen with P waves by Lees and Nicholson (1992). We have plenty of source receiver pairs to map out shallow S wave velocity variations.

The surface wave velocity information is particular useful because tomographic body wave velocity inversions have poor resolution at shallow depths, and fixing the shallow velocities can help stabilize the inversion for deeper velocities.

We will be acquiring all broadband data from Caltech's TERRAscope stations in order to further investigate these low frequency signals.

Figure 1. Group velocities found by multiple filter analysis of vertical component seismograms of a shallow M 4.9 earthquake recorded at four sites showing dispersion of R_g waves. See Figure 1 for site and event locations. Note that the group velocities at BRCC and UCVF are similar, as are those at RIMR and YKNF, reflecting local variations in the shallow shear wave structure.

Figure 2. Portable station locations, and locations of earthquakes exhibiting the R_g phase. Events outlined in black were analyzed for S wave velocity.

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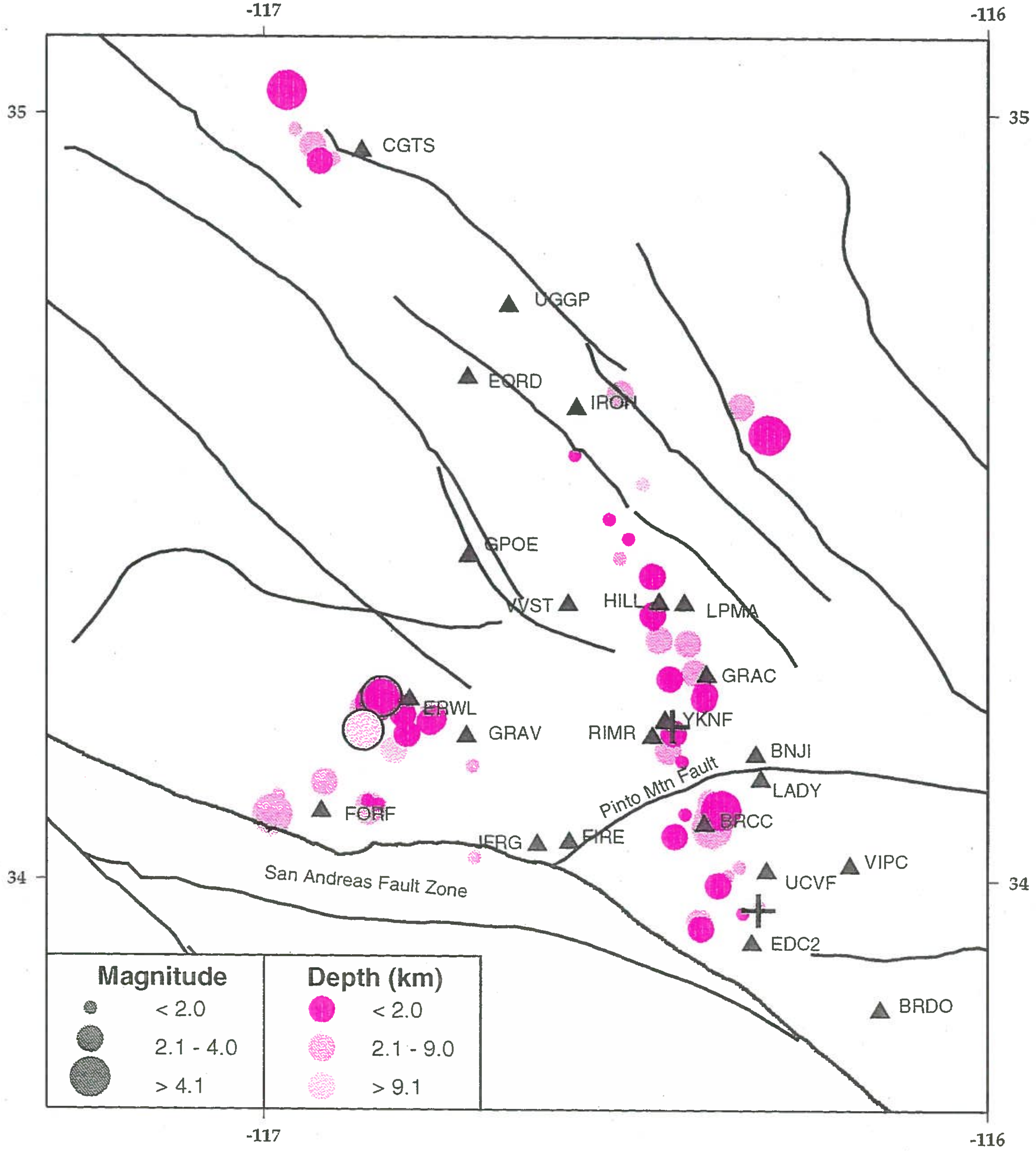

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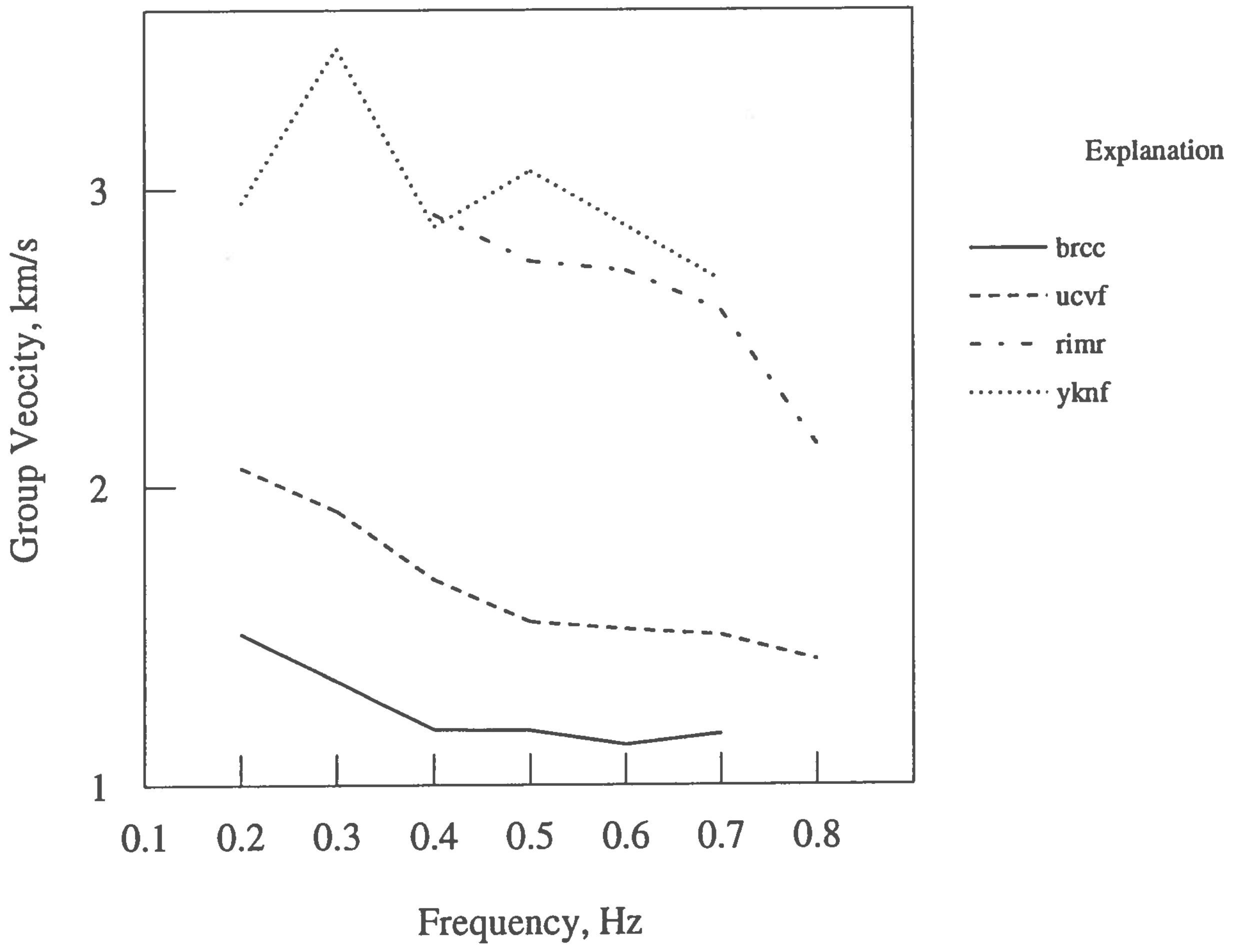
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SCEC Project: Progress Report, 01 Dec. 1993

PIs E. Hauksson, H. Kanamori, J. Scott, and P. Maechling
Institution: California Institute of Technology
Title: **Towards, Real-time, Routine Broadband Seismology**

INVESTIGATIONS

The goal of this project is to establish rapid data analysis methods for data from the TERRAscope broad-band seismic network.

RESULTS

We report the following accomplishments:

Software Development for TERRAscope

As part of the TERRAscope project we have developed several new software programs at Caltech to enhance our ability to monitor Southern California Earthquakes as they happen. We use inputs from both the real-time continuous data feeds from TERRAscope stations and the Southern California Seismographic Network (SCSN). A summary flow chart of the different software modules is shown in Figure 1.

We have written a new program that allows TERRAscope data to be received through the USNSN VSAT system. This software that was developed at Caltech makes it possible to telemeter data from TERRAscope stations through a Very Small Aperture Terminal (VSAT) link. Prior to this, the real-time telemetry from TERRAscope stations was done only via dedicated ADN phone lines.

A second program takes event locations produced by an associator and determines magnitudes for the events using time series data from the TERRAscope stations. To accomplish this, software has been written which allows reliable high speed communications between VAX and Sun computers.

A third program allows seismologist to rapidly review the quality of computer generated locations. The seismologist uses a remote PC computer to plot the TERRAscope time series for an event with estimated P and S wave arrivals superimposed on the time series plot. Each available TERRAscope time series is plotted. The plots are sorted by distance to event. The estimated P and S wave arrival times are calculated for each station. These estimated arrivals are superimposed on top of the time series. If the actual arrivals match the estimated arrivals for each station, then the location can be considered accurate. A magnitude calculation is also done for each times series and is included on the plot. If a location appears to be inaccurate, the user can revise the location and origin time and generate plot using the revised information. The plots are usually available within 3 minutes after an event.

A fourth program provides early warning of ground motion at a site by using rapidly produced locations, estimating the P and S wave travel time to a specific site, and producing an audible or visual warning if the seismic waves have not yet arrived at that site. This system is a prototype. The primary drawback at this point is that the magnitude of the event is not considered. Therefore users are frequently warning of shaking which is too small to be felt.

A practical 3-D southern California velocity model

In a region as geologically complex as southern California, the effect of small-scale near surface velocity variations on seismic travel times is large. This signal interferes with the accurate near real-time determination of earthquake hypocenters where short ray path information is critical and contaminates the data used to determine large-scale 3-D velocity models of the crustal structure. Numerous researchers have constructed 3-D models of southern California with resolution at scales greater than 25 km which represent the average velocity of the crust and contain information on deeper structures. We are in the process of refining this 3-D model so that it accurately accounts for the effect of near surface structure and thus can be used for improving the routine network locations of the SCSN.

The preliminary phase of evaluating currently used crustal models of southern California has led to identification of the major areas of improvement required in modeling efforts. The resurvey of the seismic stations has been completed and eliminates some large systematic errors in the dataset. Improvements can be made by incorporating station delays as approximate compensation for near source structure that reduces the rms travel-time residuals from .35 seconds to .20 seconds. We are in the process of constructing refined velocity models, first using 1-D then 3-D methods, to improve the locations of earthquakes in southern California and to remove the effect of near surface velocity variations on interpretations of large scale 3-D structure.

Global Positioning System Re-survey of Southern California Seismic Network and TERRAscope Stations

Systematic errors in travel-time data from local earthquakes can sometimes be traced to inaccuracies in the published seismic station coordinates. This prompted a resurvey of the stations of the Caltech/USGS Southern California Seismic Network (SCSN) using the Global Postitioning System (GPS). We surveyed 241 stations of the SCSN using Trimble and Ashtech dual frequency GPS receivers and calculated positions accurate to 3 meters using differential positioning from carrier phase measurements. 12% of the stations which were surveyed were found to be mislocated by more than 500 meters (Figure 2). Stations of the Terrascope and USC networks were also surveyed, as well as a network of portable seismic stations deployed shortly after the 1992 Joshua Tree and Landers earthquakes. The new coordinates are availabe in ascii format from the SCEC Data Center.

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TERRAscope Data Flow and Analysis

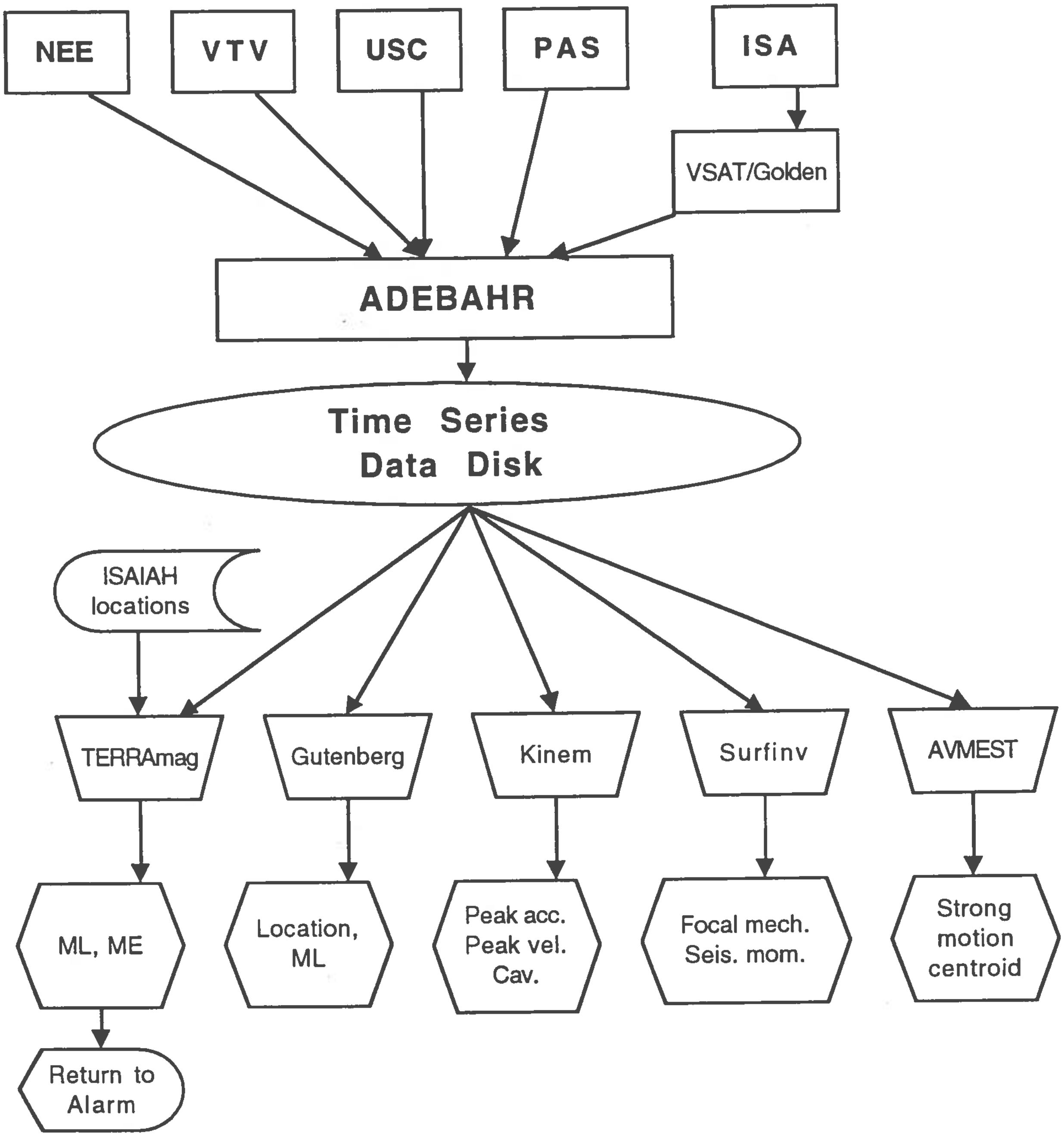

Figure1. Flow chart showing data flow and software modules developed for TERRAscope.

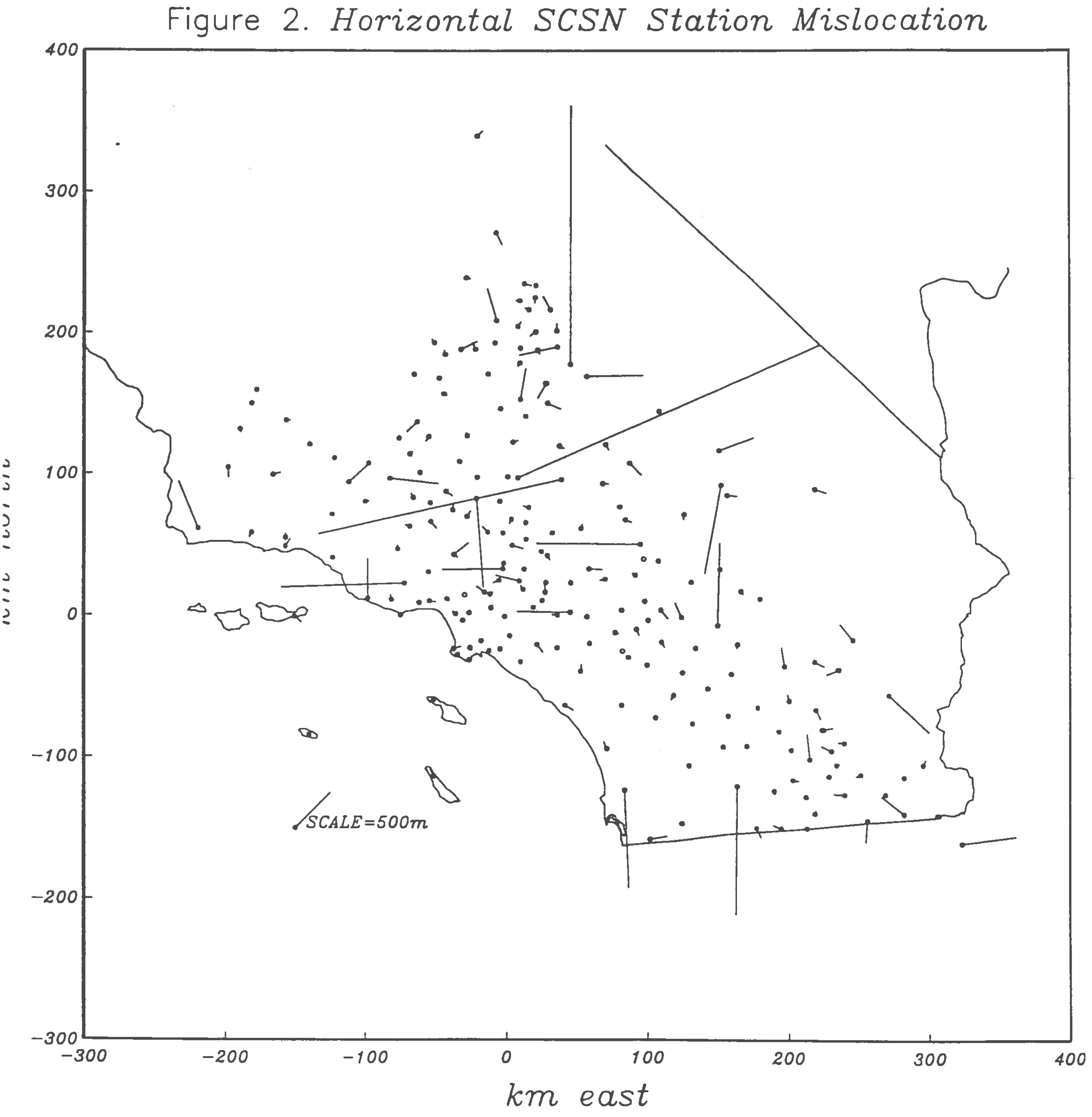

Figure 2. Horizontal mislocation vectors for stations in the SCSN. Old locations were read from topographic maps while new locations are determined with GPS.

Rapid Source Retrieval

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Objective: One of the fundamental reasons why seismology is contributing to the earthquake hazards program is its prediction capability. That is, given a set of seismograms we can predict the nature of the source and its location. This has been demonstrated with both teleseismic body waves and well dispersed long period surface waves. To retrieve source information from regional phases requires an understanding of complicated path effects. This project addresses this issue of calibrating paths to the new Streckeisen stations and rapid source estimation.

Research Accomplished: With the installation of the broad-band, high dynamic range instruments, it has become possible to compare the regional waveforms of different sized events. In many cases, events in the range of $M_L = 3$ to 6 for a particular source region have similar waveforms indicating the prominence of regional Green's functions. Once these functions are established it becomes possible to estimate source parameters for small events from just one station, Dreger and Helmberger (1993). This means, theoretically, we can predict the motions at other stations before the motion actually arrives.

Two papers has been submitted on this project to date: (a) Rapid source estimation from Broadband Regional Seismograms (Zhao and Helmberger) and (b) Analysis of broadband records from the June 28, 1992 Big Bear Earthquake (Jones, Hough and Helmberger).

a) Rapid source estimation
Recently developed source inversion techniques do not take full advantage of the broadband nature of regional seismograms. The reason is that deterministic derived Green's functions can not explain the complicated short period propagational phenomena associated with realistic crustal structure. This problem is generally solved by removing short periods and inverting only selected portions of the records. In this study, we introduce a source estimation technique that allows for better use of the entire broadband record when only imperfect Green's function are available. The procedure desensitizes the timing between the principal crustal arrivals by fitting portions of the Green's functions independently, both in waveshape and energy content, by applying a direct grid search approach. In addition to the source parameters we obtain "δt" phase alignment shifts which can be used as Green's function corrections for relocating other events or as a quide to deriving new crustal models.

We will briefly introduce some of this data and discuss how it can be used to determine source characteristics. For example, the broadband displacements sampling three different azimuth of the Sierra Madre event is displayed in figure 1. These three stations are about 160 km away from the epicenter and show a clear separation between the early arriving P-waves (P_{nl} in the figure) and later arriving S-waves and surfaces waves. The three columns on the right display the vertical, radical and tangential motions with peak amplitudes given in cm. Displayed on the left are enlarged portions of the first ten secs of motion. The top trace of each set is the observed data. The lower two are synthetic motions predicted by Green's function appropriate for Southern California and a set of source parameters found by waveform matching Green's functions. The upper set of synthetics used the entire records in determining the source while the lower traces are based on the mechanism determined by the early P-wave portion (P_{nl}): The synthetics on the right than become predictions. The comparisons suggest that modeling the early portions of seismograms is sufficient in predicting later motions. Furthermore, if we have one TERRAscope station near an event we can do reasonably well at estimating the source parameters, for example see Dreger and Helmberger (1992 and 1993) and Zhao and Helmberger (1993). These studies show that in many situations one station solutions can be used to predict the observations at other stations. For example, using the LA Basin response such as derived by Craig and Helmberger (1993) and others we could predict the motions before they arrive and establish a Early Warning System.

b) Big Bear Earthquake

The June 28, 1992 Big Bear earthquake in southern California occurred at 15:05:21 gmt on June 28, 1992 and is considered to be an aftershock of the earlier $M_W = 7.2$ Landers earthquake. From overall aftershock locations and long-period focal studies, rupture is generally assumed to have propagated northeast. No surface rupture was initially found, however, and the mainshock locations determined from both strong motion and TERRAscope data are mutually consistent and do not lie on the assumed fault plane. Further, directivity analysis of records from the TERRAscope array suggest significant short- and long-period energy propagating northwest along the presumed antithetic fault-plane, as well as some long-period moment release in the direction of the presumed fault-plane. This observation is supported by significant early aftershocks distributed along both the presumed rupture plane and the antithetic plane to the northwest. An empirical Green's function approach using both the M = 5.2, June 28, 1992 14:43 gmt foreshock and M = 5.0 the August 18, 1992 aftershock produces results consistent between the two eGf's, and suggests that the Big Bear event comprised at least two substantial subevents. From the eGf results, we infer that the second, and possibly a third subevent occurred on the presumed (northeast striking) mainshock rupture plane, but that significant moment release occurred on the antithetic northwest striking plane. We present results from line-source finite-fault modeling for the Big Bear mainshock, which indicate that a two source or two fault event is necessary to produce the waveforms observed during the Big Bear mainshock. The constraint imposed by the directivity analysis required that the initial rupture be towards the northwest, striking 320°. This was followed approximately 5 seconds later by bilateral rupture along a northeast-southwest trending fault, striking at 50° east of north. The modeling was done in broadband displacement and involved summation of empirical Green's functions along a pair of finite, line-source faults.

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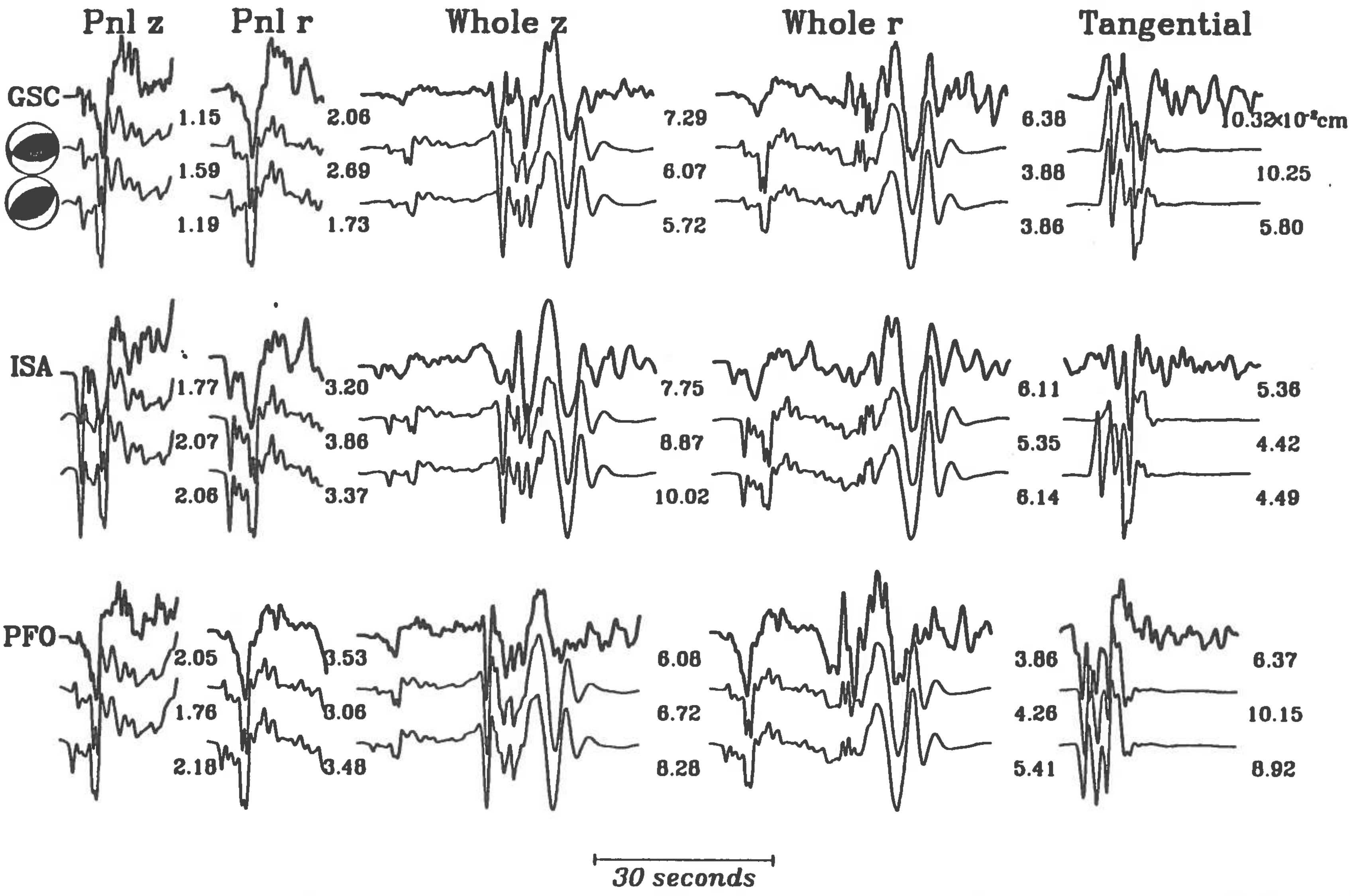

Figure 1. Comparison of Sierra Madre broadband observations at three stations (GSC, ISA, and PFO) with synthetics generated by estimating the fault parameters. Three windows of observed waveforms are used, namely the beginning portion P_{nl} (first two columns), the Raleigh waves (middle two columns), and the tangential (column on the right). The corresponding Green's functions are shifted in time for best alignment and used to estimate strike, dip and rake. The amplitude fits determine the moment (numbers indicate peak amplitudes in cm). The bottom trace of each set corresponds to the source estimation using only the P_{nl} columns and the middle traces correspond to using all 5 columns. Both solutions yield the same moment of 3. x10^{24} ergs. Single station solutions and various combinations of the datasets are discussed in Zhao and Helmberger (1993). The depth estimate is obtained by applying Green's functions at various depths and choosing the one with the smallest error (best fit). Several event sequences are considered in the above paper, some well outside the array (Yucca Mtn., Nev.) for example.

Report to SCEC, 1993

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In 1993 we have nearly completed our structural interpretation of southern California seismicity based on the data from the Caltech-USGS network. We have also started a systematic analysis of stress and stress changes using the same data. The abstract and 3 figures from a paper that deals with this work and that we are about to submit for publication are incuded here.

THE SAN ANDREAS FAULT SYSTEM THROUGH THE TRANSVERSE RANGES AS ILLUMINATED BY EARTHQUAKES: TRANSPRESSION AND TRANSTENSION BY STRAIN PARTITIONING

Abstract

The pattern of seismogenic faulting in the San Gorgonio Pass-San Bernardino basin area of the San Andreas fault zone is mapped from more than 4000 focal mechanisms. Key for exploiting high density of data in a structurally complex area is a new software to visualize and classify focal mechanisms. These units of structural data are represented by one of the two slip planes; a mechanism is associated with a given fault by "fixing" the corresponding nodal plane. Focal mechanisms are derived from 1981-92 phase data of the southern California seismic network via a single relocation procedure over most of the area covered by the network. This procedure accounts for three-dimensional velocity variations by ten distinct subregional 1-D velocity structures and by location-dependent station-corrections. A classical grid-search program yields focal mechanisms which are then quality-selected by multiple criteria, including a minimum number of first-motions and a maximum variance within the range of satisfactory fit.

One of the most prominent seismogenic features in the area of this study is a volume of diffuse, persistent, and unusually deep seismicity between the San Andreas fault (SAF) and the San Jacinto fault (SJF) from San Gorgonio Pass to a left-lateral cross fault corresponding to the Crafton Hills. Although individual faults are difficult to resolve within the zone, the dominant pattern of deformation appears to be dexteral shear parallel to the SJF. A mixture of thrusts and normal faults accomplishes both north-south shortening and east-west extension. This zone of seismicity has a sharp downward cut-off that defines a surface dipping gently (25°) northeast, toward the SAF, and is interpreted as a detachment. The dip of slip planes tends to decrease with depth suggesting listric faults that merge into this basal detachment. Right-lateral slip planes delineate a continuous fault with a steep northeast dip connecting the Coachella Valley segment of the Banning fault and the San Bernardino branch of the SAF. This transcurrent fault defined by geologic and earthquake data exhibits the simplest geometry of any structure through San Gorgonio Pass and is interpreted to be the main strand of the SAF. This fault intersects the proposed detachment along an asymmetrical trough in the lower boundary of the seismicity that marks the deepest well-defined seismic zone in southern California. From the southwest to the northeast side of the SAF, the floor of the seismicity steps up by as much as 10 km. Thrusting dominates the tectonic regime near the constricting bend of the SAF at San Gorgonio Pass. Gradually, normal faulting becomes dominant towards the northwest. In the San Bernardino Basin area, seismicity is concentrated along the SJF but is primarily generated by a system of normal faults. The SJF is currently seismogenic only below the intersection with an east-dipping normal fault. The transtensional regime in the San Bernardino Basin changes abruptly to a transpressional regime in the eastern San Gorgonio Mountains. A sharp stress boundary coincides with the merger of the SJF int the SAF and their intersection with the Cucamonga fault. This boundary projects into the Cajon Pass area and may account for the unexpected stress conditions inferred from deep borehole data.

The prominent Yucaipa cluster, centered on the Mill Creek fault near the intersection of the Crafton Hills cross fault and the SAF and about 10 km from the M=6.5, 6/28/92 Big Bear main rupture, has been very active since that earthquake, but was also active during the previous decade. Most of the ≈100 focal mechanisms in this ≈5km wide cluster can be associated with three intersecting structures: the Mill Creek fault, a northerly mapped branch of this fault, and a normal fault localized at the intersection of these steep right-lateral faults. Seismicity preceding the Big Bear main shock was almost exclusively on the Mill Creek fault; after this event, seismicity shifted to the other faults. The structural singularity represented by the fault intersection may be associated with a mechanical singularity responsible for the persistent and localized source of seismicity. The change in fault kinematics at the cluster may reflect static stress changes induced by the large nearby rupture of 1992.

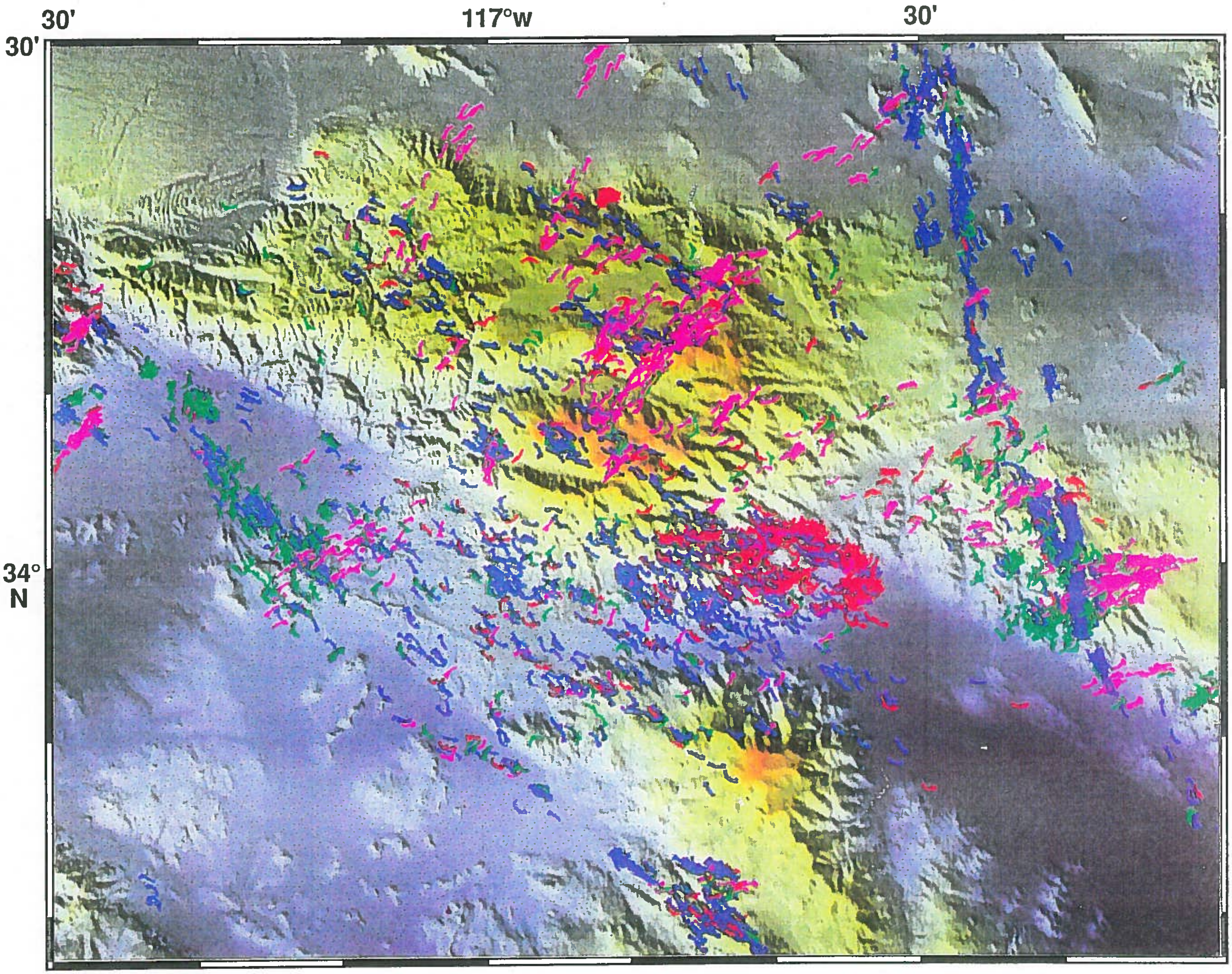


Figure 1: About 3500 slip planes (see Figure 2) from Jan 1981 to November 1992 superimposed on digital topographic data of the eastern Transverse Ranges (synthetic illumination from the southwest). These slip planes represent about 2/3 of our data base of focal mechanisms; they have been selected on the basis of structural interpretation and have been incorporated in our structural model of seismicity. They are color coded according to rake: purple=-45° to 45° (right-lateral); green=45° to 135° (normal); pink=135° to 225° (left-lateral); red=225° to 315° (reverse).

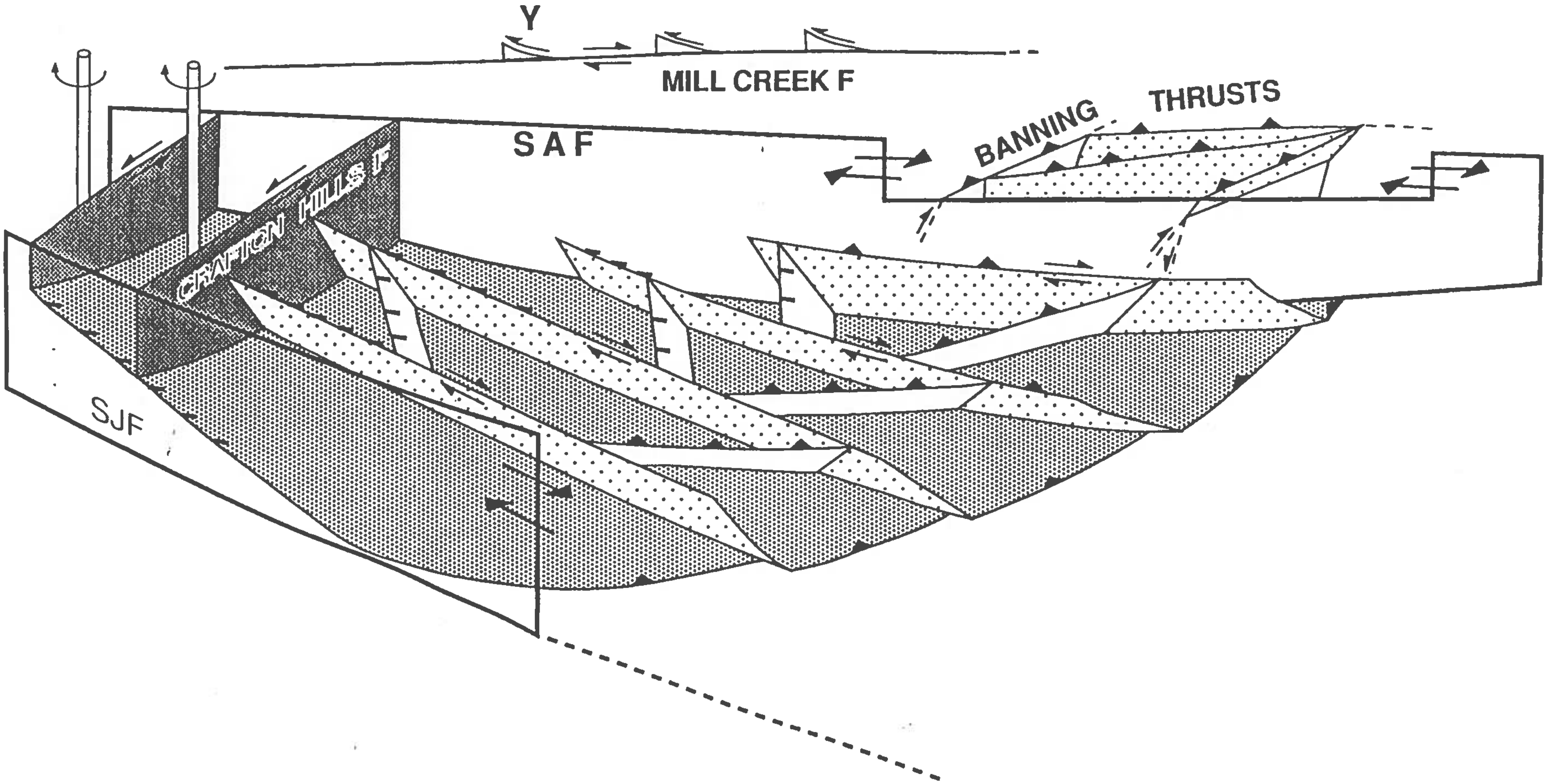


Figure 2. Tectonic sketch for the San Gorgonio Pass-San Bernardino Basin area. Oblique view from the southwest. Barbs on upthrown side of thrusts; short segments on downthrown side of normal faults. Y indicates approximate location of the Yucaipa cluster. SAF=San Andreas fault; SJF=san Jacinto fault.

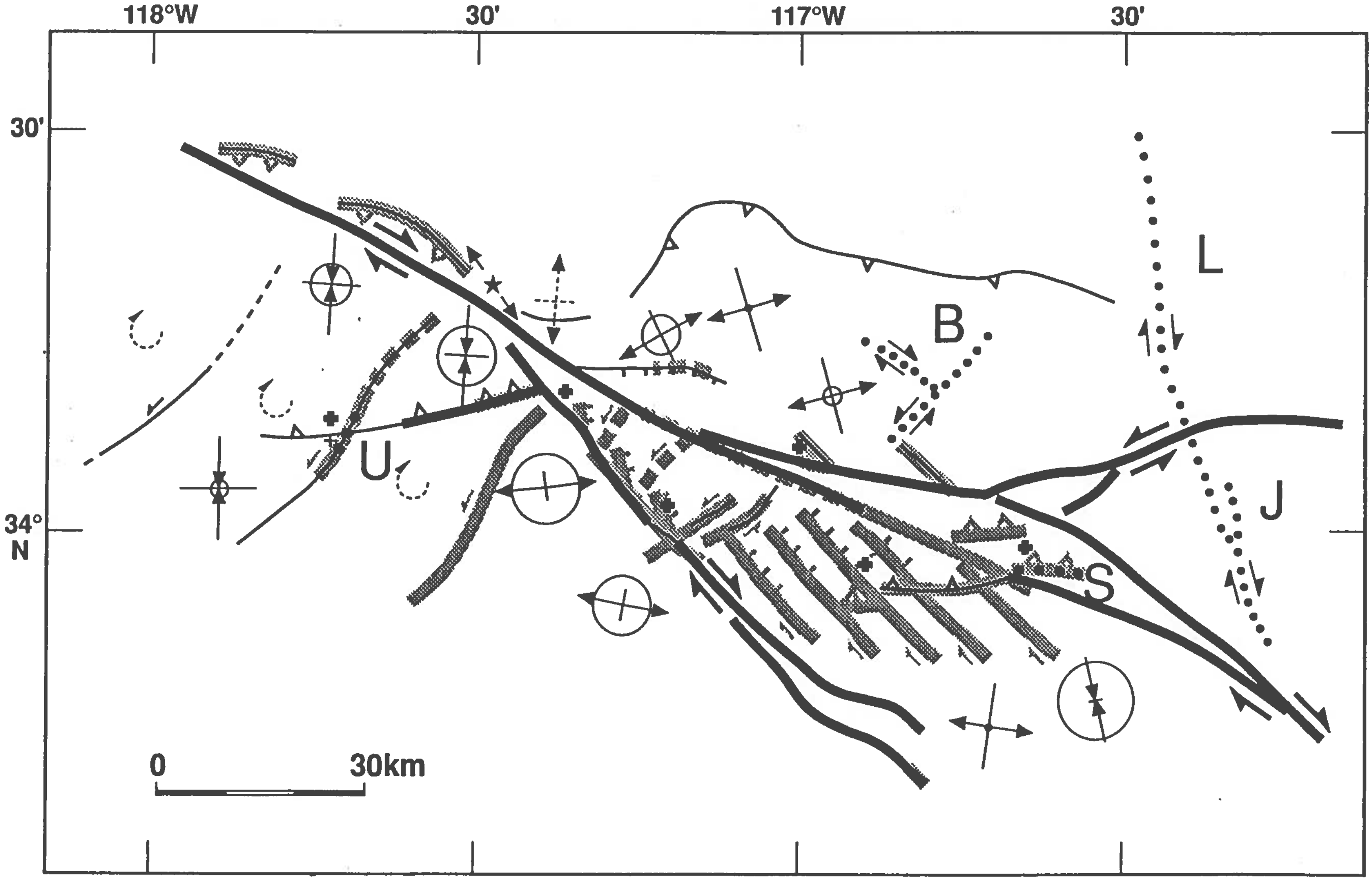


Figure 3. Tectonic sketch showing the main structural elements of the Cajon Pass-San Gorgonio Pass area. Solid lines are previously known faults (barbs of upthrown side of thrusts and short segments on downthrown side of normal faults); thick lines denote faults thought to play a primary role in the tectonic regime. Shaded strips denote some of the faults inferred from seismicity in this study. Dotted lines indicate faults delineaded by principlal aftershock sequences during data sampled in this study: S=1986 North Palm Springs; U=1990 Upland; J=1992 Joshua; L=1992 Landers; B=1992 Big Bear. Stresses calculated from slip planes are also shown. Principal stress axes tend to be either nearly horizontal (plotted as segments) or nearly vertical (plotted as circles). Lengths of segments and radii are proportional to the deviatoric component of the corresponding principal stresses; the polarity of the largest component is indicated by the arrows and is opposite to the polarity of the other two components. Of the nine stress symbols, the northern most four are centered in the areas pertaining to them, the others are drawn outside their areas which are centered at the plusses closest to each symbol. The dashed simbol refers to T and P axes of a single focal mechanism. The star indicates the scientific borehole site and the related arrows show the direction of maximum horizontal extension at the well.

Preparation of Seismic Data Collected on Portable Recorders from the Landers-Big Bear Aftershocks

Principal Investigator: Frank Vernon, UCSD

A collaborative study to record aftershocks was undertaken by several institutions following the June 28 Landers and Big Bear earthquakes. The M7.6 Landers earthquake occurred at 04:58 PDT approximately 6 miles north of Yucca Valley along the southern extension of the Johnson Valley fault. The earthquake produced over 70 km of ground rupture, with cumulative right-lateral offsets of 3 to 6.5 m along segments of the Homestead Valley, Emerson Lake, and Camp Rock faults, all of which were involved in the sequence. The primary aftershock activity occurred in a narrow band from 33.6N, -116.2W north to 34.5N, -116.6W, with a separate cluster at 35.0N, -117.0W. The M6.5 Big Bear earthquake occurred at 08:04 PDT approximately 35 km west of the Landers epicenter in the San Bernadino Mountains, involving left-lateral slip on a fault that strikes N45°W and dips 70°SE. The Big Bear aftershocks occur over an area of about 30 km long, extending northeast from 34.1N, -117.0W to 34.4N, -116.6W.

Personnel from Caltech, SDSU, UCSB, UCSD, and USC participated in the installation and maintenance of the portable stations. Within 12 hours, four portable instruments were installed and recording data, and an additional 18 were up and running within 48 hours. Approximately 10 Gb of raw data from thirty-one individual stations were acquired in the 2 months following the main shocks.

The processing scheme required several steps: raw data retrieval followed by formatting, quality control, timing corrections, and event association. A Sun Sparc field computer was set up in a motel room several days after the main shocks. Most of the data reformatting, quality control and timing corrections were performed on this field computer. The computer was operated for about three weeks and data collected afterwards were processed at one of the participating institutions.

Initially, a REFTEK Exabyte drive was used to dump the data at the station, but it was found to be more reliable to exchange hard discs and copy data via the SCSI bus on a Sun Sparc station. After the raw data were downloaded to disk, TAR backup tapes were made. Next the data were converted to PASSCAL SEGY format and reviewed using PASSCAL's quick look program PQL to evaluate the station performance. Data recorded on SSR-1s were brought back to SDSU, then copied to a Sun Sparc station and converted to PASSCAL SEGY format.

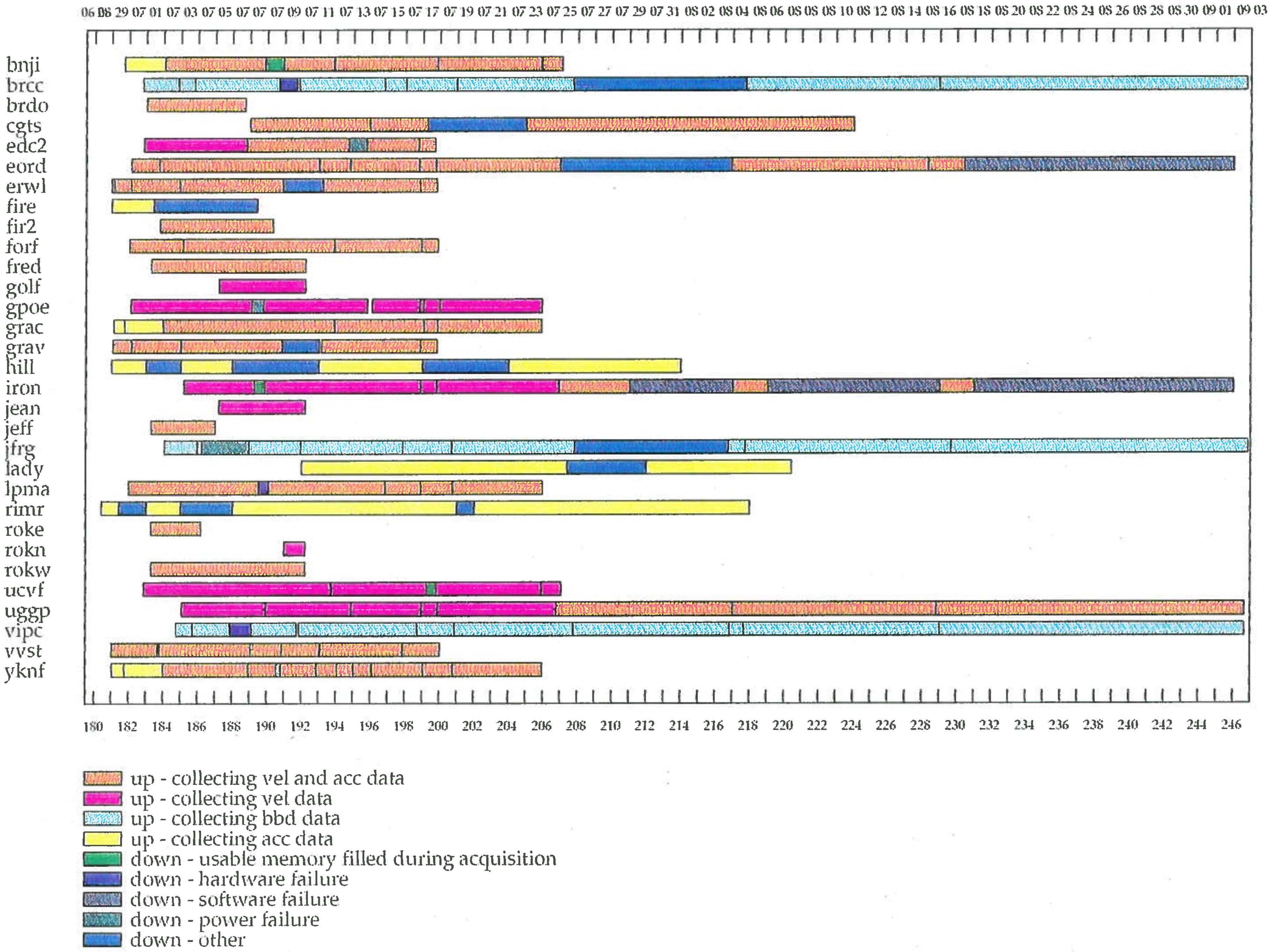
Errors in timing were also corrected at this point. The common timing errors that were present in the raw data resulted from improper leap second settings and unlocked Omega time clocks. Unfortunately, not all the RT72A-02 had the same firmware revisions. Firmware revisions 2.44, 2.45, and 2.46 were all used and each has a different leap second setting. To further complicate matters, an additional leap second was inserted on June 30 two days into the experiment. The timing shifts were accomplished by applying a shift to the trace start time via the TotalStatic field in the SEGY header. The program SEGYSHIFT was used to accomplish this.

The next step involved event association between the portable stations. This was accomplished by running the UCSB_TABLE and REAP programs. UCSB_TABLE creates a listing of event times, while REAP associates the data according to specified time and array parameters. Both the LDEO and SDSU datasets were then associated with the PASSCAL dataset based on event time windows. Figure 1 is a timeline showing the status of each station during the experiment.

At this stage all data meeting certain time criteria are organized into a sequence of events, and both P and S phases were picked. In order to determine event locations and magnitudes, two methods were used to associate the portable station records with the SCSN catalogue. An event-time association was performed, utilizing an ORACLE relational database, and an association between predicted arrivals and the P and S phase picks was performed, utilizing the CSS 3.0 database format.

All waveform record information, arrival information, station parameter information, and binary waveform files are ready to be converted into the SCEC database format and shipped to Caltech on DAT cartridges. A data report describing the field deployment, the data processing scheme, and the data itself will be included with this shipment.

Landers-Big Bear Earthquake Aftershock Deployment (28 June 1992 - 03 Sept 1992)



SCEC ANNUAL PROGRESS REPORT: FY1993

SCEC SCIENTIST: Craig Nicholson, Institute for Crustal Studies, University of California at
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This investigator did not receive any research support from SCEC in FY1993. Funds allocated to UCSB in FY1993 and assigned to this investigator were reimbursements for costs already incurred by ICS/UCSB in FY1992 during the portable instrument deployments for the April M6.1 Joshua Tree and June M7.4 Landers and M6.5 Big Bear earthquake sequences. Some additional SCEC funds were expended in FY1993 for initial data processing, organization, and event association. These funds completed the original process of data collection, and insured that the SCEC Data Center received properly time-corrected, useable, associated data; SCEC funding was not provided for data analysis or scientific research. Both 1992 deployments were successful, largely because of the tremendous cooperation between the various participating SCEC institutions involved. Participating institutions included Caltech, UCSB, UCSD, USC, USGS, PASSCAL, and SDSU.

22 April M6.1 Joshua Tree Earthquake

Five SCEC instruments were initially deployed within 6.5 hours of the April 22 M6.1 Joshua Tree mainshock. UCSB assisted in the deployment and maintenance of these sites. Six PASSCAL recorders were added to the deployment in the following days. The array was maintained until early June and collected about 5-6 Gbytes of raw digital data. At ICS, we corrected timing and performed event association on 3-4 Gbytes of data left after initial data processing and reduction. Over 10,700 events were associated, and the data were made available to the SCEC Data Center at Caltech.

28 June M7.4 Landers and M6.5 Big Bear Earthquakes

Nine PBIC DAS's were deployed for this aftershock sequence. PASSCAL supplemented the SCEC array with 10 DAS's in the days following the mainshock. SCEC member institutions, including UCSB, worked together to deploy and maintain the array. Once fully deployed, the array consisted of 18 sites including 3 STS-2 and 2 CMG-3 broadband sensors. A prototype field computer was used to perform initial field quality control of the data. Over 8 Gbytes of raw data were collected. Data processing, event association and timing corrections were performed at UCSD. Over 8,000 events were associated, and the data made available to the SCEC Data Center at Caltech.

FY1993 RESEARCH RESULTS

1. Changes in Attitude - Changes in Latitude: What Happened to the Faults in the Joshua Tree Area Before and After the M7.4 Landers Mainshock?

CRAIG NICHOLSON, RUTH A. HARRIS, AND ROBERT W. SIMPSON

The M6.1 Joshua Tree earthquake of 23 April 1992 occurred about 8 km northeast of the southern San Andreas fault and about 20 km south of the Pinto Mt fault. It was followed by over 6,000 M>1 aftershocks. No surface rupture for this sequence was found; although ground fractures were discovered in this area after the Landers earthquake on June 28. From the distribution of aftershocks and directivity effects, the mainshock ruptured unilaterally to the north along a fault about 15 km long. The focal mechanism indicated right-slip on a plane striking N14°W, dipping 80°W, with a rake of 175°. We relocated 10,570 events between 23 April and 24 July using the data from the regional network; and determined 3,030 single-event focal mechanisms with 15 or more first-motions. A large number of aftershocks occurred off the mainshock rupture plane on adjacent secondary structures that strike either sub-parallel to the Joshua Tree mainshock plane or on relatively short, left-lateral faults that strike at high angles to the mainshock plane. Aftershocks continued to migrate to the north and south following the mainshock, and ultimately extended from the southern San Andreas fault near the Indio Hills to the Pinto Mt fault. The northern 15-km section of the aftershock zone had a strike more nearly N10°E. Seismicity on this fracture network ceased in the hours prior to the 28 June M7.5 Landers event, and has not yet resumed. Instead, the Landers mainshock appears to have caused the activation of a new fracture network located farther west, that intersects the previous Joshua Tree activity in the area of the Joshua Tree mainshock, and is oriented more nearly N15°W. We investigate possible explanations for this change in the pattern of earthquake activity as a result of inferred stress changes induced by the Landers mainshock and some of its larger aftershocks.

2. Joint 3-D Tomography Using Seismic And Gravity Data Of The 1992 Southern California Sequence: Constraints On Dynamic Earthquake Ruptures?

JONATHAN M. LEES AND CRAIG NICHOLSON

Linear tomographic inversion of P-waves from the recent 1992 Southern California earthquakes is used to produce 3-D images of subsurface velocity. The 1992 dataset, augmented by 1986 M5.9 North Palm Springs earthquakes, consists of 6458 high-quality events providing 76,306 raypaths for inversion. The target area consists of a 104×104×32 km^3 volume divided into 52×52×10 rectilinear blocks. Laplacian regularization was applied and the residual RMS misfit was reduced by ~40%. Significant velocity perturbations are observed that correlate with rupture properties of recent major earthquakes. Preliminary results indicate a low-velocity anomaly separates dynamic rupture of the M6.5 Big Bear event from the M7.4 Landers mainshock; a similar low-velocity region along the Pinto Mt fault separates the April M6.1 Joshua Tree sequence from the Landers rupture. High-velocity anomalies occur at or near the nucleation sites of all 4 recent mainshocks (North Palm Springs-Joshua Tree-Landers-Big Bear). A high-velocity anomaly is present along the San Andreas fault between 5-12 km depth through San Gorgonio Pass; this high-velocity area may define an asperity where stress is concentrated. To test model reliability, a joint inversion of seismic and gravity data was performed. Gravity data can be used by assuming a linear relation between density and velocity perturbations. Gravity may be important to subsurface structure because the Landers rupture follows a strong gravity gradient. Gravity also helps constrain near-surface regions of the model where incident rays are nearly vertical and seismic resolution is poor. The joint 3-D model is required to fit both seismic data and isostatic gravity anomalies to a specified degree of misfit. A joint tomographic inversion in which 40% of seismic data residual misfit and ~80% of the gravity anomalies are explained does not differ significantly from previous models. These results suggest that high-resolution 3-D tomography may be a more effective means of segmenting active faults at depths than near-surface mapping.

3. The April 1992 M6.1 Joshua Tree Earthquake Sequence: Analysis of Portable Data and 3-D Tomographic Inversion

AARON MARTIN, CRAIG NICHOLSON, AND JONATHAN M. LEES

The M6.1 Joshua Tree earthquake of 23 April 1992 occurred about 8 km northeast of the southern San Andreas fault and about 20 km south of the Pinto Mt fault at a depth of 12–13 km. The mainshock was followed by over 6,000 M>1 aftershocks recorded by the permanent regional network and an 11-element portable array deployed by the Southern California Earthquake Center. No surface rupture for this sequence was found; although ground fractures were discovered in this area after the M7.4 Landers earthquake and its large aftershocks of June 28. We relocated 10,570 events between 23 April and 24 July using the data from the regional network; and determined 3,030 single-event focal mechanisms with 15 or more first-motions. A large number of aftershocks occurred off the mainshock rupture plane on adjacent secondary structures that strike either subparallel to the Joshua Tree mainshock plane or on relatively short, left-lateral faults that strike at high angles to the mainshock plane. The northern 15-km section of the aftershock zone had a strike more nearly N10°E. Seismicity on this fracture network ceased in the hours prior to the 28 June Landers event, and did not resume. Instead, the Landers mainshock appears to have caused the activation of a new fracture network located farther west, that intersects the previous Joshua Tree activity in the area of the Joshua Tree mainshock, and is oriented more nearly N15°W. This change in activity corresponds to a net tilt of about 30°–40° of the least-principal stress (σ_3) down to the northwest towards the Landers mainshock. Much of this later activity also coincides with a first-order discontinuity in 3-D velocity structure imaged by tomographic inversion of P-wave arrival times [*Lees and Nicholson,* 1993]. We investigate in more detail the structure of the Joshua Tree seismicity, changes observed before and after the Landers mainshock, and the local 3-D velocity structure using the portable digital data. Over 10,700 events were identified with recordings at 2 or more portable stations. Preliminary analysis of the portable data indicates that initial timing problems can be overcome and that the data are extremely useful for increasing model and structure resolution.

Group G: Physics of Earthquake Sources

Group Leader: Leon Knopoff

Group Leader: Leon Knopoff

REPORT OF WORKING GROUP G

Rice has shown that smooth, featureless, i.e. homogeneous, fault zones on a continuum model undergo repeated large earthquakes; the manifestations of chaotic behavior involving a Gutenberg-Richter spectrum of earthquake sizes is a consequence of the small scale disorder that is typical of the discrete lattice models on the scale of the lattice spacing. Xu and Knopoff have shown that there is no incompatability between the discrete and continuum models as long as both describe homogeneous systems that are scale-independent and have periodic end conditions; both lead to periodic large earthquakes; the chaotic behavior often ascribed to the lattice models is either a transient self-organizing state consequent on the initial conditions, or it is due to inhomogeneities that arise from healing pulses reflected from the ends of the model due to mismatched end (boundary) conditions. Both Rice and Knopoff argue that irregular fault system geometry is a major cause of chaotic seismicity. Shaw shows that the periodic state will not arise if it is possible to limit the size of the largest earthquakes; in this case the system organizes itself into a chaotic, non-repetitive state. The physical influence that limits the sizes of the largest events is a property of the models that resembles that of finite fault width; if an effective stiffness of a long section of a fault of finite width in Shaw's model exceeds the elasticity of the region, then fractures are limited in size. Thus the dichotomy between the homogenenists and the geometrists persists, and is reducible to the problem of the modeling of the fault in the direction perpendicular to it.

Rice's models are those of 2-D fracture surfaces imbedded in an elastic continuum. The Shaw and Knopoff models are 1-D reductions of these fault geometries. Chen and Knopoff constructed a dynamical plane-strain 2-D fracture model and applied it to an elongated fault structure designed to simulate a fault zone 15 km in depth and having a very long horizontal dimension. The applied stress is parallel to the long dimension of the fault. Faulting nucleates and grows initially in a more or less elliptical shape. Because of interaction with the upper and lower boundaries, the crack splits into two "Heaton pulses" that move in opposite directions with more or less constant velocity. If the crack encounters a near-surface asperity, a patch can be prolonged by growth around and below the asperity. There will be no slip at the surface at the asperity. This mimics the kink in the slip pattern in the Landers earthquake. Chen and Knopoff argue that inhomogeneities are important influences in pattern formation in seismicity.

One of the critical concepts in the models used in the simulations of seismicity, is that friction, in its static form inhibits the onset of the earthquake, and in its dynamic form inhibits sliding. The friction is usually modeled as a property of a point contact between the two blocks astride the fault. However, in the earth, the contact between the plates is a fault zone of finite width; explosion seismology and trapped-mode studies show that the fault zone has low seismic wave velocities, which is probably due to its being a zone of crushed rock of a possibly fractal distribution of sizes. Can we find equivalent rheological properties for a contact point that will model the properties of the extended fault zone? Sammis interprets the results of experiments on the deformation of gouge material as validating the rate-state dependent framework of precursory instability, but with a critical strain condition instead of a critical slip distance for the onset of the fracture instability;

the critical strain can be modeled as a critical slip distance if the width of the fault zone is taken into account, thereby allowing for the much larger critical slip distances that seem to be required to scale results from laboratory experiments up to dimensions appropriate to faulting.

The problem of precursory slip-weakening has been suggested as a mechanism for producing intermediate-term precursory effects. Landoni and Knopoff have shown that a comparison of results form modeling of inhomogeneous systems with and without precursory slip-weakening does not seem to produce significant changes in the space-time clustering of seismicity on any time scale. However a slow recovery of strength after fracture does produce significant clustering effects. Based on this observation it is suggested that much more experimentation is needed to understand slow recovery of strength in fault materials, as well as further numerical work on modeling these effects.

All investigators (Rice, Sammis, Shaw, Knopoff) agree that the understanding of the causes of the increase in the rate of intermediate magnitude seismicity before strong earthquakes, but not of the numbers of smaller earthquakes, is a major problem for the working group. Keilis-Borok and Levshina have shown that the precursory intermediate-magnitude seismicity for California earthquakes is distributed over several hundreds of km, which are distances many times greater than the classical fracture length of the strong earthquake that terminates the precursory episode. The termination of the increased activity is relatively abrupt, i.e. over a time scale probably of the order of one year or less. Thus modeling efforts should focus on long range effects.

RELATING FRICTION TO FAULT ZONE STRUCTURE

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Progress Report to the
Southern California Earthquake Center

1 December, 1993.

Earthquakes have traditionally been associated with frictional instabilities on preexisting faults. To a first approximation, frictional instabilities may be divided into dynamic instabilities and mechanical instabilities. Dynamic instabilities develop once the fault surfaces are moving and, as recently proposed by Brune and co-workers, may involve modes of vibration or waves which relieve normal stress on the fault. Mechanical instabilities develop if the initial displacement on a fault weakens the fault faster than that same displacement reduces the driving stress. The nucleation of earthquakes may be thus controlled by mechanical instabilities, while continued propagation may depend on dynamic instabilities.

Mechanical instabilities are commonly modeled using the Bowden-Tabor asperity model in which two sliding surfaces contact at a number of asperities. Asperities grow in strength with time, but their lifetime is limited by their size and the sliding velocity. A sudden increase in sliding velocity produces an instantaneous strengthening of the existing asperities "a" due to the increase in strength associated with the higher loading rate. However, as sliding proceeds at the higher velocity, the average asperity lifetime decreases which results in a decrease in asperity strength by an amount "b" over a characteristic sliding distance D_c which, in the Bowden-Tabor model is interpreted as the sliding distance required to completely change the population of asperities to ones having the new shorter lifetime. If $b > a$, then the material velocity weakens and, depending on the unloading rate of the fault, a stick-slip instability is possible. Stability is determined by comparing the apparent stiffness of the fault-zone:
$(b-a)\sigma_n / D_c$ with the elastic stiffness of the fault walls which, for a circular dislocation patch of radius r may be approximated as: $7\pi G/24r$ where G is the shear modulus of the wall rock.

Because fault zones generally contain a layer of crushed rock between the wall rocks, the direct application of the Bowden-Tabor model is problematical in terms of the identification of asperities and characteristic displacements. Experimental studies of friction in which a layer of crushed rock is introduced between the sliding rock surfaces have observed the same rate- and state-dependent phenomenology. Step changes in velocity still produce a signal which can be parameterized using a, b, and D_c as discussed above, but the values of all three parameters are significantly larger than those observed in rock-on-rock experiments. We interpret the larger values of both "a" and "b" observed for rough surfaces as being due to a velocity dependent dilatancy commonly observed in granular layers and show that the observed dilatancy produces instantaneous and evolutionary signals indistinguishable from those produced by the asperity model. The large increase in "b" and slight decrease in "a" which produce the transition from velocity strengthening to velocity weakening observed in gouge layers are produced by a transition from fracturing particles which has no lifetime effect to slip between particles which does. This work has been accepted for publication in a special issue of PAGEOPH on fault-zones and friction to be published in early 1994.

Sammis, C.G. and S.J. Steacy, The micromechanics of friction in a granular layer, PAGEOPH, in press, 1993.

The significance of the above observations is as follows: if the rate and state parameters in a fault zone depend on dilatancy, then they may not depend directly on fault displacement, but on strain within the fault-zone. This result is predicted by both soil mechanics and damage mechanics models for the strength of a crushed rock layer. The stiffness of the wall rock still depends on the displacement as discussed above, but the stiffness of the fault-zone now depends on strain=displacement/width. The immediate result is that wider fault zones should be more stable in the sense that a larger sliding patch is required to nucleate an instability. There are indeed hints that the creeping segment of the San Andreas fault has a wider crush zone than locked portions, and that small characteristic quasi-stable creep events also occur in these regions.

A second problem we have begun to work on is a physical model for the patterns of seismicity which are observed to precede large earthquakes: namely an increase in intermediate sized events (M>5) with no corresponding increase in smaller (M<4) events. These events do not occur in the rupture zone of the impending mainshock, but on other faults in the broader surrounding region. We have developed a heterogeneous bond-breaking model to test our working hypothesis that the precursory seismicity is a consequence of regional heterogeneity in that small events are more likely to break barriers and become large events late in the seismic cycle when the stresses are higher. A typical result is shown in Figure 1 where we have plotted the maximum event size at each strain increment. This figure clearly shows precursory activity; however we find that this is only the case when strength heterogeneities overwhelm stress fluctuations, and the strength of the barriers is proportional to the size of the fault. We are presenting this model at the Fall AGU meeting in San Francisco this month and at a workshop on geological hazards at the Santa Fe Institute for the Study of Complexity in January.

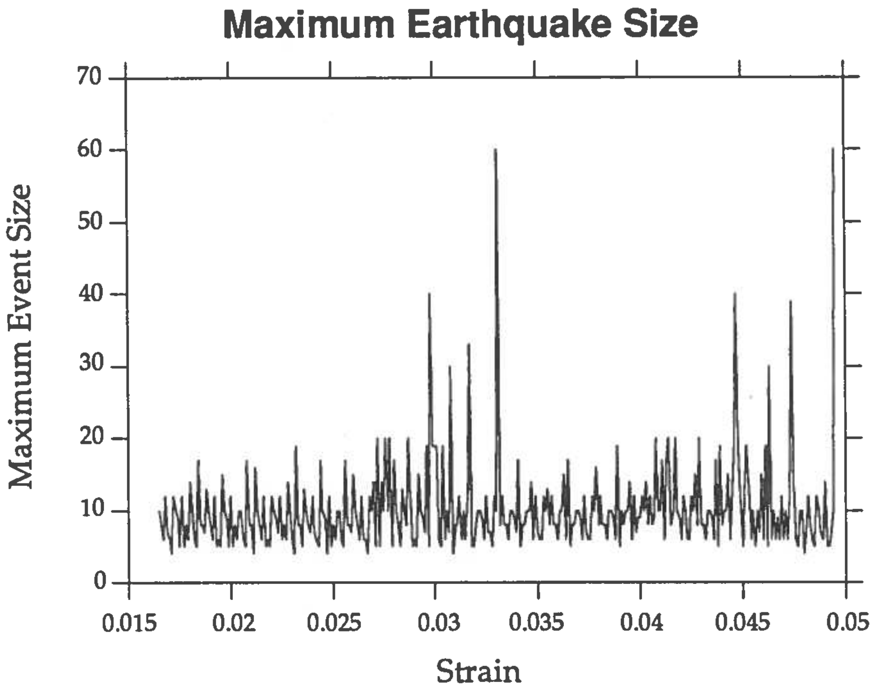

Figure 1: The largest event in each strain increment is plotted as a function of strain for a typical realization of a heterogeneous bond-breaking model for regional seismicity. Note the increase in intermediate-size events prior to each of the two largest events, consistent with observations of natural seismicity.

Annual Summary Report, Southern California Earthquake Center, USC P.O. 569928

Rupture heterogeneity and evaluation of the characteristic earthquake concept (seismicity in relation to geometric complexity, rheology and rupture dynamics of fault zones)

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November 1993

Our aim is to relate seismic response to the geometric disorder of fault zones, as represented by segmentation with kinks and jogs, and to the rheology of the frictional seismogenic region and its ductile surroundings. The studies were initiated under the title *Rupture Heterogeneity and Evaluation of the Characteristic Earthquake Concept.* They attempted to identify physical origins of characteristic earthquake response and to examine limitations to the concept by addressing inter-relations between fault zone property variations, geometric disorder, and heterogeneity of seismic response. An initial focus, retained in current work, was on modeling recurrent earthquakes along fault surfaces embedded in 3D (or sometimes 2D) elastic solids with a specification of physically based fault zone constitutive response of a kind that could lead to spontaneous failures. Additional themes added in the current grant year are: (1) Seismicity correlations and precursory patterns suggested by catalogs from our 3D fault models, and their relation to model assumptions, and (2) Interaction of stress heterogeneity, resulting from the elastodynamics of rupture propagation and arrest, with recurrent seismicity.

An understanding is emerging of which class of earthquake models will give repeated large events, which will show a spectrum of earthquake sizes, and when such a size distribution has Gutenberg-Richter self-similarity out to the largest events on a given fault segment [Rice (JGR, 1993; Fall AGU Abstract, 1992), Ben-Zion and Rice (JGR, 1993; USGS Redbook, in press, 1993)]. For example, our work suggests that smooth, featureless fault zones undergo repeated large earthquakes, principally because the stress concentration at a spreading rupture tip is too compelling for arrest by other than extraordinarily large variations in driving stress or toughness. However, geometrically disordered zones, so far simulated only approximately in our work by the finite size fault cells of a, then, inherently discrete model, have some probability of stopping sufficiently small ruptures, and give a Gutenberg-Richter spectrum of earthquakes over at least some small size range. We have described theoretical reasons (Ben-Zion and Rice, JGR, 1993), and confirmed from our numerical modeling, that a single size of heterogeneities could induce self-similar failure sequences only over a limited size range (e.g., 1 to 200 cell areas). In recent work (Ben-Zion and Rice, USGS Redbook, in press, 1993) we have been able to verify from numerical modeling our conjecture that the introduction of additional, stronger, heterogeneities at larger scale, but not necessarily with any self-similar of fractal features of their own, suffices to extend a simple Gutenberg-Richter power-law scaling to larger event sizes.

More importantly, these studies are helping to understand how one should interpret small-event seismicity statistics for an individual fault zone in terms of the largest probable events there. The large-event occurrence rate can generally be expected to coincide with power-law extrapolation of the instrumental record for small events only when strong disorder extends to the largest event scales; otherwise, the region is enriched in large "characteristic" events. Such considerations seem consistent with what is known from the statistics of instrumentally detected events and from the historical recurrence record at Parkfield, as we have noted. Also, preliminary results from S. Wesnousky (draft manuscript, 1993), who is comparing instrumental statistics with paleoseismic and geologic recurrence evidence for various fault zones in Southern California, lead us to believe that our considerations are on the right track. He finds that high geometric complexity, as characterized by the number of fault jogs or step-over distance per unit length along strike, is a feature which distinguishes fault zones such as the Newport-Inglewood and San Jacinto, whose paleoseismic rates are approximately coincident with extrapolation of the instrumental statistics, from zones such as Whittier-Elsinore, Garlock and San Andreas which seem to respond more nearly like the characteristic earthquake model.

Our work on theoretical models of recurrent seismicity has begun to search model catalogs for precursor patterns, based on time variations of minor seismicity, and to relate the presence or absence of such effects to model features. A focus is the statistical relation between small and slightly larger events, including any evidence that the probability of a small rupture growing into a larger one increases as stresses gradually build in time in and near the focal region. Additionally, we have developed an understanding of features that can lead to repetitions of similar small earthquakes at a given location; this is a response mode that can occur in some types of heterogeneous fault models at a border between locked and creep-slipping zones. Results from other groups (e.g., W. Foxall, T. McEvily and co-workers) suggest that such repeated events are common at Parkfield but rare at Anza.

A major new initiative in our work has been on developing truly elastodynamic models of unstable ruptures [Perrin and Rice (Spring AGU Abstract, 1993), Rice (Fall AGU Abstracts, 1993)], and on beginning the study of their consequences for some of the issues on complex response mentioned above. [Previously, our studies of recurrent events have been done with quasistatic models which only approximate to dynamic effects by inclusion of a radiation damping term (Rice, JGR, 1993) or provision for dynamic overshoot (Ben-Zion and Rice, JGR, 1993).] This elastodynamic work has begun with the simple setting of 2D anti-plane deformation. We have developed an efficient and stable computational technique, based on spectral representations of the stress and slip histories, that includes velocity weakening friction in the now standard rate- and state-dependent framework. The spectral representations are truncated at short (and very long) period, with rapid FFT techniques used to evaluate the interrelation between the stress and slip histories. The methodology is open to generalization to 2D problems of in-plane slip and general 3D problems, and we are exploring such as time allows. Further, its spectral basis leads to results that are apparently free of numerical oscillation problems that have plagued previous work based on related boundary integral formulations, but whose basis is instead stress (e.g., Das, Kostrov, Andrews) or slip (Madariaga and Cochard) over cellular domains.

We are currently studying dynamic models of rupture scenarios, in the anti-plane elastic setting, to begin to understand issues such as the following: How does the heterogeneous stress state along a fault, as created in the wave-mediated elastodynamics of arrest of slip, set the initial conditions for the next earthquake(s) there? Can such stress heterogeneity be regenerating from event to event, in that strong but heterogeneous dynamic overshoots provide under-stressed regions that can stop future ruptures, and thus provide a basis for sustained spatio-temporal complexity of faulting? Along the way, we are gaining an understanding of the remarkably complex sequences of slips that occur in the elastodynamics of starting of rupture along a suddenly loaded fault segment that carries a highly heterogeneous pre-stress.

Also, we have rewritten the quasistatic computer coding with radiation damping (Rice, JGR, 1993), used for the modeling of recurrent events, converting to a new code with fully explicit procedures and adopting a similar framework and spectral basis for slip as in the elastodynamic code. Thus we will soon have a 2D code which can properly switch to an elastodynamic mode when response requires, but which can nevertheless simulate the 100's to 1000's of years of seismic history and recurrence statistics that we now routinely study using the quasistatic models; that approach should ultimately be extendable to our 3D fault modeling.

Leon Knopoff

PROGRESS REPORT 1993, UCLA SEISMICITY MODELING GROUP

Chen and Knopoff have constructed a program to simulate plane strain fracture on a two-dimensional fault structure. The model is a fusion of the Mikumo/Miyatake plane strain model of fracture and the Burridge/Knopoff model of recurrence. The model is a 2-D particulate model in which each lattice site is coupled to nearest and next-nearest neighbors by 16 springs in the plane plus the usual transverse spring that drives the model. The 16 springs simulate the pure shear, pure compression and coupled shear/compression modes of deformation (the latter term presents some computational difficulties when applied near free surfaces.) We have simulated dynamical stress transfer in the elastic medium astride the fault by means of an equivalent vector dynamical friction proportional to the particle velocity. We have applied the model to an elongated 15x500 fault lattice in dimension; we imagine that the grid spacing is 1 km, with obvious implications for California faulting. The driving stresses are parallel to the long dimension the fault, and are applied through the transverse springs that extend from the anvils to the lattice sites.

The ends of the fault structure have periodic boundary conditions, the upper surface is free and the lower surface has a viscous boundary condition, i.e., it is unbreakable during the rupture event but any stress stored by the fracture is dissipated in the slow time interval between earthquakes. In these simulations we have considered a case of homogeneous friction and prestress with nucleation at a point in the interior. The fracture grows in a more or less elliptical shape until the fracture surface encounters the upper and lower boundaries. Healing is initiated as a reflection from both boundaries; an observation of healing initiated at the free surface was unexpected, but is now understood to be a consequence of the energy loss due to transport by elastic waves away from the faults. The fracture event then splits into two patches, which we identify as Heaton patches, and which then travel away from each other with constant velocity and constant shape for a given transverse (driving) spring constant. When a patch encounters a small asperity in its path, the fracture wraps around it and the patch continues to travel in a relatively unperturbed state. If the asperity is located at the surface it yields a kink in the surface slip, not unlike the observations in the Landers earthquake.

Rice has recently pointed out an incompatability between the homogeneous discrete lattice models of the B-K type and continuum models of faulting. While this does not directly impact on our focus on inhomogeneous systems, the discrepancy between our lattice system and the homogeneous continuum casts a shadow of unease on our use of the discrete lattice systems in the inhomogeneous cases. Xu and Knopoff have therefore considered a homogeneous version of the B-K 1-D system, with a dynamical friction adjusted to simulate the stress concentrations in the elastic medium adjoining the fracture surface, and with periodic boundary conditions in 1-D. We find that, for arbitrary initial conditions, the finite periodic lattice system at first undergoes a transient state in which it generates a Gutenberg-Richter power law distribution of earthquake sizes. After the G-R transient, it settles into a permanent state of periodic runaway events, in which the entire chain ruptures; in the permanent or steady state there are no smaller events. The periodicity leads us to agree with Rice that inhomogeneity must be introduced into these systems: it also restores our confidence in the relevance of our version of the B-K model. This result also indicates that reports of G-R distributions on finite homogeneous discrete lattice systems are due either to observations of a transient state, i.e., the computations were not carried out for a long enough time, or due to internal scale sizes not considered in our scale independent model, or due to hidden inhomogeneities in the system, such as reflections of healing stresses at incompatible end conditions, such as free or open end conditions.

Landoni and Knopoff have pursued the interaction between the long-term organization of seismicity implicit in model systems without viscous, e.g. creep effects, and the influences of viscous processes on intermediate-term clustering. Non-elastic deformation such as strain-hardening or slip-weakening obviously advance the times at which fractures take place. We have compared synthetic seismicity on a 1-D B-K model with an inhomogeneous distribution of critical fracture thresholds, and without other non-elastic effects, with the results from these same models with a precursory viscous rheology in the inter-earthquake interval. The viscous effects are assumed to be strongest immediately before or after the rapid fracture event. Although we have performed experiments on several forms of weakening of fracture strength prior to rupture, in general we find no significant influences on the seismicity patterns whether slip-weakening is present or absent. However if we introduce a slow restoration of fracture strength after rapid rupture, we find a significant change in pattern away from the irregular space-time organization of the instantaneous healing model and toward a localized periodic organization of events on all scales. We argue that postcursory creep is a potentially potent influence on organization of seismicity and hence if present in the real earth, could play an important role in contributing to the earthquake prediction enterprise. We urge that more attention be paid to postfracture anelastic effects both in the field and in the laboratory.

Keilis-Borok, Knopoff and Levshina have studied the space-time relationships between strong earthquakes and intermediate-magnitude earthquakes both before and after the strong earthquakes. Seventeen out of the 18 strong earthquakes in California with magnitudes greater than 6.4 in the interval 1941 to 1993 were preceded by an increase in intermediate-magnitude precursory activity (defined as events with magnitudes greater than about 4.7) over times ranging from a few months to several years. The precursory activity is concentrated in well-defined regions having linear dimensions of the order of a few hundred kilometers; these dimensions are significantly larger than the estimated fracture lengths of the ensuing strong earthquakes. Earthquakes with magnitudes less than about 4.4 or so, do not exhibit a similar increase in rate prior to strong earthquakes. The precursors to the largest of these strong earthquakes may occur over a longer precursory time interval and have larger magnitudes than do the precursors to smaller ones. Most frequently, the strong earthquake is located at the edge of a boundary between a zone of increased activity and a quiescent zone. All of the 18 strong earthquakes either switch off the increased activity abruptly, or are themselves part of a precursory pattern of continued activity before soon-to-occur additional strong earthquakes. the most remarkable of these observations is the long-range of these interrelationships as well as the fact that the decrease in seismicity over these long distances is relatively abrupt. We have developed a skeletal theory for the long range, intermediate-term, intermediate-magnitude interactions that invokes only the elasticity of the seismogenic plates and the distribution of fractures.

Progress report for Bruce Shaw for 1993

Two papers appeared in print this last year [Shaw, 1993a; Shaw, 1993b]. Two other papers were accepted for publication [Pepke, Carlson, and Shaw, 1993; Carlson, Langer, and Shaw, 1993]. A fifth paper was completed and submitted for publication [Shaw, 1993c]. Below, some of the results from these papers are briefly summarized.

"Moment Spectra in a Simple Model of an Earthquake Fault" recently appeared in *Geophysical Research Letters*, [Shaw, 1993a]. In this paper, the dynamics of the Burridge-Knopoff model was studied on the timescale of the rupture process. Large events were seen to consist of narrow pulses of slip propagating down the fault. The pulses of slip roughly inverted the displacement field, with places that were more retarded moving more, and places that were less retarded moving less. The moment release rate fluctuated as the pulses of slip passed over the rough displacement field. 'Subevents' were seen in the large events, with fluctuations in the moment release rate being of order the rate itself. A quantitative characterization of the motion was given by measuring the average moment spectra in the far field. Power laws in the spectral amplitudes were seen. A bend in the spectra of large events was seen, at a frequency corresponding the the length scale marking the transition from small to large events.

"Generalized Omori Law for Aftershocks and Foreshocks from a Simple Dynamics" recently appeared in *Geophysical Research Letters*, [Shaw, 1993b]. In this paper, I present a simple dynamical explanation for the time delay associated with aftershocks and foreshocks, and then present a series of measurements of aftershocks and foreshocks of small magnitude mainshocks, using the USGS catalogue for Central and Northern California from 1969-1990. The derivation of the Generalized Omori Law is based on the response to sudden forcing of a nucleation dynamics of self-driven acceleration to failure. The physical idea the dynamics is meant to represent is subcritical crack growth. One of the most interesting aspects of the derivation, is that an Omori law decay exponent of 1 is seen to be a generic value for strongly accelerating systems. Next, the simplest explanation of foreshocks is supposed– that they are events that happened to have an afterevent that was bigger. From this hypothesis, and the time dependence of aftershocks, the time dependence of foreshocks is derived. The last half of the paper involves the measurements from the USGS catalogue to see whether they are consistent with the simple theory. First, the time dependence of aftershocks as a function of mainshocks magnitude is examined; the exponent of the Omori law decay is seen to be independent of mainshock magnitude. Second, the spatial and temporal dependence of aftershocks is examined; it is observed that the dependence is separable into a dependence on space and a dependence on time. The figure from the paper showing this is reproduced in Figure 1. This is an important simplification, and allows for explanations which only consider temporal dynamics to be possible. A third measurement examined the number of aftershocks and foreshocks as a function of mainshock magnitude, and observed that the number of aftershocks approaches the number of foreshocks as the mainshock magnitude becomes smaller. This observation is expected by the simplest explanation of the relationship of foreshocks to aftershocks.

"Prediction of Large Events on a Simple Dynamical Model of a Fault" [Pepke, Carlson, and Shaw, 1993] was accepted for publication in *Journal of Geophysical Research*. The paper presents results for long term and intermediate term prediction algorithms applied to a catalogue generated by the Burridge-Knopoff model. The idea in this paper is to study issues related to algorithm optimization and the intrinsic limitations of algorithms, in a situation where we have well controlled, intrinsically complex catalogues. The catalogues generated by the model are of arbitrary length, and arise from a model which is deterministically chaotic. Here, we seek not to show that any particular complex seismicity pattern generated by the model matches the Earth, but rather to study how algorithms based on intrinsically complex patterns work, and how algorithm optimization works on such catalogues. Some of our results are as follows.

One methodological question we address is the evaluation of the performance of a prediction algorithm. For this purpose, we introduce a linear cost-benefit function Q, which quantifies the tradeoffs that necessarily must be made between the different goals of the prediction scheme. It measures the extent to which an algorithm is able to fulfill all of the prediction goals ($Q = 1$) relative to the option of doing nothing at all ($Q = 0$). In the cases we consider, the goals are to predict the future event, with the alarm time on for as little time as possible, and with the minimum of false alarms.

As a benchmark for evaluating the results of the intermediate predictions, we first evaluated long term predictability. Three commonly used methods were examined: the time-predictable and slip-predictable models, as well as a prediction based on recurrence intervals. Neither the time-predictable nor the slip-predictable models described the behavior very well, though the time-predictable model did slightly better. Interestingly, for either the time or slip-predictable models, it was possible to find good correlation over just a few subsequent large events. At any point, however, such a short time "pattern" could be broken, with the next event differing dramatically from the proposed model.

Intermediate term prediction, based on individual precursor measures of the small event activity, produced forecasts with much smaller time windows than the long term predictors. Four predictors were considered. In order of best performance, they were active zone size, activity, rate of change of activity, and finally, fluctuations in activity, which did much worse than the other three.

Finally, we considered the effect of finite catalogue lengths. We measured the average and standard deviation of Q as the catalogue length was increased. The average Q rose rapidly to its maximum, and the standard deviation dropped rapidly to its minimum in less than a repeat time. This is relevant for the question of the stability of the learning process for algorithms. In the model, we find that catalogues containing one large event are sufficient for stability in learning. If these results also apply in the Earth, one would expect continued improvement in algorithm performance as catalogue lengths reach the repeat times of large events, with a much slower improvement after that.

"Dynamics of Earthquake Faults" [Carlson, Langer, and Shaw, 1993] has been accepted for publication in *Reviews of Modern Physics*. In this paper, we review the variety of results that have been found concerning the behavior of homogeneous fault models with stick-slip friction and inertial dynamics. This paper was solicited by the editors, due to widespread interest in the physics community in the work our group has been doing on these fault models.

"Complexity in a Spatially Uniform Continuum Fault Model" [Shaw, 1993c] was completed and submitted for publication in Geophysical Research Letters. This paper addressed the question raied by Rice [JGR, 1993; a "top ten" on the SCEC list] of whether faults with a continuum limit could generate complex nonperiodic sequences. Here, I show that the introduction of a viscous term to the Burridge-Knopoff model provides a small lengthscale cutoff which allows a well defined continuum limit, and which continues to generate complex nonperiodic sequences. The figure from the paper demonstrating this is reproduced in Figure 2. Thus spatial heterogeneity or inherent discreteness is shown to not be a necessary condition for complex sequences. Rice has shown that long range quasistatic interactions appear not to give complex sequences in the continuum limit; here I show that short range interactions with inertial dynamics do. The big question for seismology– what happens with both long range and fully dynamic interaction remains an open question.

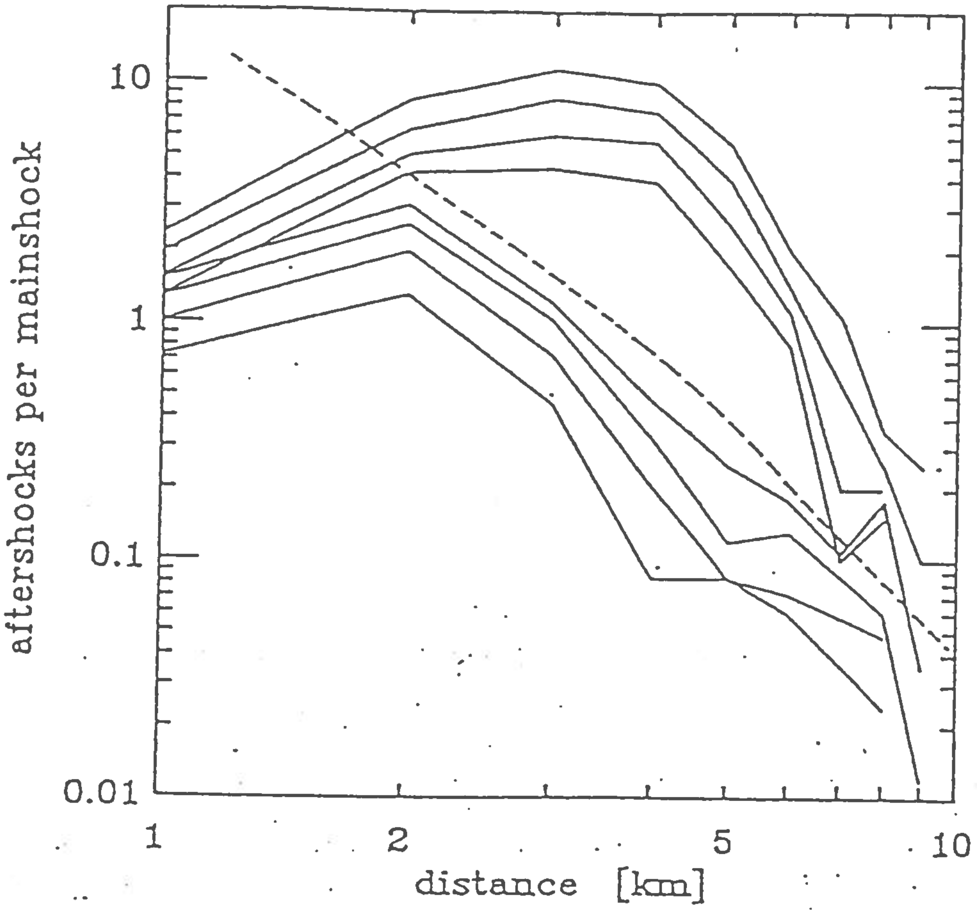

FIG 1. The spatial distribution of aftershocks for real earthquakes. The number of aftershocks per mainshock as a function of distance is plotted, for events happening up to a given time following the mainshock. Distance is measured between hypocenters, in units of kilometers. The four solid curves are for mainshocks with magnitudes between 4 and 5, while the four dotted curves are for mainshock magnitudes between 5 and 6. The long dashed curve is a theoretical curve (see Eq.(15)). The times of the four curves in each set are all the events before 1/3, 1, 3, and 9 days. Observe that the spatial distribution appears stationary in time; it does not broaden, and only the rate of events changes. The finite size of the source can be seen in the drop in events at small distances.

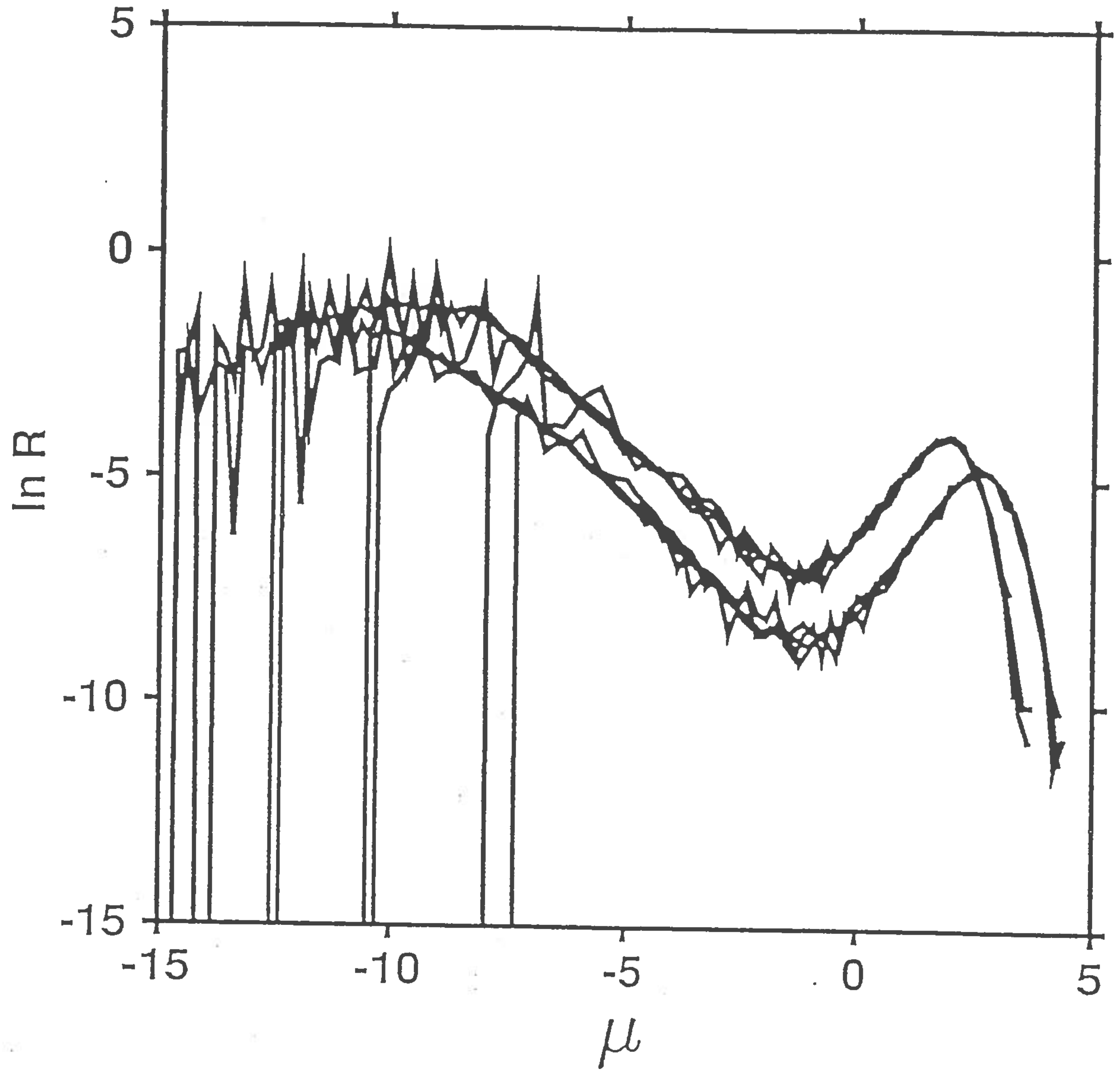

FIG 2. The distribution of sizes of events for a homogeneous continuum fault model. The relevant small lengthscale is set by a viscous term. There are eight different curves on the plot, with four different values of the numerical resolution for two different viscous lengths. The eight different curves collapse onto two sets, corresponding to the two different values of the viscous term. The important thing to see in the figure is that the distributions that are obtained are independent of the numerical resolution, and depend instead on the viscous term. Thus, we have obtained a complex nonperiodic sequence of events with a spatially uniform continuum fault model.

3-D DYNAMIC MODELING - EFFECTS OF FAULT GEOMETRY ON EARTHQUAKE RUPTURES IN SOUTHERN CALIFORNIA

FY93 PROGRESS REPORT TO THE SCEC

Ruth A. Harris
(U.S.G.S., Menlo Park)

In FY 1993 I was a Visiting Scientist at the SCEC and received $16,500.00 of financial support for my research on '3-D Dynamic Modeling-Effects of Fault Geometry on Earthquake Ruptures in Southern California'. My tenure was at the USGS in Menlo Park and my sponsor was Ross Stein.

This has been a very exciting year for my research on dynamic rupture propagation. For the past 2 years, with the generous collaboration of Steve Day, I have been using a 2D finite-difference computer code to numerically simulate earthquake ruptures jumping between fault segments [Harris et al., 1991; Harris and Day, 1993]. In 1992 I started using a 3D code and extended my modeling efforts to the more realistic 3D case. The 3D simulations have been specifically applied to the scenario of an earthquake which nucleates on the Anza segment of the San Jacinto fault zone [Harris et al., 1992; Harris et al., manuscript to be submitted]. The results of my numerical modeling efforts have been presented to the scientific community at a number of meetings, workshops, and seminars, but the implications of my results were not widely appreciated at first (as is the usual case for new research). Then, on June 28, 1992 the M7.4 Landers earthquake occurred. This earthquake jumped previously defined segment boundaries [Wesnousky, 1986], rupturing 5 southern California faults, and evolved into the largest earthquake to strike California in the past 40 years.

Since the Landers earthquake, detailed analyses of the strong motion data [e.g. Kanamori et al., 1992; Wald and Heaton, submitted; Campillo and Archuleta, 1992] have revealed that the Landers earthquake did indeed follow many of the patterns predicted by the Harris and Day [1993] numerical models. The predicted and observed patterns include time delays at the stepovers, and 'bilateral slip' after the rupture jumped to another fault segment. Most significantly, the numerical models were able to predict that jumps between fault segments spaced only 1-2 km apart are very reasonable. The Landers earthquake has demonstrated that at least for some strike-slip faults in the eastern Mojave shear zone, my numerical modeling results can be directly applied to real cases of earthquakes jumping between fault segments. With this insight I am enthusiastically continuing the 3–D modeling effort and plan to tackle the case of non–parallel strike-slip faults, with the collaboration of Steve Day.

As part of my dynamic numerical modeling efforts, I am also working with David Pollard on a project which aims to determine if it is possible to distinguish between dynamic and static effects of earthquakes when studying the geological record of paleoearthquakes. The results of our study [Pollard and Harris, in press] will be presented at a special session of the annual GSA meeting in October 1993.

On a final note, during my tenure as an SCEC visiting scientist I have also had the opportunity to investigate detailed models of the effects of the Landers earthquake's static stress changes on nearby faults in southern California. The beginnings of this study were published as a paper in the journal Nature in 1992 [Harris and Simpson, 1992], and contributed heavily to the Phase I Landers report. In FY 1993 we (Bob Simpson and I) have extended our previous study to encompass all of the known active faults in southern California. This work [Simpson and Harris, submitted] has been submitted to the BSSA Landers special issue. The paper also investigates the effects of the Landers earthquake relative to two great (M8) California earthquakes, the 1906 San Francisco earthquake and the 1857 Ft. Tejon earthquake. The investigation into the impressive effects of the 1857 earthquake on southern California faults will be discussed at the 1993 Fall AGU Meeting in San Francisco [Harris and Simpson, submitted].

I would like to thank the SCEC for the financial support during FY93. I definitely plan to continue my collaboration with the SCEC in the months and years to come.

Partial Bibliography:

1) Harris, R.A., R.J. Archuleta and S.M. Day, Fault steps and the dynamic rupture process: 2-d numerical simulations of a spontaneously propagating shear fracture, Geophysical Research Letters, vol. 18, pages 893-896, 1991.

2) Harris, R.A., and S.M. Day, Dynamics of fault interaction: parallel strike-slip faults, Journal of Geophysical Research, vol. 98, pages 4461-4472, 1993.

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HARRIS, FY93 REPORT, CONTINUED - PAGE 3

3) Harris, R.A., S.M. Day, and T.K. Rockwell, (abstract), A 3-d dynamic rupture model of fault segmentation- with applications to the next Anza Gap earthquake, EOS Trans. AGU, vol. 73, page 389, 1992.

4) Harris, R.A., S.M. Day, and T.K. Rockwell, 3-D dynamic models of a segmented fault, with applications to the next Anza Gap earthquake, manuscript in prep.

5) Harris, R.A., and R.W. Simpson, Changes in static stress on southern California faults after the 1992 Landers earthquake, Nature, vol. 360, pages 251-254, 1992.

6) Simpson, R.W., and R.A. Harris, Static stress changes generated by the 1992 Landers earthquake on southern California faults, with comparisons to the 1906 San Francisco and the 1857 Ft. Tejon earthquakes, manuscript submitted to BSSA, August, 1993.

7) Harris, R.A., and R.W. Simpson, (abstract), In the shadow of 1857; an evaluation of the stress changes generated by the M8 Ft. Tejon, California earthquake, submitted to AGU, September, 1993.

8) Pollard, D.D., and R.A. Harris, (abstract), Quasi-static and dynamic stress changes during faulting: Implications for paleoearthquake identification, GSA, in press, 1993.

Southern California Earthquake Center

Summary Report on the Research Contract

Sponsored by

The State of California Department of Transportation
The Los Angeles County Department of Public Works
The City of Los Angeles Department of Public Works

on

The Characteristics of Earthquake Ground Motions for Seismic Design

Principal Investigators: Geoffrey R. Martin
Assistant Director for Engineering Applications
Keiiti Aki
Science Director

I. Tasks

The three year contract was initiated in April, 1992. The research tasks complement ongoing SCEC research, and have as their general objective the development and completion of seismological and geotechnical data relevant to State, County, and City programs in seismic design of bridge and buildings. The research program is presently subdivided into eight asks as listed below.

Task H-1: Characteristics of Earthquake Response Spectra in Southern California — See H4
V. Lee and M. Trifunac, University of Southern California

The goal of Task H-1 is to develop improved empirical models for scaling the amplitudes of smooth elastic earthquake response spectra characteristics of the Southern California region, for use in design. These empirical scaling equations can be used directly for prediction of site-specific spectrum amplitudes given the earthquake magnitude, the distance from the source, and the geological and local site conditions at a particular site. The scaling equations also provide the means for providing improved attenuation relationships for use in probabilistic earthquake hazard analyses. The new scaling equations will be developed by regression analyses of a large number of strong motion records. During the first year of work of this task, the focus was on preparation of earthquake data for analysis and on developing functional relationships to guide critical parameters for the regression analyses.

Task H-2: Southern California Fault and Earthquake Parameters — See Group C
K. Sieh, California Institute of Technology

Research supported by Task H-2 has focused on identifying sources of destructive earthquakes in the Los Angeles metropolitan region, particularly in the northern Los Angeles basin. Results of research have been extremely productive in delineating the seismic hazards posed by the Santa Monica and Hollywood faults and has provided a major contribution in the understanding of potential earthquake behavior of the blind thrust faults that underlie much of urban Los Angeles.

Task H-3: Effects of Local Site Characteristics on Ground Accelerations See H5
K. Aki and G. Martin, University of Southern California

The goal of Task H-3 is to evaluate the extent of amplification of ground motions arising from the presence of site specific soil profiles. This task becomes complex for very strong ground motion as amplification factors depend on the level of ground shaking, that is, site effects are nonlinear. As part of the first year activities, a preliminary GIS based map of weak motion amplification factors for Southern California has been constructed. To further pursue questions related to weak motion amplification factors and nonlinear effects, several portable broad band seismometers have been installed close to existing sites of strong motion seismographs in the Los Angeles basin. Data acquisition is in progress utilizing regularly occurring small earthquakes. Analysis of data recorded on the portable instruments is continuing together with evaluation of methods to correct for nonlinear effects.

Task H-4: Duration of Strong Motion Shaking in Southern California See H8
M. Trifunac and V. Lee, University of Southern California

The goal of Task H-4 is to develop improved empirical models by scaling the duration of strong ground motion of the Southern California region by utilizing regression analyses of recorded data. The developed regression equations describe the duration of strong ground motion in terms of the seismic energy available to excite the structures. As all the processes effecting duration are frequency dependent, analyses of duration have been performed in twelve narrow frequency bands with a central frequency between 0.1 to 25 Hz. The developed functional relationships and scaling models have been verified by currently available strong motion data in California.

Task H-5: Geotechnical Site Data Base for Southern California See H10
M. Vucetic, University of Southern California

The objective of Task H-5 is to compile a geotechnical database for the Los Angeles Basin for use in strong ground motion site characterization. Such a database will be particularly valuable in assessing questions related to site amplification and site stability during strong ground motion. The program TECHBASE (a mining and geotechnical oriented three-dimensional GIS software package with capabilities of generating soil and geologic profiles and boring logs is being used. Collection and digitization of relevant geotechnical and geologic data, particularly shear wave velocities, is continuing.

Task H-6: Evaluation of Bridge Damage in Recent Earthquakes No Report
J. Hall and R. Scott, University of Southern California

The objective of this task is to study the earthquake performance and damage to bridges in the magnitude of 7.8 Lugos, Philippines earthquake (July, 1990) and the magnitude 7.5 Costa Rica earthquake (April, 1991). Research activity to date has largely focused on completion of a report on the Costa Rica earthquake. In the second year, research is focusing on the Philippines earthquake.

Task H-7: Probabilistic Evaluation of Acceleration Response Spectra and Earthquake Time Histories for Southern California (Year Two)
G. Martin and K. Aki, University of Southern California

The initiation of this task in year two of the research program has the objective of developing a consensus among the scientific and engineering earthquake community in Southern California, regarding the critical input data needed for proposed probabilistic analytical studies planned in year three.

A series of four mini-workshops to develop a consensus regarding the database are planned. These mini-workshops will bring together earthquake engineers, geologists, and seismologists (from both the consulting and academic environment) and will include input from Southern California Earthquake Center scientists working on related studies. The workshops will encompass the following areas:

1) The seismotectonic characterization of Southern California.

2) Attenuation relationships required for probabilistic analyses.

3) Probabilistic computer codes.

4) Methodologies available to develop earthquake time histories.

Task H-8: Liquefaction Characteristics and Liquefaction Potential of Southern California Sites (Year Two) See H13
G. Martin, University of Southern California

The objectives of this task are to:

1) Digitize available liquefaction potential maps as part of our developing GIS database.

2) Re-assess and improve the database used to develop the above maps by taking advantage of the developing database of borehole data being compiled as part of Task H-5.

3) Develop a more quantitative approach for assessment of post liquefaction ground deformation potential suitable for mapping.

Task H-8 is in effect an extension of Task H-5. The two tasks together have the overall objective of providing a comprehensive geotechnical site database, including seismic hazard assessments in a form suitable for both planning and engineering design purpose.

Brief progress summaries of individual tasks follow with the exception of Tasks H-6 and H-7. Progress on Task H-6 has been limited due to the rescheduling of planned travel to the Philippines. The Task H-7 workshops have been initiated, the first two-day workshop on "Seismotectonic Characterization of Southern California," being held on November 8-9, 1993. The workshop was attended by about 40 leading scientists and engineers in various disciplines, and provided a forum for a critical evaluation of the SCEC seismotectonic model.

TASK H-1 CHARACTERISTICS OF EARTHQUAKE RESPONSE SPECTRA IN SOUTHERN CALIFORNIA

CO PI's: TRIFUNAC, LEE AND TODOROVSKA

SUMMARY

The empirical equations for scaling Fourier and Response amplitude spectra in the frequency band from ~ 0.1 to 25 Hz can be extrapolated to describe the long and short period strong motion amplitudes. The results of this extrapolation agree with (1) the seismological and field estimates of permanent ground displacement (near field), and with (2) the independent estimates of seismic moment and the observed corner frequencies of far field Fourier spectrum amplitudes.

At high frequencies ($f > 25$ Hz) the spectral amplitudes can be described by $\exp(-\pi\tau f)$, where τ ranges from .02 (near the source) to about .06 at epicentral distance of ~ 200 km.

The amplification of strong motion amplitudes by local soil and geologic site conditions can be defined to apply in the same broad frequency range.

To propose the final generation of empirical scaling equations, we are at present working on the refinement of the frequency dependent attenuation equations, and on the more detailed classification of the local soil and local geologic site conditions.

The work completed to date is summarized in the following publications:

Trifunac, M.D. (1993). Fourier Amplitude Spectra of Strong Motion Acceleration: Extension to High and Low Frequencies, Earthquake Eng. and Structural Dynamics, (in press).

Trifunac, M.D. (1993). Long Period Fourier Amplitude Spectra of Strong Motion Acceleration, Soil Dynamics and Earthquake Eng. (in press).

TASK:H-3

Effects of Local Site Characteristics on Ground Accelerations

K. Aki, B.H. Chin and G.R. Martin
University of Southern California

The well established separability of source, path and site effects on coda waves of local seismic events offers the most effective means for determining the site amplification factor empirically. Many studies have confirmed that the coda amplification factor represents those of S waves averaged over various directions of wave approaches. A systematic relation has been found between the coda amplification factor and the age of surface geology at the recording site in California, and has been used to interpolate coda amplification factors observed at selected sites to construct maps of amplification factors in California.

We found that, in general, the coda amplification factor is applicable to strong ground motion at rock sites. It is also applicable to soil sites, if the basement acceleration level is lower than about 0.1 g. We found, however, the coda amplification factor overestimates the observed strong motion amplification at soil sites when the basement acceleration level exceeds 0.1-0.2 g. These discrepancies can be explained by the increased absorption due to the non-linear histeresis in soil response. A preliminary method by M. Mahdyiar and others (1993) for correcting the coda amplification factor for the non-linear effect is also being tested. This method is based on the following two assumptions.

(1) The non-linear effect attenuates the coda amplification factor as a function of frequency f in the form exp(-αf), where α is a constant. This assumption is consistent with the interpretation that the non-linear soil response is primarily due to stress-strain histeresis. In that case, the fractional loss of energy is independent of frequency (constant Q), and the frequency dependence of attenuation will be of the form exp(-αf).

(2) We assume the existence of a universal relation between the peak ground acceleration observed at the surface of a soil site and that at the basement rock beneath the site. This is a drastic, and probably oversimplifying assumption, but is supported from several studies.

Fig 1 shows comparison between observed and predicted 5% pseudo relative velocity response at various stations from the Landers earthquake of 1992. Also shown are the expected values with the 84% confidence interval based on regression analysis of strong motion data by Trifunac and Lee (1989). The applicability and uncertainty of predicted response spectra for our calculation is compatible with the one calculated from regression analysis of strong motion data as shown in Fig 2. Similar results can also be found for the 1989 Loma Prieta earthquake.

We are currently measuring the coda amplification factor, at the site of strong motion seismographs where strong motion data from past earthquakes are available, and where subsurface shear wave velocities have been estimated for geotechnical studies in order to develop the non-linear correction.

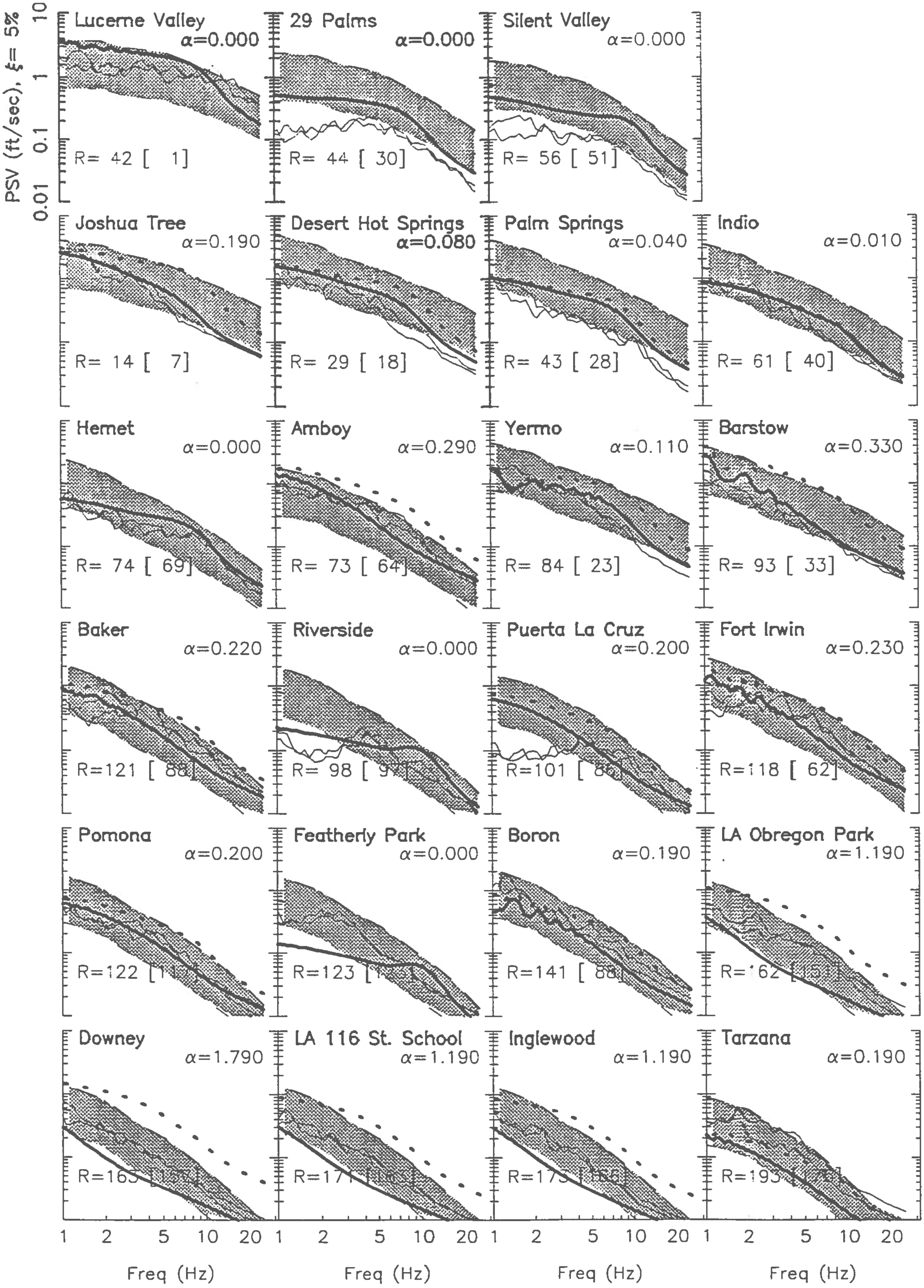

Fig. 1. The comparison between observed (thin lines) and predicted (thick lines) 5% pseudo velocity response spectra correct by the factor exp(-αf). The thick dashed line indicates the predicted spectra for α=0. The shaded region represents the expected values with the 84% confidence interval based on regression analysis of strong motion data by Trifunac and Lee (1989).

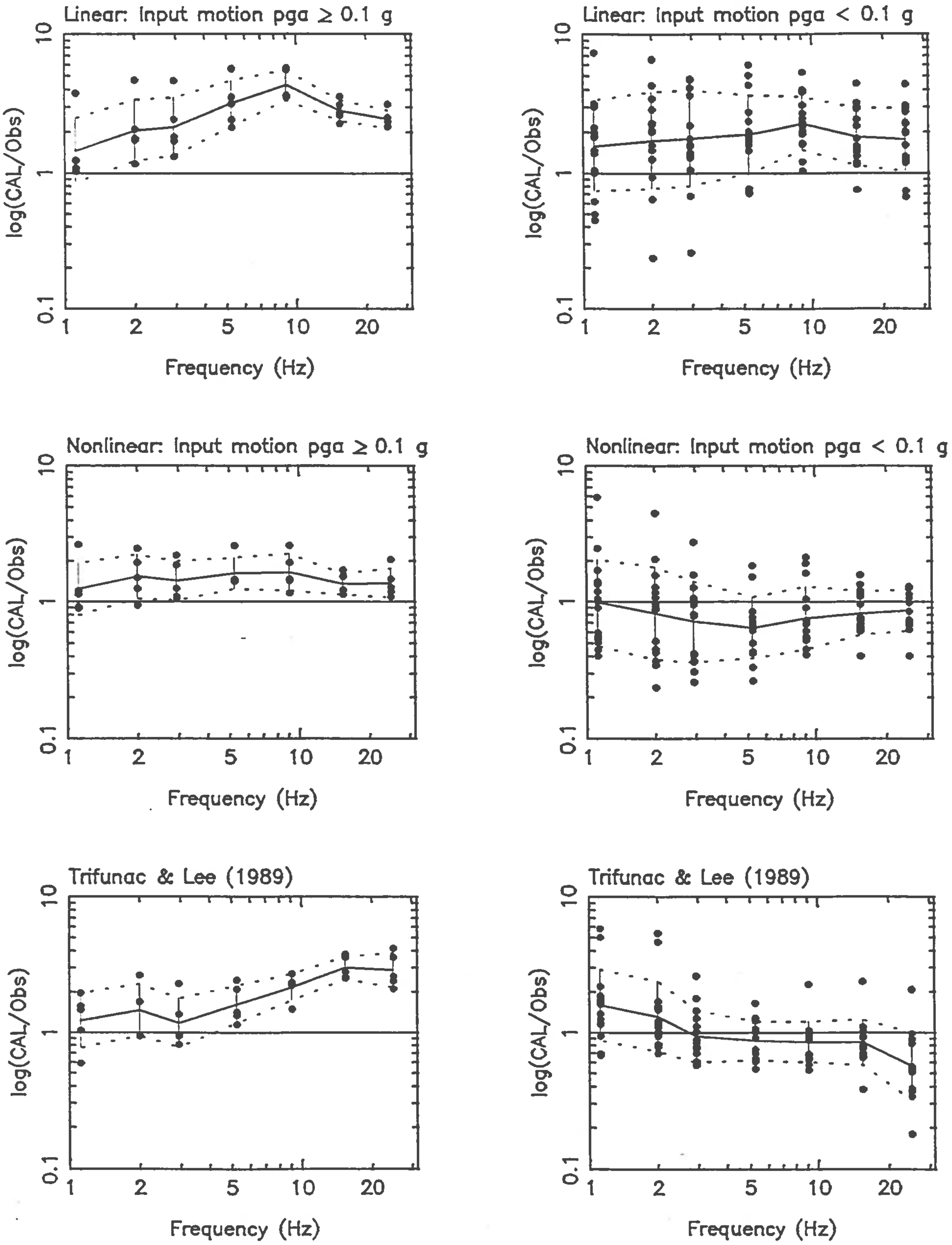

Fig. 2. The response spectral ratio of predicted to the observed as a function of frequency based on our calculation and empirical equation derived from regression analysis for the strong motion data (Trifunac and Lee, 1989). At high basement acceleration level (pga>0.1 g) as shown on the left hand side of the figure, the calculation based on the linear model (for $\alpha=0$), nonlinear model and the Trifunac and Lee's empirical equation are shown at the top, middle and bottom, respectively. The same results shown on the right hand side are for lower basement acceleration level (pga < 0.1 g).

TASK H-4 DURATION OF STRONG MOTION SHAKING IN SOUTHERN CALIFORNIA

CO PI's: TRIFUNAC, LEE AND TODOROVSKA

SUMMARY

The physical bases and empirical equations for modelling the duration of strong earthquake ground motion in terms of the earthquake magnitude, the epicentral distance and the geological and local soil site conditions are investigated. At 12 narrow frequency bands, the duration of a function of motion $f(t)$, where $f(t)$ is acceleration, velocity or displacement, is defined as the sum of time intervals during which the integral $\int_0^t f^2(\tau)d\tau$ gains a significant portion of its final value. All the records are band-pass filtered through 12 narrow filters and the duration of strong ground motion is studied separately in these frequency bands. It is shown that the duration of strong motion can be modeled as a sum of the source duration, the prolongation due to propagation effects and the prolongation due to the presence of the sediments and local soils. It is shown how the influence of the magnitude on the duration of strong ground motion becomes progressively stronger, in going from low to moderate frequencies, and that the duration is longer for "soft" than for "hard" propagation paths, at low and at moderated frequencies. At high frequencies, the nature of the broadening of the strong motion portion of the record with increasing distance is different, and is most likely related to the diffraction and scattering of the short waves by the velocity inhomogeneities along the wave path. It is also shown that the geological and local soil conditions should both be included in the model. The duration can be prolonged by 3.5 sec at the site on a deep sedimentary layer at frequencies near 0.5 Hz, and by as much as $5 \div 6$ sec by the presence of soft soil underneath the station, at frequency of about 1 Hz. Empirical equations for probabilistic estimates of the discrepancies of the predictions by our models relative to the observed data (distribution function of the residuals) are presented.

To date, the following papers have been completed:

Novikova, E.I and M.D. Trifunac (1993). Duration of Strong Ground Motion in Terms of Earthquake Magnitude, Epicentral Distance, Site Conditions and Site Geometry, Earthquake Eng. and Structural Dynamics (in press).

Novikova, E.I. and M.D. Trifunac (1993). The Modified Mercalli Intensity and the Geometry of the Sedimentary Basin as Scaling Parameters of the Frequency Dependent Duration of Strong Ground Motion, Soil Dynamics and Earthquake Eng. (in press).

Novikova and Trifunac (1993). Modified Mercalli Intensity Scaling of the Frequency Dependent Duration of Strong Ground Motion, Soil Dynamics and Earthquake Eng. (in press).

Novikova, E.I. and M.D. Trifunac (1993). Influence of the Geometry of Sedimentary Basins on the Frequency Dependent Duration of Strong Earthquake Ground Motion, Earthquake Eng. and Eng. Vibration (in press).

Novikova, E.I. and M.D. Trifunac (1994). Duration of Earthquake Fault Motion in California, (submitted for publication).

TASK H-5: GEOTECHNICAL SITE DATA BASE FOR SOUTHERN CALIFORNIA

by
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During the first 1.5 years of this three-year project the following tasks have been achieved: (i) the geotechnical parameters related to earthquake damages that are most relevant for mapping were selected, (ii) suitable computer hardware and GIS software were acquired and installed, (iii) basic and advanced seminar training with the selected GIS geotechnical software "Techbase" was taken, (iv) digitized maps comprising base layers of GIS (coastline, highway and freeway system, earthquake faults, etc.) have been acquired and transformed into a desired format, (v) the collection of relevant geotechnical and geological data, their organization and evaluation has started and continues, and (vi) the digitization of relevant geotechnical and geological data has started.

During the last several months the following progress has been made:

(i) Learning of more advanced "Techbase" tasks and computer data manipulations continues with help from "Minesoft" company, which is the author of "Techbase"
Manipulations with large data bases and utilization of their relations have been studied. The most efficient ways to generate boring logs and associated data are explored. The boring logs can now be plotted automatically using data organized in various "Techbase" fields and tables.

(ii) The boring log format has been generated
The selected boring log format is given in appendix along with the legend of symbols and terms used. There will be two boring log forms, one in *SI* units and the other in *British* units. The transformation between the two forms will be automatic. There will be one boring log for each location on the map, regardless of the data available. This means that not all of the information will be included in all boring log forms. The information included in the boring logs in digitized form will be subsequently manipulated to obtain different GIS maps.

(iii) Organization and digitization of data
The soil properties data, shear wave velocity distribution data and Standard Penetration Test results are being digitized, as specified in the boring log form. Undergraduate students are also being trained to help with this task. To date, approximately 40 boring logs have been digitized. The rest of the second year will be spent mainly on further digitization.

BORING LOG PATTERN AND SOIL TYPE

▨	GRAVEL	GR
▨	SAND	SA
▨	SILT	SI
▨	CLAY	CY
▨	SANDY CLAY OR CLAYEY SAND	SA.CY CY.SA
▨	SANDY SILT OR SILTY SAND	SA.SI SI.SA
▨	SILTY CLAY	SI.CY
▨	CLAYEY SILT	CY.SI
▨	PEAT/ORGANIC MATTER	PO
▨	FILL MATERIAL	FM
▨	IGNEOUS ROCK	IR
▨	SEDIMENTARY ROCK	SR
▨	METAMORPHIC ROCK	MR

UNIFIED CLASS. SYMBOL

ACCORDING TO UNIFIED SOIL CLASSIFICATION

PLASTICITY DESCRIPTIVE

NON LOW MEDIUM HIGH

ACCORDING TO FIELD IDENTIFICATION, VISUAL INSPECTION OR LABORATORY CLASSIFICATION

PLASTICITY INDEX (PI)

PI = LIQUID LIMIT – PLASTIC LIMIT

SILT CONTENT

% OF FINES PASSING THROUGH STANDARD SIEVE NO.200 WITH OPENINGS 0.075 mm

STIFFNESS OR DENSITY

ACCORDING TO THE STANDARD PENETRATION TEST

PENETRATION INDEX (BLOWS/FT)	GRANULAR	COHESIVE
0–4	VERY LOOSE	VERY SOFT
5–9	LOOSE	SOFT
10–19	SLT COMPACT	STIFF
20–34	COMPACT	VERY STIFF
35–69	DENSE	HARD
>70	VERY DENSE	VERY HARD

NOTE: SLT COMPACT = SLIGHTLY COMPACT

MOISTURE DESCRIPTIVE

DRY

SLT MOIST

MOIST

WET

ACCORDING TO FIELD VISUAL INSPECTION

NOTE: SLT MOIST = SLIGHTLY MOIST

SPT BLOWS PER FOOT

THE SPT VALUES ARE UNCORRECTED

SCEC GEOTECHNICAL DATA BASE BY UCLA–USC

PREPARED BY: MACAN DOROUDIAN
DATE: 10/05/93

EASTING: 1981787.19
NORTHING: 530001.68
LONGITUDE: −118.1966
LATITUDE: 33.7703

ELEVATION: 7.3 (m)
DEPTH TO GW: 25.0 (m)

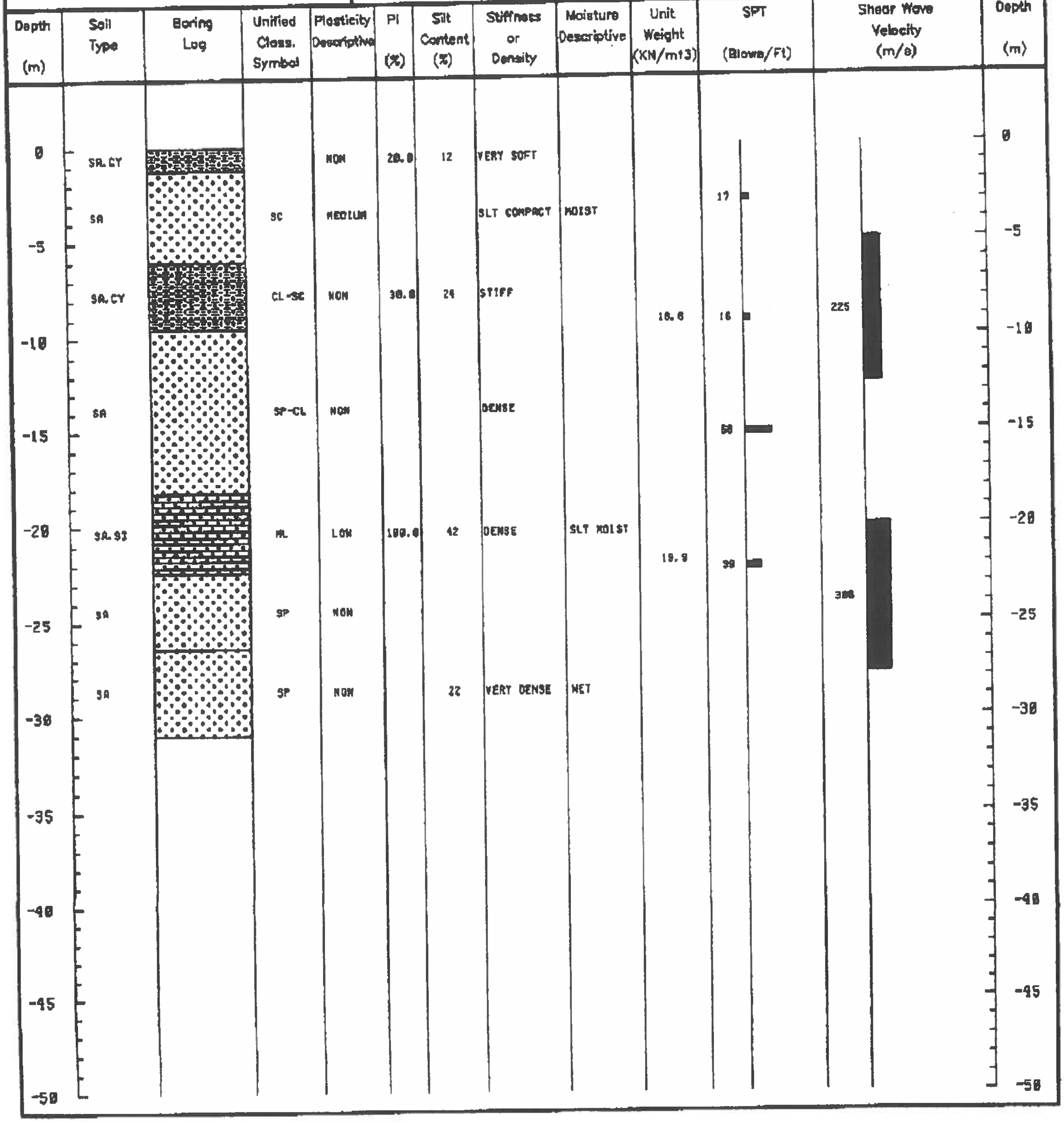
HOLE ID: usgs−1

SOURCE: usgs

LOCATION: LONG BEACH,CA (MAGNOLIA)

DATE: 3/20−22/78

COMMENTS:



Depth (m)	Soil Type	Unified Class. Symbol	Plasticity Descriptive	PI (%)	Silt Content (%)	Stiffness or Density	Moisture Descriptive	Unit Weight (KN/m†3)	SPT (Blows/Ft)	Shear Wave Velocity (m/s)
	SA.CY		NON	20.0	12	VERY SOFT				
									17	
	SA	SC	MEDIUM			SLT COMPACT	MOIST			
	SA.CY	CL-SC	NON	30.0	24	STIFF				
										225
								16.6	16	
	SA	SP-CL	NON			DENSE				
									50	
	SA.93	ML	LOW	100.0	42	DENSE	SLT MOIST			
								19.9	30	
										300
	SA	SP	NON							
	SA	SP	NON		22	VERY DENSE	WET			

TASK H-8: Liquefaction Characteristics and Liquefaction Potential of Southern California

PI: Geoffrey Martin
University of Southern California

Past earthquake induced liquefaction of saturated cohesionless soils has resulted in major damage to man-made structures and facilities. Maps showing areas of liquefaction potential have been produced, and are used by authorities to both prepare for and help mitigate any possible damage. The objective of this new research task is to reassess and improve the Southern Californian database used to develop liquefaction potential maps, and develop a more quantative approach for assessment of post liquefaction ground deformation potential, suitable for mapping.

A review of the literature concerning methods of evaluating potential liquefaction induced ground displacements has been carried out in the last few months. Although this work is of prime importance for assessing potential damage, and thus determining for development and planning purposes the amount of ground remedial work necessary, relatively little research has been carried out in this area to date. One of the objectives of this task is to improve on the current methods, which are mainly empirically based.

Compiling, manipulation and mapping of data is being performed using "Techbase", a GIS software package from MINEsoft Ltd, with special geotechnical capabilities. A Sun SPARC 10 workstation capable of storing and manipulating the large amount of data needed for this project has been purchased, along with a HP color inkjet plotter for use in producing high quality 24" x 36" maps. Delivery of a GTCO 24' x 36" digitizer is expected within the next few days. This will be used to transform geological, lifeline, and other surface map data to digital form, suitable for use in future analysis and presentation.

Work to be carried out in the near future includes digitizing data from available maps, transfering into the database raw data and previously digitized data from various sources, including USGS, CDMG, and LA County. This data will later be manipulated in order to develop liquefaction potential maps and approaches for assessment of post liquefaction ground deformation potential. A long term goal is to transfer Techbase data to the Arc Info database at UC Riverside. Development of the overall database will be coordinated with the geotechnical database being compiled as part of TASK H-5.

Banning segment, from which the second largest cluster was removed, has continued at a rate higher than recorded before Landers.

Seismicity Rate

In Figure 3 we show the number of events per day and the cumulative rate along the five segments of the San Andreas fault from October 1991 until September 1993. Quantitative statistical evaluation of changes in the seismicity rate is difficult because the background rate is low and because of contamination with aftershocks. Because of the low background rate, many years can be needed to detect any significant statistical changes. The known temporal decay of Joshua Tree and Landers - Big Bear aftershocks near the fault makes it difficult to discriminate any changes in the non-aftershock seismicity of the San Andreas fault. To reduce the effect of the aftershocks, the two largest spatial clusters in the Palm Springs and Banning segments, both on the north side of the San Andreas fault were removed (Figure 2). Variations in the rates of seismicity were evaluated with the ß-statistics of Reasenberg and Matthews [1988].

The seismicity rate in all five segments changed at the time of the Landers earthquake, but in only two cases were the changes significant above the 90% confidence level. Quickly decaying aftershocks are evident in the Banning and Palm Springs segments even though the largest clusters of aftershocks were removed from the catalog. After the first few weeks, the rate of seismicity in the Palm Springs region decreased to a level below that recorded before Joshua Tree. Comparing the spatial distribution of the seismicity before and after the Landers earthquake, this decrease appears to be real, and not caused by removing too many earthquakes as Landers aftershocks. In the Banning region, after the decay of the first few weeks of aftershocks, the seismicity rate became constant at a higher rate. Much of the new seismicity was located south of the trace of the San Andreas fault although spatially distinct aftershocks were confined to the north of the main fault. Again the change is not statistically significantly.

The three segments of the San Andreas fault that did not abut the aftershock zone also showed changes in seismicity rate. No earthquakes were recorded in the Mojave segment from June 28 until mid September 1992 when the seismicity resumed but still at an anomalously low rate. Because of the low rate of seismicity, this variation is not significant at the 90% confidence level. The rates of seismicity in the San Bernardino and Coachella segments increase significantly, both above the 90% confidence level. Most of the earthquakes after Landers in the San Bernardino segment are located south of the San Andreas fault, spatially separate from any aftershocks. The increase in Coachella is seen throughout the segment but is most pronounced at its northern end, near Indio. Neither region shows a pronounced decay in the rate with time after Landers.

CONCLUSION

The seismicity along the southern San Andreas fault changed because of the June 28, 1992, M_W7.3 Landers earthquake. As predicted by three different stress model calculations, the seismicity rate temporarily decreased along the Mojave and Palm Spring segments. Along the Banning segment that is located closest to the Landers sequence, the seismicity rate increased and the spatial distribution of seismicity as well as the dominant type of focal mechanisms all changed. The seismicity rate increased along the San Bernardino and Coachella segments as predicted by the stress models. The seismicity rate thus seems to be a sensitive indicator of small stress changes associated with major earthquakes occurring near the southern San Andreas fault.

PUBLICATIONS

H. X. Qian, E. Hauksson, and L. M Jones, The Effect of the 1992 M_W7.3 Landers Earthquake on the Southern San Andreas Fault, to be *submitted to Geophys. Res. Letters.*

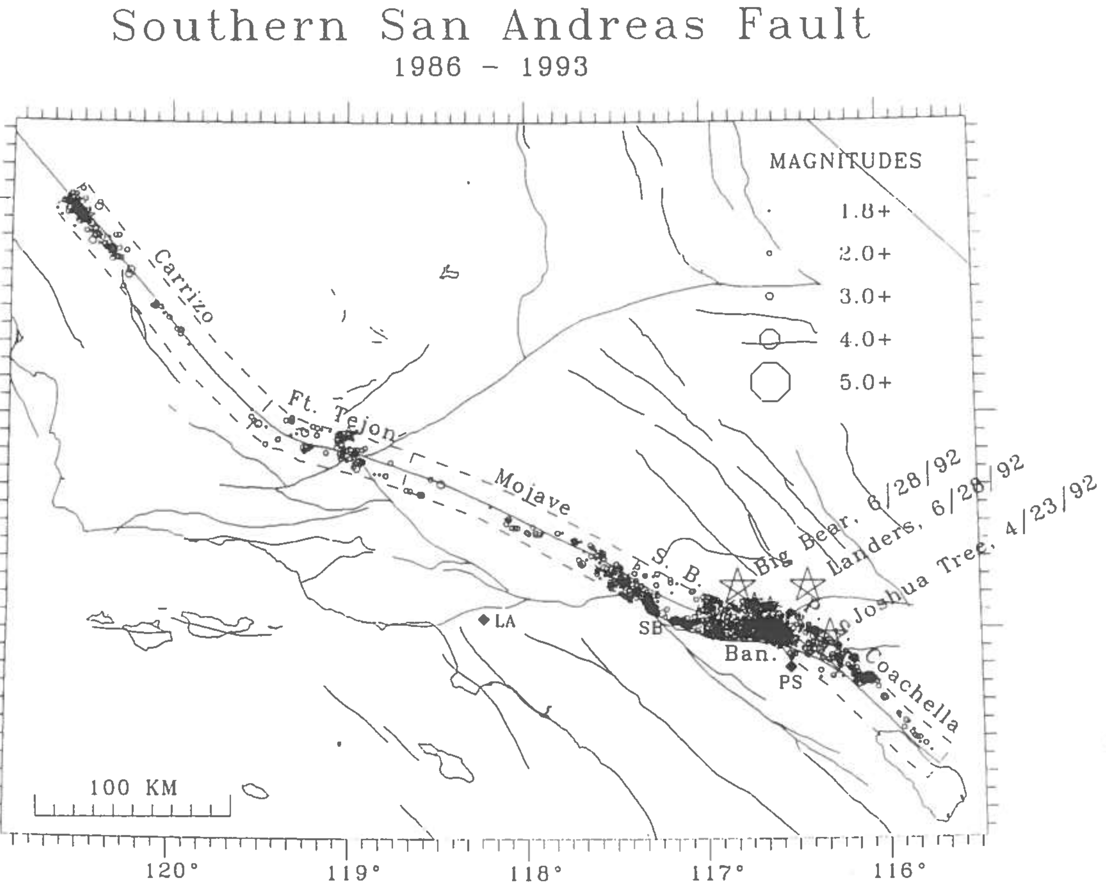


Fig. 1 Map of the southern San Andreas fault in southern California showing the M≥ 1.8 seismicity 1986-1993. Major faults are shown as solid lines or dashed where inferred [*Jennings*, 1975]. The dashed boxes around the San Andreas fault indicate the study region. The fault is divided into seven segments [Jones, 1988], from northwest to southeast: Carrizo, Fort Tejon, Mojave, San Bernardino, Banning, Palm Springs, and Coachella. The stars indicate the epicenters of the 1992 M_W7.3 Landers, M_W6.2 Big Bear, and M_W6.1 Joshua Tree earthquakes.

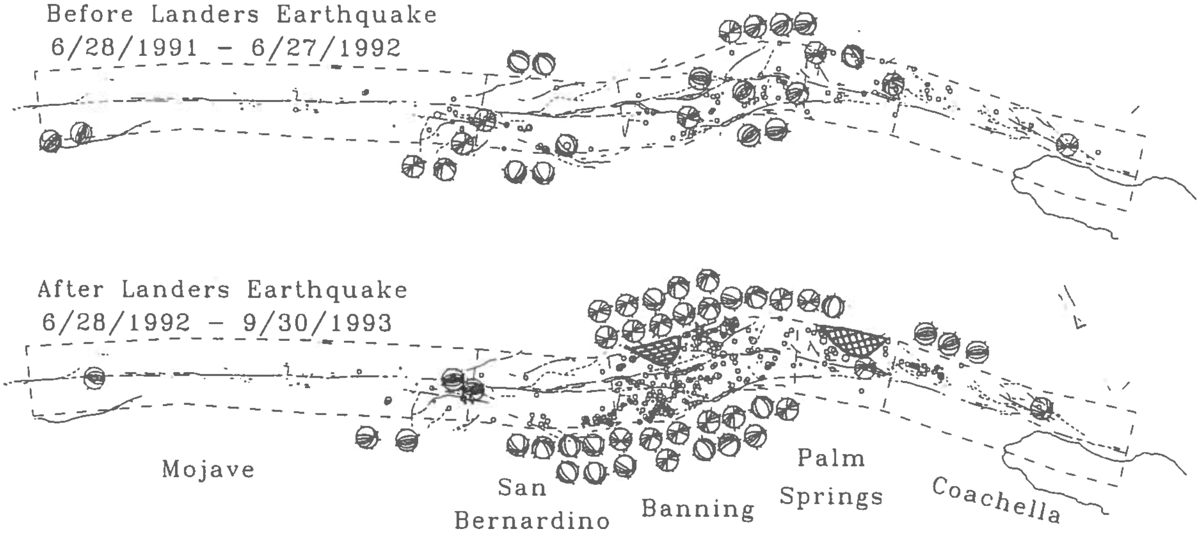


Fig. 2 Spatial distribution of seismicity and typical lower hemisphere focal mechanisms along the southern San Andreas fault one year before and after the Landers earthquake. The seismicity include M≥1.8 events. The focal mechanisms are for M≥2.5 events. The shaded regions indicate the large aftershock clusters of the Landers sequence that are not included in the seismicity rate shown in Figure 3.

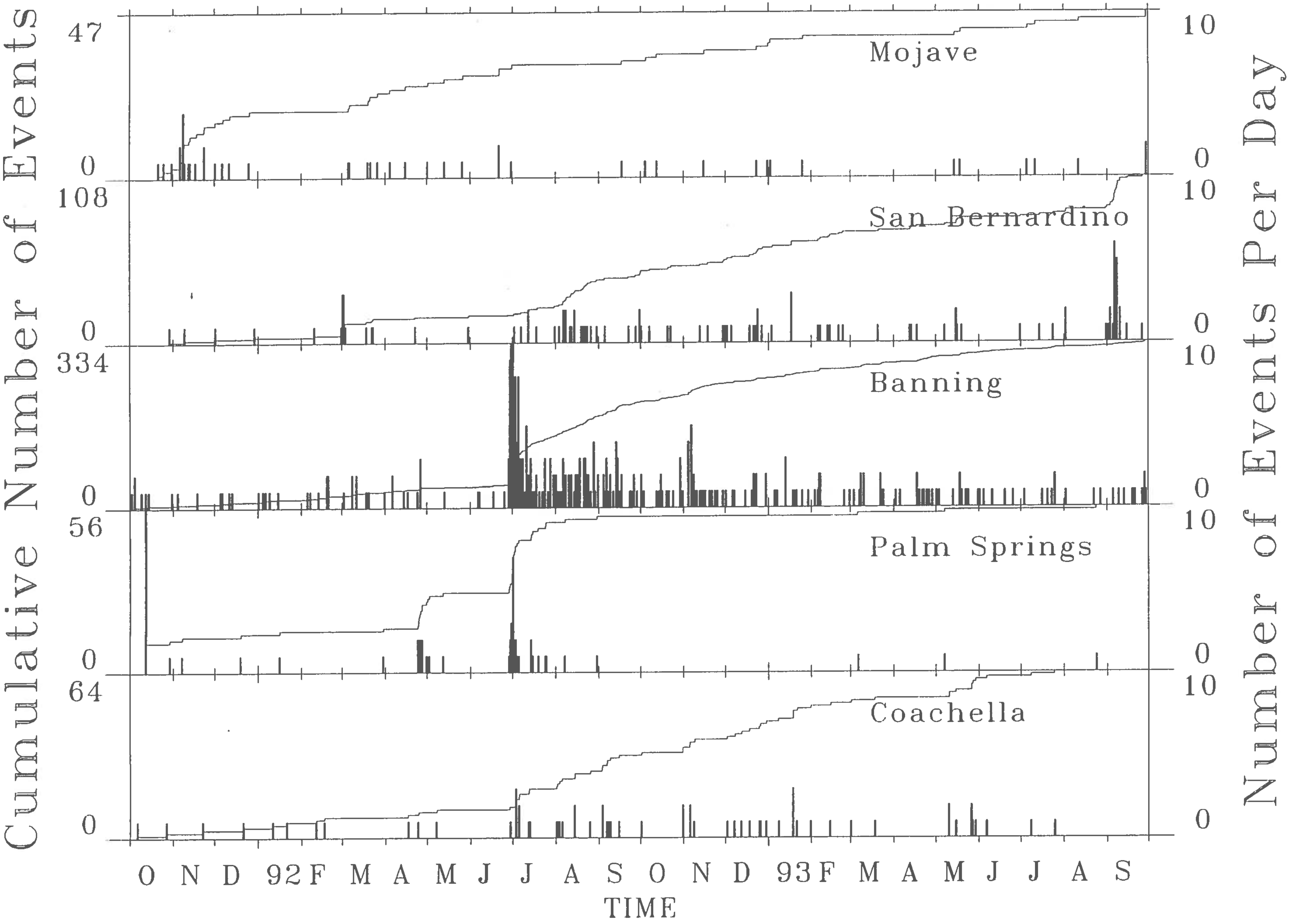


Fig. 3 Number of earthquakes per day and cumulative number of earthquakes along each segment. Events of M>1.8 from October 1, 1991, to September 30, 1993, are included, except the large clusters of aftershocks of the Landers sequence have been removed (see Figure 2).

Fault Dynamics of the Landers Earthquake

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Objective: To obtain the spatial and temporal distribution of the slip occurring during the Landers earthquake by inverting the various data sets.

Results: To date, we have determined a source rupture model for the 1992 Landers earthquake (M_W =7.2) compatible with multiple data sets, spanning a frequency range from zero to 0.5 Hz. Geodetic survey displacements, near-field and regional strong motions, broadband teleseismic waveforms and surface offset measurements have all been used explicitly to constrain both the spatial and temporal slip variations along the model fault surface. Our fault parameterization involves a variable-slip, multiple-segment, finite-fault model which treats the diverse data sets in a self-consistent manner, allowing them to be inverted both independently and in unison. The high-quality data available for the Landers earthquake provide an unprecedented opportunity for direct comparison of rupture models determined from independent data sets that sample both a wide frequency range and a diverse spatial station orientation with respect to the earthquake slip and radiation pattern. In all models, consistent features include: 1) similar overall dislocation patterns and amplitudes with seismic moments of .7-.8 x 10^{27} dyne-cm (seismic potency of 2.3-2.7 km^3), 2) very heterogeneous, unilateral strike-slip distributed over a fault length of 65 km and over a width of at least 15 km, though slip is limited to shallower regions in some areas, 3) a total rupture duration of 24 sec and an average rupture velocity of 2.7 km/sec, and 4) substantial variations of slip with depth relative to measured surface offsets. The extended rupture length and duration of the Landers earthquake also allowed imaging of the propagating rupture front with better resolution than for those of prior shorter-duration, strike-slip events. Our imaging allows visualization of the rupture evolution, including local differences in slip durations and variations in rupture velocity. Rupture velocity decreases markedly at shallow depths as well as near regions of slip transfer from one fault segment to the next as rupture propagates northwestward along the multiply-segmented fault length. The rupture front slows as it reaches the northern limit of the Johnson Valley/Landers faults where slip is transferred to the southern Homestead Valley fault; an abrupt acceleration is apparent following the transfer. This process is repeated, and is more pronounced, as slip is again passed from the northern Homestead Valley fault to the Emerson fault. Although the largest surface offsets were observed at the northern end of the rupture, our modeling indicates that substantial rupture was also relatively shallow (less than 10 km) in this region.

We model the Landers earthquake with a fault model consisting of three linear, vertical fault segments as shown in map view in Figure 1 (hatchured lines) and displayed in cross section. As indicated in these figures, the three segments represent, from south to northwest, the Johnson Valley and Landers faults (strike 355°), the Homestead Valley Fault (strike 334°) and the Emerson and Camp Rock faults (strike 320°).

This segmentation was chosen based on the locations of the surface rupture expression (Sieh *et al.*, 1993) and the aftershock seismicity (Hauksson *et al.*, 1993), both of which are depicted in Figure 1. The three segments generously contain and closely approximate the correct strike of the fault segments which ruptured. Noting that significant seismicity yet little surface slip occurred south of the epicenter (star) we allowed for the possibility of extended rupture into this region as well.

The choice of three segments represents a trade-off between accommodating the obviously complex faulting geometry observed at the surface, and the desire to keep the problem tractable. For example, the straight segment approximation to the complex surface trace and aftershock pattern near strong-motion station LUC (Fig. 1) fits the overall fault trend, but may be inadequate to properly model the higher-frequency aspects of the waveforms recorded there. Fortunately, the complexity of the faulting at depth appears to be less intricate than the surficial offset would lead us to believe (see numerous cross-sections in Hauksson *et al.*, 1993).

We can easily convert our maps of slip in time windows that are moving with the rupture front to a set of maps of the slip velocity as a function of absolute time. Figure 2 depicts the slipping portion of the fault and the amount of slip during 1 sec "slices" in time; hence, the image can be thought of as slip velocity. For each time ``slice", the time duration after rupture initiation is given. Again, the contour interval is 0.5 m.

Several observations are notable. As mentioned above, shallow slip usually lags slightly behind slip at depth, suggesting a slower shallow rupture velocity. And, although the rupture propagates at an average constant velocity of 2.7 km/sec over the length of the rupture (a distance of roughly 60 km in 22 sec), there are indications of significant local variations.

Rupture is slowed and delayed along the Landers fault (time slices 6-9 sec, 12-18 km). Just beyond this point, on the southern Homestead Valley fault, it appears that the rupture almost ended, but in an erratic fashion, began to accelerate across the central Homestead Valley fault and continue onward (time slices 9-12 sec, 22-32 km). It again slowed on the northern Homestead Valley fault (time slices 12-16 sec, 36-40 km) before jumping to the Emerson Fault (time slices 17-19 sec, 44-50 km). Finally, the rupture trickled out on the shallow Emerson and Camp Rock faults (time slices 21-23 sec, 50-60 km). For reference, lines of constant rupture velocity of the leading edge of slip are given for selected regions which exhibit roughly uniform rupture velocities. A slowing of the rupture front as it nears a fault step-over, followed by a acceleration is intuitively appealing as corresponding to a large stress build-up near the step-over and rapid release as the step-over barrier is overcome.

We can also interpret these observations in light of recent finite-difference analyses of the dynamics of fault interactions by Harris and Day (1993). They found that dilational steps (as are the Landers stepovers) delay the rupture, with larger steps causing longer delays. If we consider the decreasing rupture velocity within the stepovers, there are time delays of a few seconds from the time of the arrival of the rupture front at the stepovers and the time rupture continues onward. Though the geometry and aftershock seismicity within the Landers stepovers suggest that they are continuous at depth (Hauksson, 1993), and Harris and Day modeled unconnected fault steps (and specifically caution that their conclusions might change in such a case), these delays are consistent with their general results.

References

Harris, R. A. and S. M. Day (1993). Dynamics of fault interaction: parallel strike-slip faults, *J. Geophys. Res.*, **98,** 4461-4472.

Hauksson, E., L. M. Jones, K. Hutton, and D. Eberhart-Phillips (1993). The 1992 Landers Earthquake sequence: seismological observations, *J. Geophys. Res.,* submitted for publication.

Sieh, K., L. Jones, E. Hauksson, K. Hudnut, D. Eberhart-Phillips, T. Heaton, S. Hough, K. Hutton, H. Kanamori, A. Lilje, S. Lindval, S. F. McGill, J. Mori, C. Rubin, J. A. Spotila, J. Stock, H. Thio, J. Treiman, B. Wernicke, and J. Zachariasen (1993). Near-field investigation of the Landers earthquake sequence, April to July, 1992, *Science*, *260*, 171-176.

Wald, D. J. and T. H. Heaton (1994). Spatial and Temporal Distribution of slip for the 1912 Landers, California Earthquake, submitted to *BSSA*.

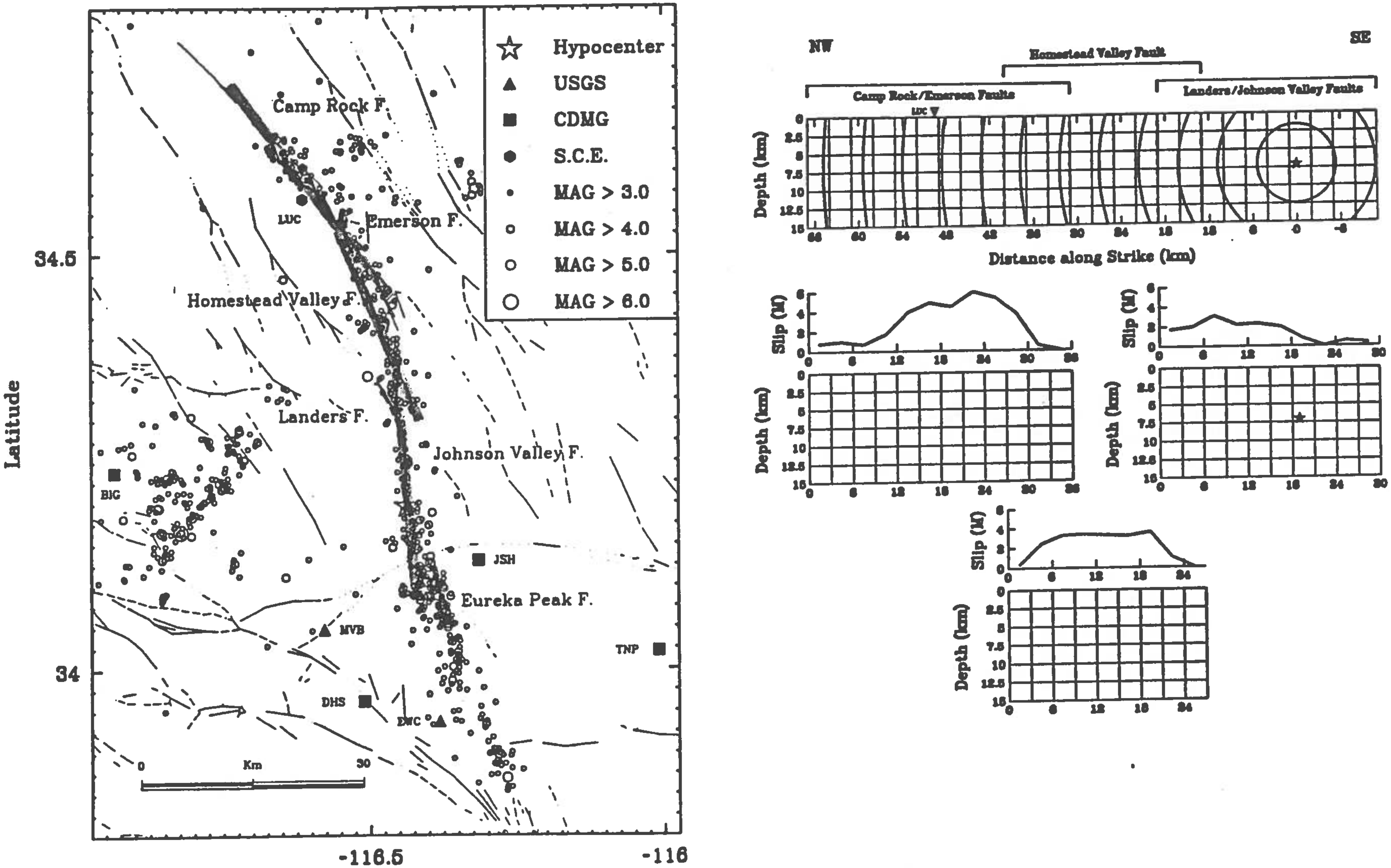


Figure 1. On the left is a map showing the fault surface offset (dark lines) and the surface projection of the three fault segments of the model fault (hatchured lines). Aftershocks are shown as circles with magnitude as given in the legend. Solid symbols mark locations of strong-motion stations. On the right is a fault model cross-section (northwest on left, southeast on right) displaying the subfault discretization of the three model fault planes (bottom 3 faults) which make up the complete Landers fault model (top fault). Presented above each fault segment is the observed surface offset as averaged over each subfault length. The location along strike of station LUC is marked with a triangle and the hypocenter is shown as a star. The circular curves depict the advance of the rupture front at 2 sec intervals for a constant 2.7 km/sec rupture velocity.

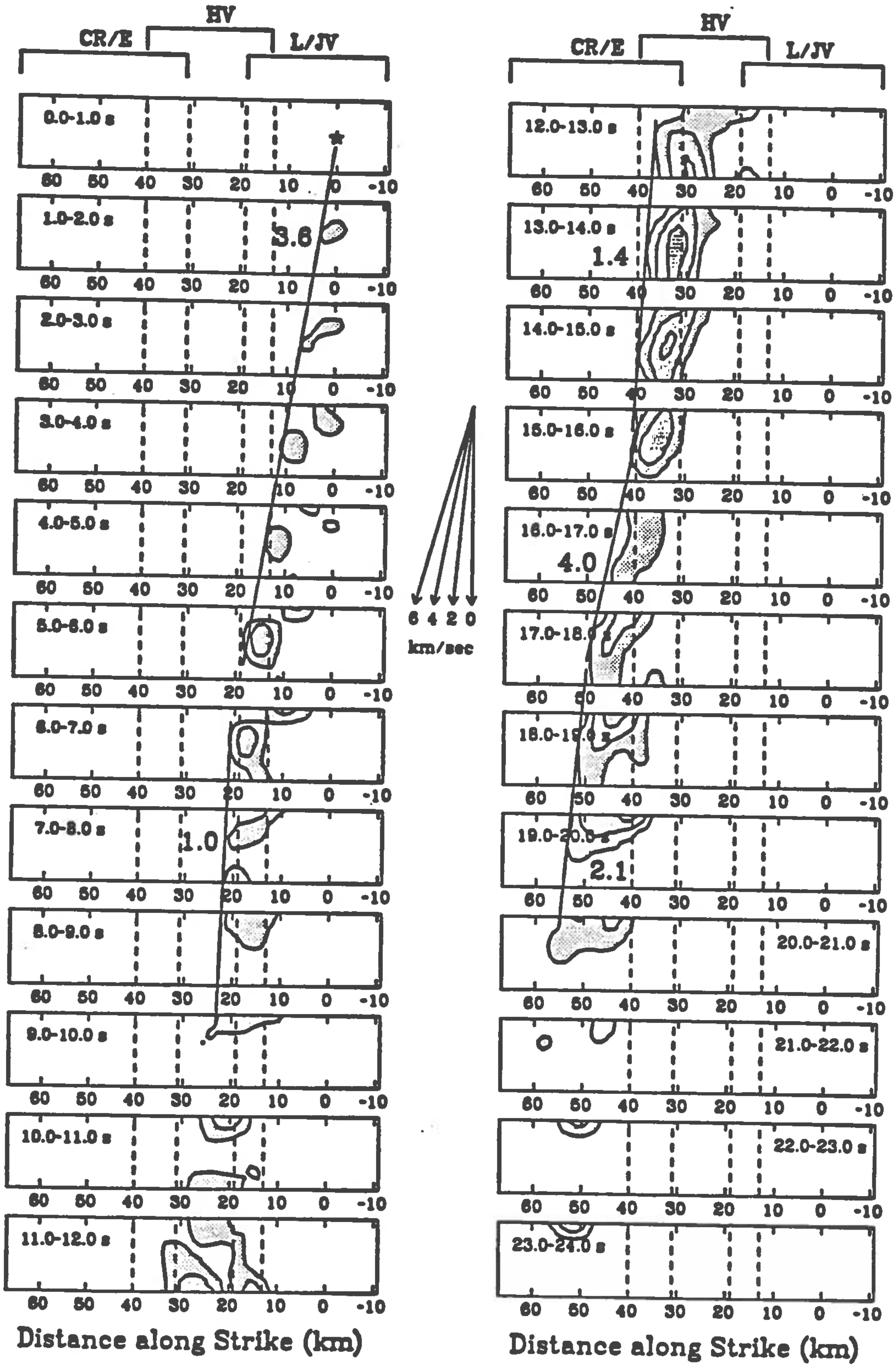


Figure 2. Time progression of the Landers rupture for the combined data model given at intervals of 1 sec as labeled. The contour interval is 0.5 m. For reference, a rupture velocity roset is given with arrows. Lines indicate selected regions of fairly constant rupture velocity. From top to bottom, these lines represent 3.6, 1.0, 1.4, 4.0, and 2.1 km/sec, respectively, as labeled, after Wald and Heaton (1994).

Scaling Law of Aftershock Spectra of Joshua Tree-Landers-Big Bear Earthquakes

Anshu Jin and Kei Aki
University of Southern California
Task 3, Group F
(progress report)

Our subject of study is the relationship between fault zone structure and the seismic spectra generated by earthquakes on the fault. From a rupture mechanics point of view, a fault zone governed by a friction law with given parameters such as the break-down zone size and the magnitude of critical weakening slip should result in a scaling law of seismic spectrum which deviates from the self-similarity. In order to detect such departure from self-similarity we study the relationship between seismic moment and corner frequency for aftershocks of Joshua Tree, Landers, and Big Bear earthquakes. Our study is still on-going and the following is a progress report.

An observed seismic spectrum is a function of source, path, and receiver site. The simplest way of eliminating the path and receiver effects is to take spectral ratio between two earthquakes sharing a common path and receiver. The Joshua Tree-Landers-Big Bear earthquakes created a huge number of aftershocks which offers a unprecedented opportunity to find aftershock pairs which share a common path approximately and the similar source radiation factor judged from the first P arrival waveform on 3 component records).

Joshua Tree aftershocks recorded at Terrascope stations.

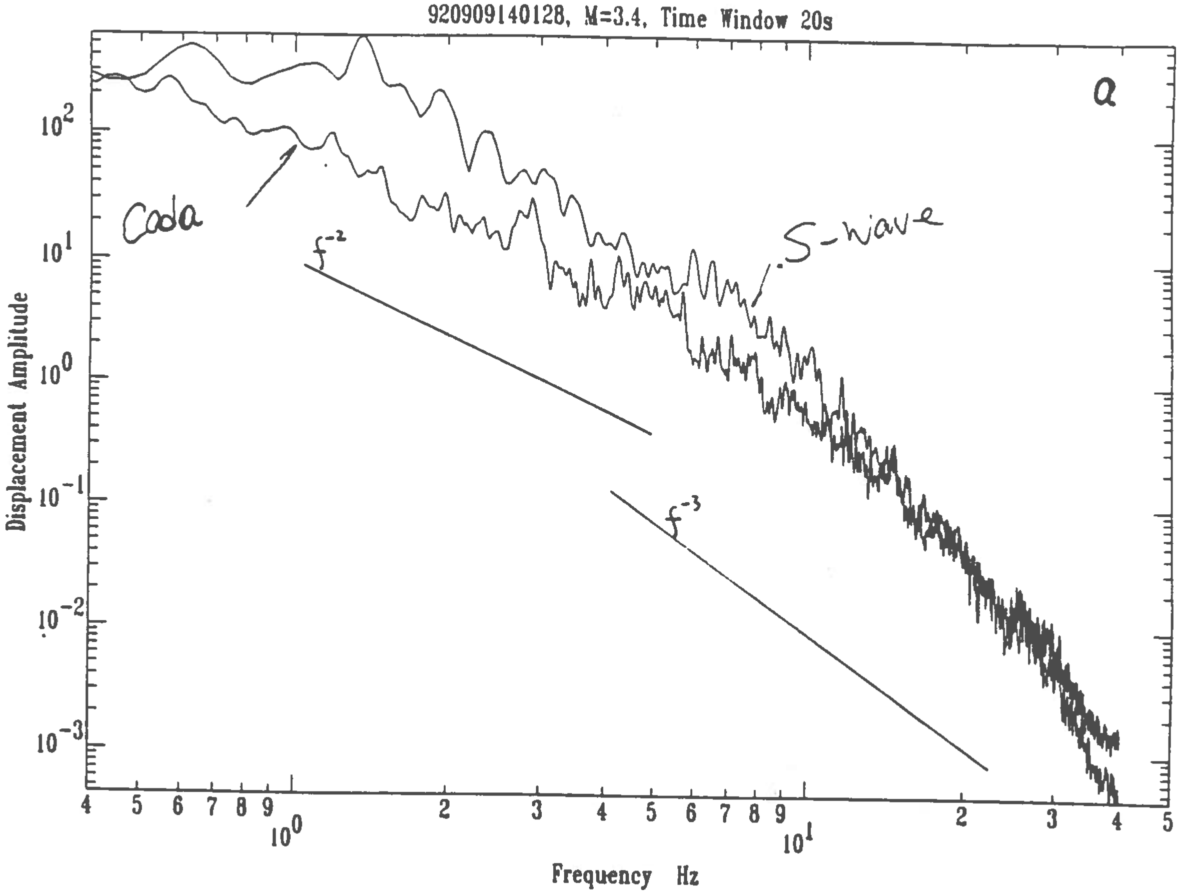
Spectral property Figure 1a shows an example of the S-wave and coda spectra for a M=3.4 event averaged over available Terrascope stations. Since according to Jin et al.(1993), total seismic attenuation, Q_t, in southern California is nearly proportional to frequency, we use$Q=Q_0f$ to correct for attenuation. As shown in Figure 1a, we found that beyond the corner frequency the earlier portion of the spectrum obeys f^{-2} model until about 6 Hz, then turn to decay faster with the frequency dependence of f^{-3}.

Estimation of corner frequencies by spectral ratio If we assume similarity between large and small earthquakes, the spectral ratio between earthquake 1 and 2 sharing the same path, receiver, and source radiation factor will tend to be flat when $\omega<\omega_{10}$, and $\omega>\omega_{20}$, where ω_{10} and ω_{20} are the corner frequencies for events 1 and 2, respectively and $\omega_{10}<\omega_{20}$. Then, the corner frequencies of events 1 and 2 can be determined from the two turning frequencies of spectral ratio curve. Figure 1b shows an example of the observed spectral ratio for a Joshua Tree-aftershock pair with magnitudes 5.3 and 3.8.

During September to November, 1992, we found four Joshua Tree aftershocks with magnitude M>4.5 which can be used as the reference earthquakes, and selected smaller aftershocks to form doublets by the use of relative P times in the following way. Putting the P travel time of event 1 at station i as t_{1i}, and that of event 2 as t_{2i}, then calculate the mean of the difference $|t_{2i}-t_{1i}|$, $\Delta t = \frac{1}{N}\sum_{1}^{N} |t_{2i}-t_{1i}|$. The aftershock pairs with $\Delta t \leq 0.2$s were selected as a doublet which share a common path approximately.

Spectral ratio for each doublet was calculated at each station, then averaged over stations. First ,we read the corner frequency, fc_i^j, from station-averaged spectral ratio, visually, for event i of doublet j as shown in Figure 1b. If event i is involved in m doublets, we determine corner frequency by $fc_i = \frac{1}{m}\sum_{j=1}^{m} fc_i^j$. Totally 33 corner frequencies were estimated for aftershocks with magnitude range 2.7 to 5.3. Figure 2 is a plot of fc vs. M_0, where M_0 is the seismic moment calculated from M_L using $\log M_0 = 1.5M_L + 16.0$ (Thatcher and Hanks,1973). Interestingly, all points with $M_0 > 10^{21}$(M_L~3.5) fall above the Hanks'(1974) empirical curve, and most points with $M_0 < 10^{21}$ fall under that curve. To further substantiate this behavior of the f_c vs. M_0 relation, we need more smaller aftershocks with magnitude down to about 1. Currently we are trying to get the smaller earthquake data from both the IRIS continuously recording Terrascope seismograms for and the REFTEKs records collected by Li et al at USC. Another uncertainty is regarding the estimation of seismic moment, we shall use coda spectra at low frequencies tin stead of M_L.

The same procedure is currently being applied to Landers and Big Bear aftershocks.


920909140128, M=3.4, Time Window 20s
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Coda
S-wave
f^{-2}
f^{-3}
Displacement Amplitude
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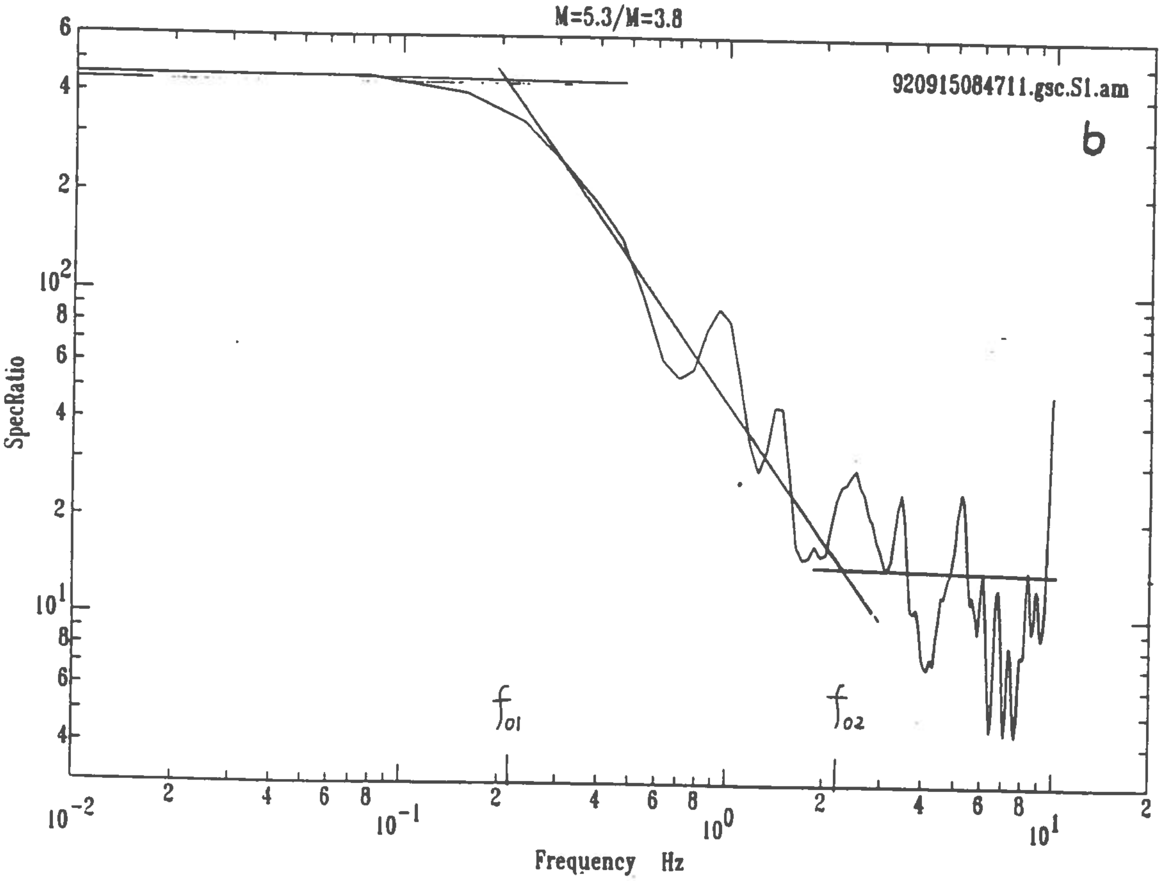
Frequency Hz


M=5.3/M=3.8
920915084711.gsc.S1.am
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SpecRatio
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Frequency Hz

Figure 1

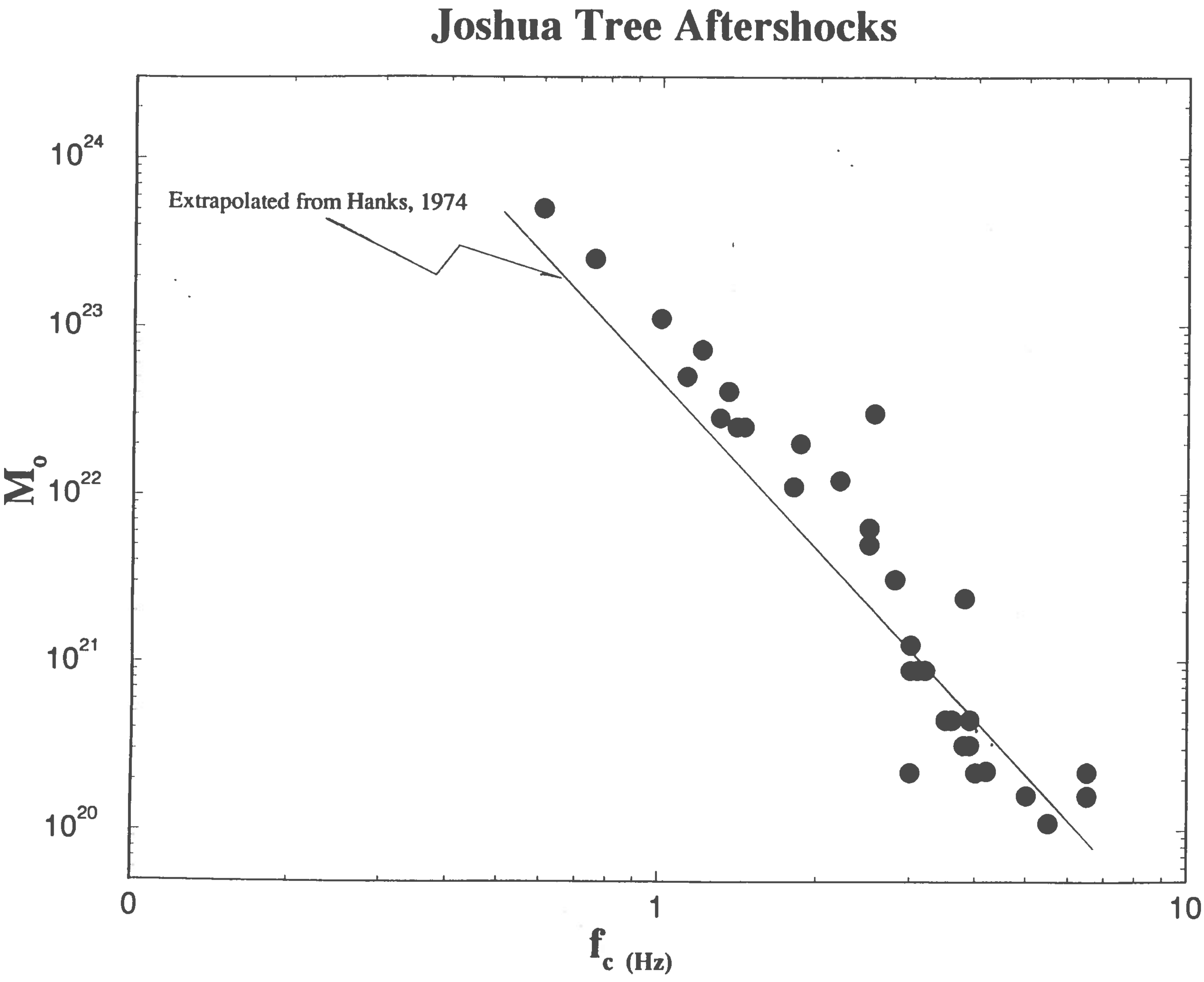
Joshua Tree Aftershocks
Extrapolated from Hanks, 1974
M_o
10^{24}
10^{23}
10^{22}
10^{21}
10^{20}
0
1
10
f_c (Hz)

Figure 2

SCEC Project: Progress Report, 01 Dec. 1993

PI	Egill Hauksson
Institution:	California Institute of Technology
Title :	**Precise Locations and Mechanisms of Aftershocks and Stress State of the 1992 M_w6.1 Joshua Tree, M_w7.3 Landers, and M_w6.2 Big Bear Earthquakes**

INVESTIGATIONS

The (M_w6.1, 7.3, 6.2) 1992 Landers earthquakes that began on 23 April with the M6.1 1992 Joshua Tree preshock are the most substantial earthquake sequence to occur in the last 40 years in California. We have synthesized aftershock data from this sequence recorded by the SCSN to provide a detailed three-dimensional picture of the deformation. The results appear in two papers, one is published in JGR while the other is submitted to BSSA special volume on the Landers earthquake.

RESULTS

The 1992 Landers Earthquake Sequence: Seismological Observations

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The (M_W6.1, 7.3, 6.2) 1992 Landers earthquakes began on April 23 with the M_W6.1 1992 Joshua Tree preshock and form the most substantial earthquake sequence to occur in California in the last 40 years. This sequence ruptured almost 100 km of both surficial and concealed faults and caused aftershocks over an area 100 km wide by 180 km long (Figure 1). The faulting was predominantly strike slip and three main events in the sequence had unilateral rupture to the north away from the San Andreas fault. The M_W6.1 Joshua Tree preshock at 33°N58' and 116°W19' on 0451 UT April 23 was preceded by a tightly clustered foreshock sequence ($M \leq 4.6$) beginning 2 hours before the mainshock and followed by a large aftershock sequence with more than 6000 aftershocks. The aftershocks extended along a northerly trend from about 10 km north of the San Andreas fault, northwest of Indio, to the east-striking Pinto Mountain fault. The M_W7.3 Landers mainshock occurred at 34°N13' and 116°W26' at 1158 UT, June 28, 1992, and was preceded for 12 hours by 25 small $M \leq 3$ earthquakes at the mainshock epicenter. The distribution of more than 20,000 aftershocks, analyzed in this study, and short-period focal mechanisms illuminate a complex sequence of faulting. The aftershocks extend 60 km to the north of the mainshock epicenter along a system of at least five different surficial faults, and 40 km to the south, crossing the Pinto Mountain fault through the Joshua Tree aftershock zone towards the San Andreas fault near Indio. The rupture initiated in the depth range of 3-6 km, similar to previous M~5 earthquakes in the region, although the maximum depth of aftershocks is about 15 km. The mainshock focal mechanism showed right-lateral strike-slip faulting with a strike of N10°W on an almost vertical fault. The rupture formed an arclike zone well defined by both surficial faulting and aftershocks, with more westerly faulting to the north. This change in strike is accomplished by jumping across dilational jogs connecting surficial faults with strikes rotated progressively to the west. A 20-km-long linear cluster of aftershocks occurred 10-20 km north of Barstow, or 30-40 km north of the end of the mainshock rupture. The most prominent off-fault aftershock cluster occurred 30 km to the west of the Landers mainshock. The largest aftershock was within this cluster, the M_W6.2 Big Bear aftershock occurring at 34°N10' and 116°W49' at 1505 UT June 28. It exhibited left-lateral strike-slip faulting on a northeast striking and steeply dipping plane. The Big Bear aftershocks form a linear trend extending 20 km to the northeast with a scattered distribution to the north. The Landers mainshock occurred near the southernmost extent of the Eastern California Shear Zone, an 80-km-wide, more than 400-km-long zone of deformation. This zone extends into the Death Valley region and accommodates about 10 to 20% of the plate motion between the Pacific and North American plates. The Joshua Tree preshock, its aftershocks, and Landers aftershocks form a previously missing link that connects the Eastern California Shear Zone to the southern San Andreas fault.

State of Stress From Focal Mechanisms Before and After the 1992 Landers Earthquake Sequence

12 Aug. 1993, Submit. to BSSA, Special issue on the 1992 Landers earthquake

The state of stress in the Eastern California Shear Zone (ECSZ) changed significantly because of the occurrence of the M_W6.1 1992 Joshua Tree and the M_W7.3 Landers earthquakes. To quantify this change, focal mechanisms data from the 1975 Galway Lake sequence, the 1979 Homestead Valley sequence, background seismicity 1981-1991, and the 1992 Landers sequence are inverted for the state of stress. In all cases the intermediate principal stress axis (S_2) remained vertical and changes in the state of stress consisted of variations in the trend of maximum and minimum principal stress axis (S_1 and S_3) and small variations in the value of the relative stress magnitudes (ø). In general the stress state in the ECSZ has S_1 trending east of north and ø=0.4-0.6 suggesting that the ECSZ is a moderate stress refractor and the style of faulting is transtensional (Figure 2).

South of the Pinto Mountain fault, in the region of the 1992 Joshua Tree earthquake, the stress state determined from the 1981-1991 background seismicity changed on 23 April and 28 June 1992. In the central zone the S_1 trend rotated from N14°±5°W to N28±5°W on 23 April and back again to N16°±5°W on 28 June. Thus the Landers mainshock in effect recharged some of the shear stress in the region of the M_W6.1 Joshua Tree earthquake.

Comparison of the state of stress before and after 28 June 1992 along the Landers mainshock rupture zone showed that the mainshock changed the stress. The S_1 trend rotated 7°-20° clockwise and became progressively more fault-normal from south to north. Along the Emerson-Camp Rock faults the change was so prominent that the focal mechanisms of aftershocks could not be fit by a single deviatoric stress tensor. The complex P and T axes distribution suggests that most of the uniform component of the applied shear stress along the northern part of the rupture zone may have been released in the mainshock.

The San Bernardino Mountains region of the M_W6.2 Big Bear earthquake has a distinctively different state of stress, as compared to the Landers region, with S_1 trending N3°±5°W. This region did not show any significant change in the state of stress following the 1992 M_W6.2 Big Bear sequence.

PUBLICATIONS

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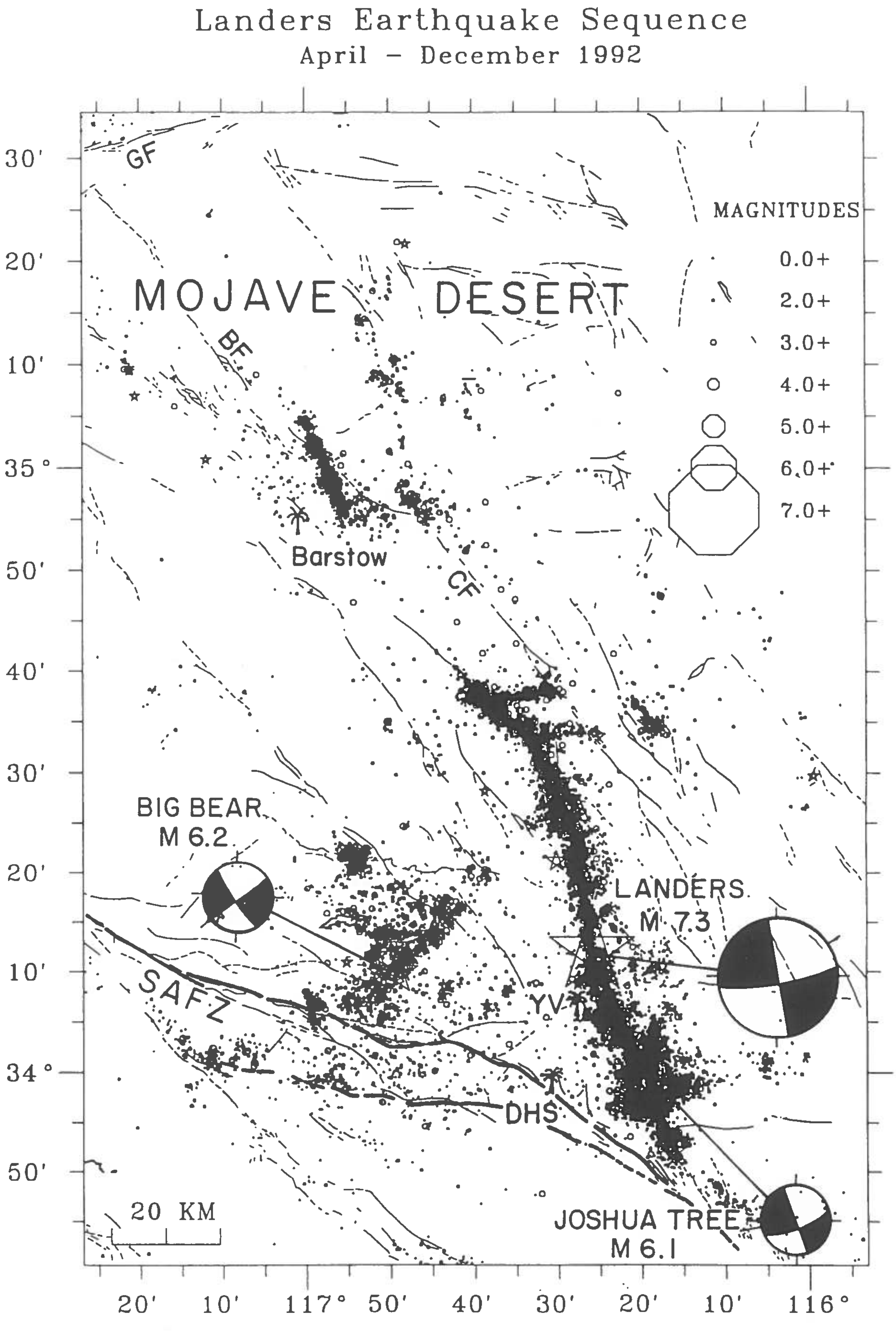
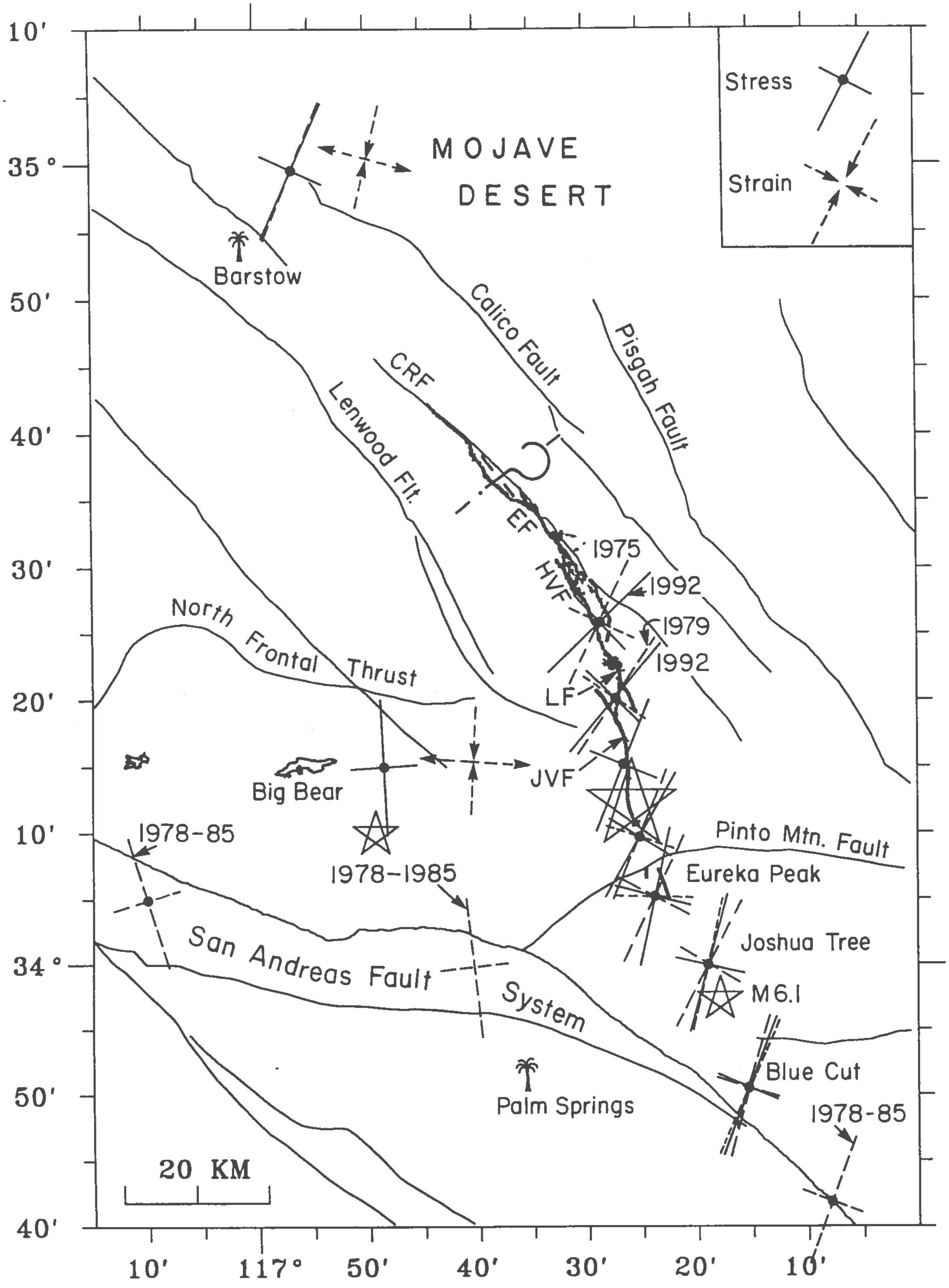


Fig. 1 Landers aftershock region showing all earthquakes recorded by the SCSN from April to December 1992, and major faults (dotted if inferred) from *Jennings* [1975]. Lower-hemisphere, first-motion focal mechanisms, compressional quadrant shaded, of the three main earthquakes are also shown. BF, Blackwater fault, CF, Calico fault, YV, Yucca Valley, GF, Garlock fault, SAFZ, San Andreas fault zone, and DHS, Desert Hot Springs. Earthquakes of $M \geq 4.0$ are shown by stars.



Eastern California Shear Zone

Stress State

Figure 2. Summary of the S_1 trends in the eastern California shear zone and along the San Andreas fault zone. The S_1 trends labeled 1978-85 are from Jones (1988). The stars indicate the epicenters of the M_w6.1 Joshua Tree, M_w7.3 Landers, and the M_w6.2 Big Bear earthquakes. The geodetic strain data are from Savage *et al.,* (1990). CRF-Camp Rock fault. The different S_1 trends are labeled with the respective year (see also Table 1). The question mark across Emerson Camp Rock faults indicates that the deviatoric stress tensor could not be determined using the method of Michael (1984). In the Joshua Tree area each set of three S_1 trends are shown as 1981-1991 data (short dashes), 23 April to 27 June 1992 (long dashes), and 28 June to 31 December 1992 solid lines.

Anomalous Low Frequency Signals from Local Earthquakes

Principal Investigators:
Steve Day and Harold Magistrale, SDSU
Frank Vernon, UCSD

A collaborative study to record aftershocks was undertaken by several institutions following the June 28 Landers and Big Bear earthquakes. The M7.6 Landers earthquake occurred at 04:58 PDT approximately 6 miles north of Yucca Valley along the southern extension of the Johnson Valley fault. The earthquake produced over 70 km of ground rupture, with cumulative right-lateral offsets of 3 to 6.5 m along segments of the Homestead Valley, Emerson Lake, and Camp Rock faults, all of which were involved in the sequence. The primary aftershock activity occurred in a narrow band from 33.6N, -116.2W north to 34.5N, -116.6W, with a separate cluster at 35.0N, -117.0W. The M6.5 Big Bear earthquake occurred at 08:04 PDT approximately 35 km west of the Landers epicenter in the San Bernadino Mountains, involving left-lateral slip on a fault that strikes N45°W and dips 70°SE. The Big Bear aftershocks occur over an area of about 30 km long, extending northeast from 34.1N, -117.0W to 34.4N, -116.6W.

Inspection of the recordings collected by the portable instruments by personnel at UCSD and SDSU revealed approximately 40 recordings with a long period wavetrain following the S wave arrival, which we interpret as a Raleigh wave (R_g). The dispersion of the R_g waves contains information about the shallow shear wave velocity structure. We determined R_g group velocities at several frequencies from radial and vertical waveforms of a M_l aftershock in the Big Bear area recorded at 4 stations (Fig. 1) using the codes of Herrmann (1987). The sensors that recorded the waveforms represent most of the types used on the portable stations: FBA-23s, L22s (a short period velocity sensor), and STS-2s (a broadband velocity sensor). We obtained robust group velocities from each type of sensor.

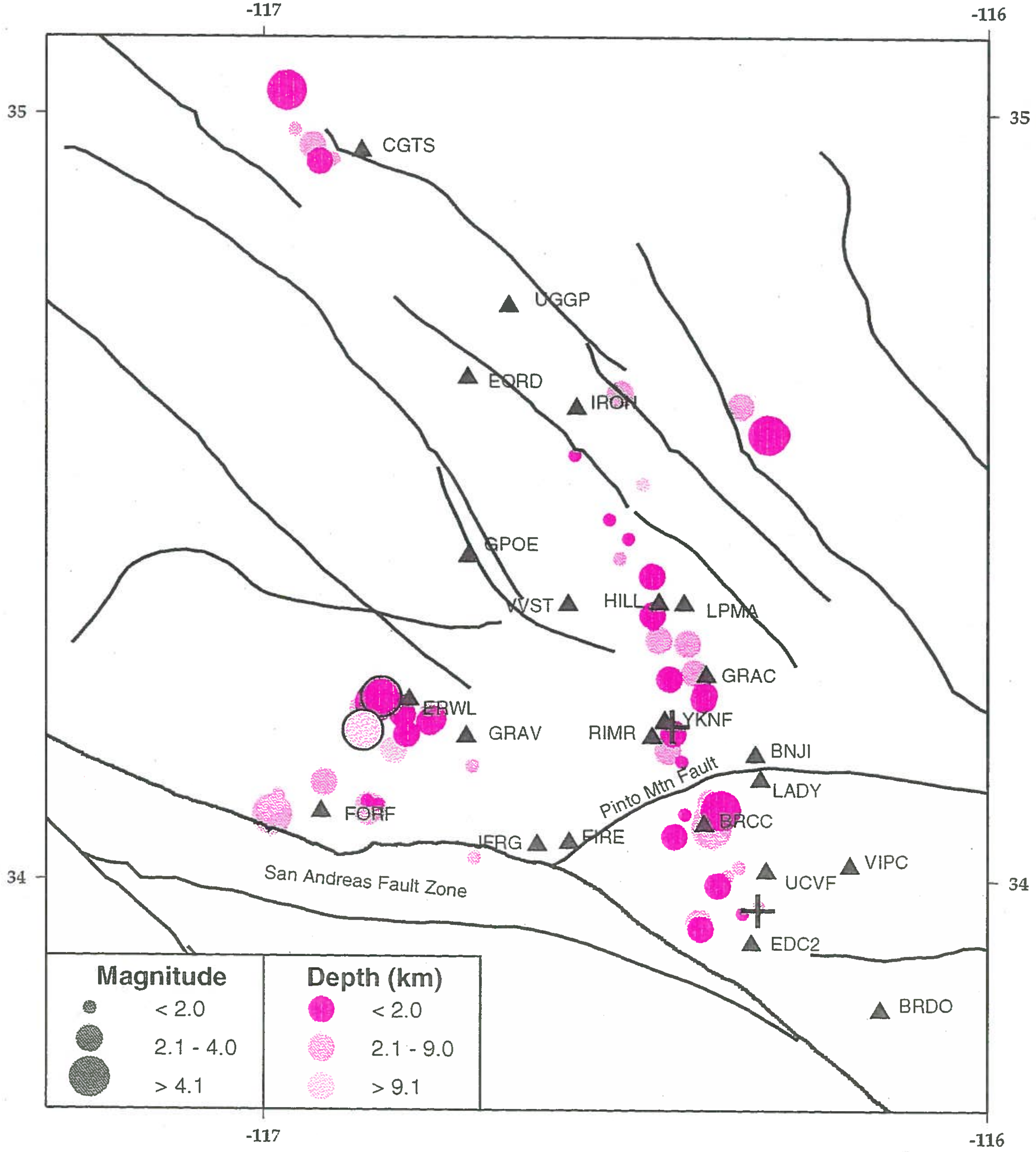
We found evidence for local variations in the shallow shear wave structure. Typical S wave velocities down to about 4 km depth were 2.5 to 3.5 km/s between the earthquake and the portable sites RIMR and YKNF. S wave velocities were lower, about 1.6 to 2.2 km/s between the earthquake and the sites BRCC and UCVF (Fig. 2). These sites are south of the Pinto Mountain fault, and RIMR and YKNF (and the aftershock) are north of the fault. These S wave velocity variations may be imaging a low velocity area along the Pinto Mountain fault also seen with P waves by Lees and Nicholson (1992). We have plenty of source receiver pairs to map out shallow S wave velocity variations.

The surface wave velocity information is particular useful because tomographic body wave velocity inversions have poor resolution at shallow depths, and fixing the shallow velocities can help stabilize the inversion for deeper velocities.

We will be acquiring all broadband data from Caltech's TERRAscope stations in order to further investigate these low frequency signals.

Figure 1. Group velocities found by multiple filter analysis of vertical component seismograms of a shallow M 4.9 earthquake recorded at four sites showing dispersion of R_g waves. See Figure 1 for site and event locations. Note that the group velocities at BRCC and UCVF are similar, as are those at RIMR and YKNF, reflecting local variations in the shallow shear wave structure.

Figure 2. Portable station locations, and locations of earthquakes exhibiting the R_g phase. Events outlined in black were analyzed for S wave velocity.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-116
35
35
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34
CGTS
UGGP
EORD
IRON
GPOE
VVST
HILL
LPMA
GRAC
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RIMR
YKNF
BNJI
LADY
Pinto Mtn Fault
BRCC
FORF
IFRG
FIRE
VIPC
UCVF
EDC2
BRDO
San Andreas Fault Zone
Magnitude
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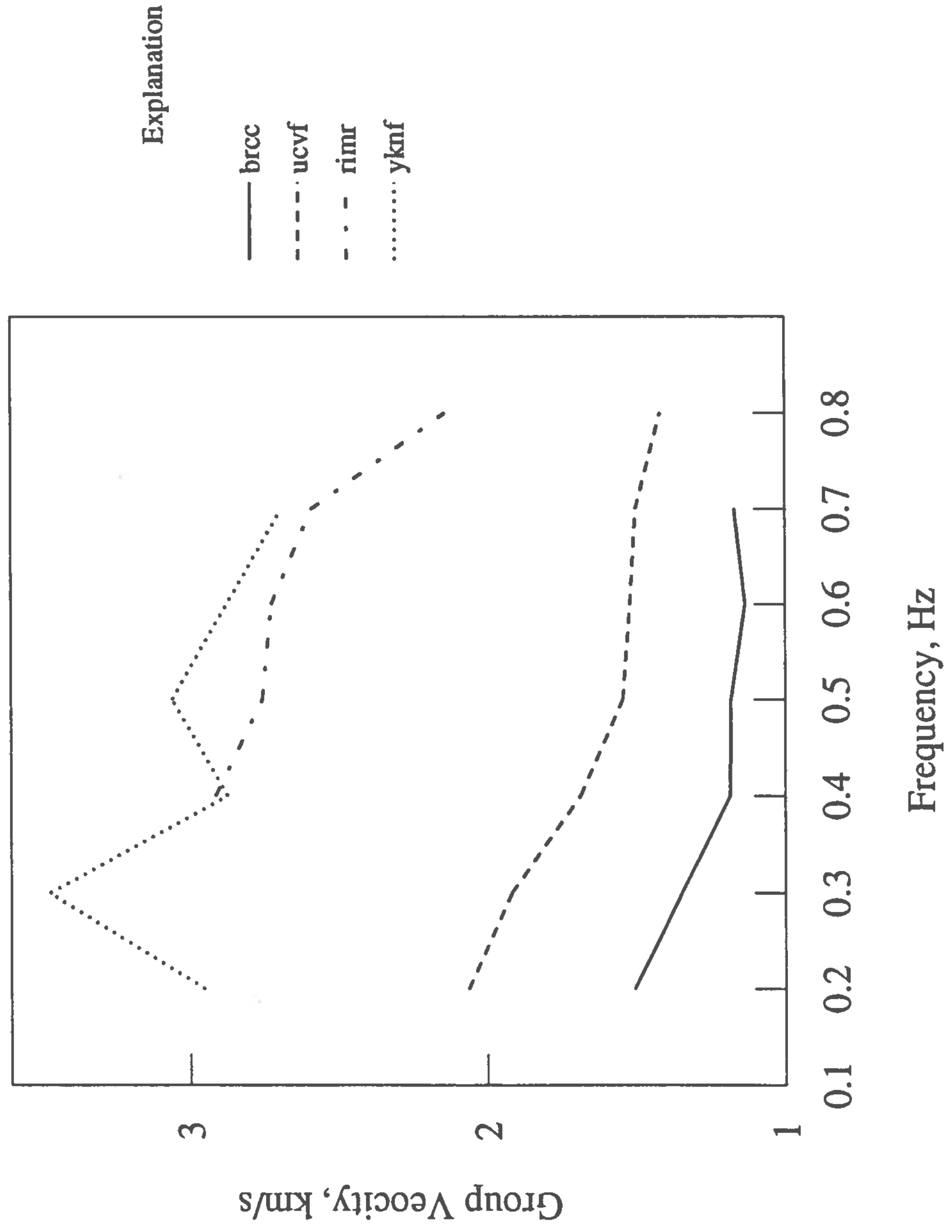
2.1 - 4.0
> 4.1
Depth (km)
< 2.0
2.1 - 9.0
> 9.1
-117
-116

F22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brcc
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yknf
Group Veocity, km/s
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2
3
0.1
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0.6
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0.8
Frequency, Hz

SCEC Project: Progress Report, 01 Dec. 1993

PIs E. Hauksson, H. Kanamori, J. Scott, and P. Maechling
Institution: California Institute of Technology
Title: **Towards, Real-time, Routine Broadband Seismology**

INVESTIGATIONS

The goal of this project is to establish rapid data analysis methods for data from the TERRAscope broad-band seismic network.

RESULTS

We report the following accomplishments:

Software Development for TERRAscope

As part of the TERRAscope project we have developed several new software programs at Caltech to enhance our ability to monitor Southern California Earthquakes as they happen. We use inputs from both the real-time continuous data feeds from TERRAscope stations and the Southern California Seismographic Network (SCSN). A summary flow chart of the different software modules is shown in Figure 1.

We have written a new program that allows TERRAscope data to be received through the USNSN VSAT system. This software that was developed at Caltech makes it possible to telemeter data from TERRAscope stations through a Very Small Aperture Terminal (VSAT) link. Prior to this, the real-time telemetry from TERRAscope stations was done only via dedicated ADN phone lines.

A second program takes event locations produced by an associator and determines magnitudes for the events using time series data from the TERRAscope stations. To accomplish this, software has been written which allows reliable high speed communications between VAX and Sun computers.

A third program allows seismologist to rapidly review the quality of computer generated locations. The seismologist uses a remote PC computer to plot the TERRAscope time series for an event with estimated P and S wave arrivals superimposed on the time series plot. Each available TERRAscope time series is plotted. The plots are sorted by distance to event. The estimated P and S wave arrival times are calculated for each station. These estimated arrivals are superimposed on top of the time series. If the actual arrivals match the estimated arrivals for each station, then the location can be considered accurate. A magnitude calculation is also done for each times series and is included on the plot. If a location appears to be inaccurate, the user can revise the location and origin time and generate plot using the revised information. The plots are usually available within 3 minutes after an event.

A fourth program provides early warning of ground motion at a site by using rapidly produced locations, estimating the P and S wave travel time to a specific site, and producing an audible or visual warning if the seismic waves have not yet arrived at that site. This system is a prototype. The primary drawback at this point is that the magnitude of the event is not considered. Therefore users are frequently warning of shaking which is too small to be felt.

A practical 3-D southern California velocity model

In a region as geologically complex as southern California, the effect of small-scale near surface velocity variations on seismic travel times is large. This signal interferes with the accurate near real-time determination of earthquake hypocenters where short ray path information is critical and contaminates the data used to determine large-scale 3-D velocity models of the crustal structure. Numerous researchers have constructed 3-D models of southern California with resolution at scales greater than 25 km which represent the average velocity of the crust and contain information on deeper structures. We are in the process of refining this 3-D model so that it accurately accounts for the effect of near surface structure and thus can be used for improving the routine network locations of the SCSN.

The preliminary phase of evaluating currently used crustal models of southern California has led to identification of the major areas of improvement required in modeling efforts. The resurvey of the seismic stations has been completed and eliminates some large systematic errors in the dataset. Improvements can be made by incorporating station delays as approximate compensation for near source structure that reduces the rms travel-time residuals from .35 seconds to .20 seconds. We are in the process of constructing refined velocity models, first using 1-D then 3-D methods, to improve the locations of earthquakes in southern California and to remove the effect of near surface velocity variations on interpretations of large scale 3-D structure.

Global Positioning System Re-survey of Southern California Seismic Network and TERRAscope Stations

Systematic errors in travel-time data from local earthquakes can sometimes be traced to inaccuracies in the published seismic station coordinates. This prompted a resurvey of the stations of the Caltech/USGS Southern California Seismic Network (SCSN) using the Global Postitioning System (GPS). We surveyed 241 stations of the SCSN using Trimble and Ashtech dual frequency GPS receivers and calculated positions accurate to 3 meters using differential positioning from carrier phase measurements. 12% of the stations which were surveyed were found to be mislocated by more than 500 meters (Figure 2). Stations of the Terrascope and USC networks were also surveyed, as well as a network of portable seismic stations deployed shortly after the 1992 Joshua Tree and Landers earthquakes. The new coordinates are availabe in ascii format from the SCEC Data Center.

Publications

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Jennifer Scott, Egill Hauksson, Hiroo Kanamori, and Jim Mori, Global Positioning System Re-survey of Southern California Seismic Network Stations, manuscript in preparation, 1993.

TERRAscope Data Flow and Analysis

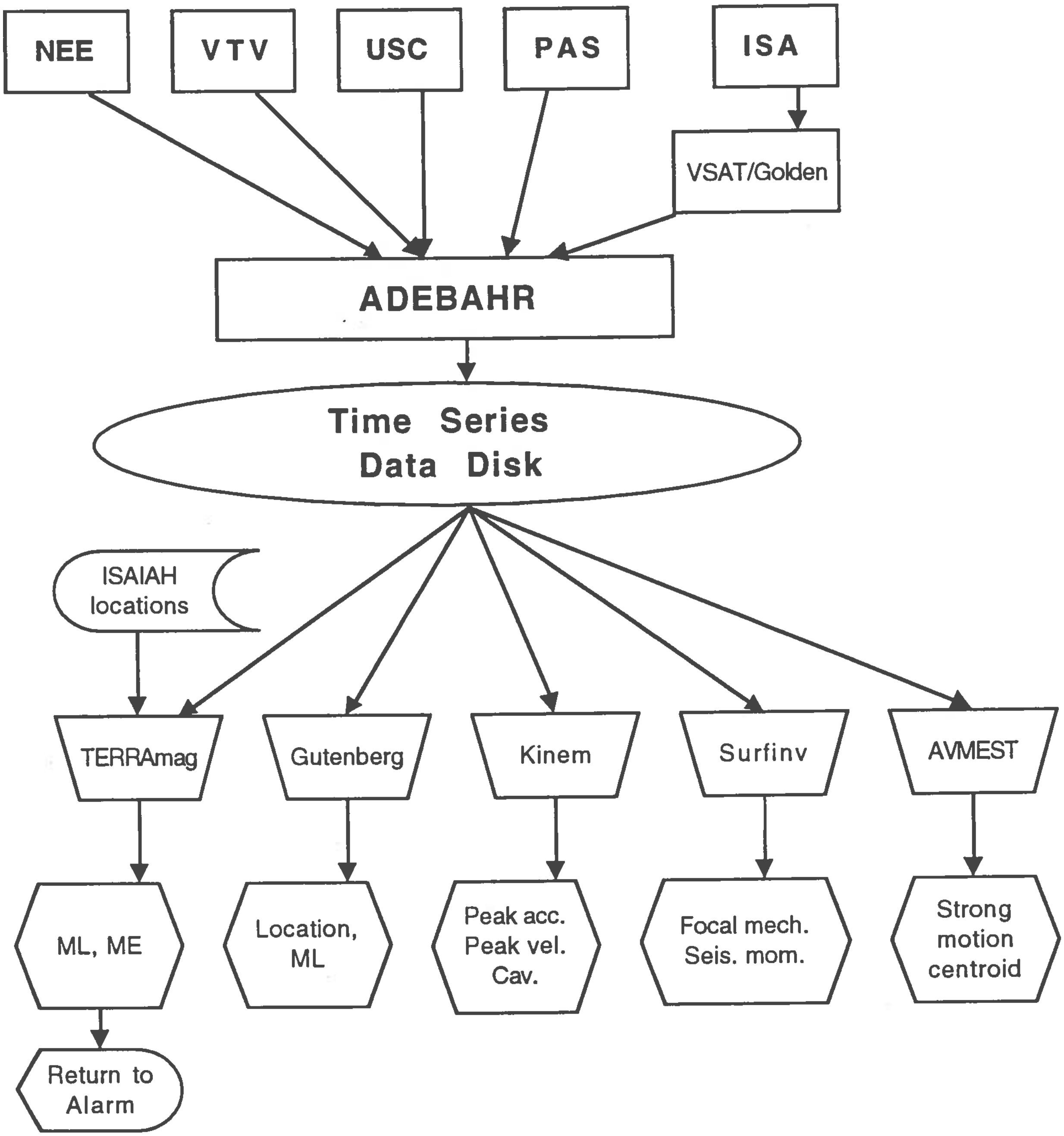

Figure1. Flow chart showing data flow and software modules developed for TERRAscope.

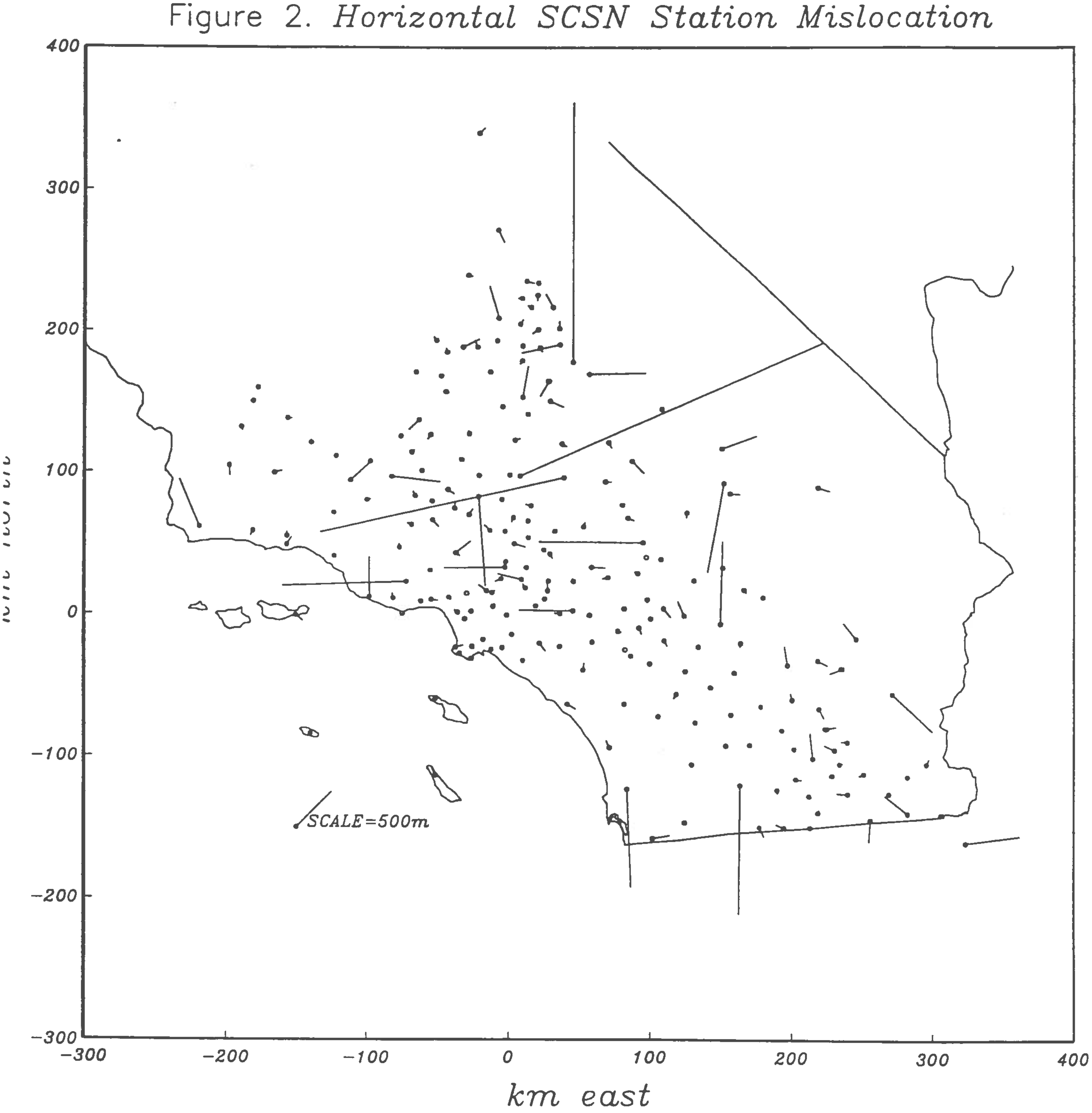

Figure 2. Horizontal mislocation vectors for stations in the SCSN. Old locations were read from topographic maps while new locations are determined with GPS.

Rapid Source Retrieval

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Objective: One of the fundamental reasons why seismology is contributing to the earthquake hazards program is its prediction capability. That is, given a set of seismograms we can predict the nature of the source and its location. This has been demonstrated with both teleseismic body waves and well dispersed long period surface waves. To retrieve source information from regional phases requires an understanding of complicated path effects. This project addresses this issue of calibrating paths to the new Streckeisen stations and rapid source estimation.

Research Accomplished: With the installation of the broad-band, high dynamic range instruments, it has become possible to compare the regional waveforms of different sized events. In many cases, events in the range of $M_L = 3$ to 6 for a particular source region have similar waveforms indicating the prominence of regional Green's functions. Once these functions are established it becomes possible to estimate source parameters for small events from just one station, Dreger and Helmberger (1993). This means, theoretically, we can predict the motions at other stations before the motion actually arrives.

Two papers has been submitted on this project to date: (a) Rapid source estimation from Broadband Regional Seismograms (Zhao and Helmberger) and (b) Analysis of broadband records from the June 28, 1992 Big Bear Earthquake (Jones, Hough and Helmberger).

a) Rapid source estimation
Recently developed source inversion techniques do not take full advantage of the broadband nature of regional seismograms. The reason is that deterministic derived Green's functions can not explain the complicated short period propagational phenomena associated with realistic crustal structure. This problem is generally solved by removing short periods and inverting only selected portions of the records. In this study, we introduce a source estimation technique that allows for better use of the entire broadband record when only imperfect Green's function are available. The procedure desensitizes the timing between the principal crustal arrivals by fitting portions of the Green's functions independently, both in waveshape and energy content, by applying a direct grid search approach. In addition to the source parameters we obtain "δt" phase alignment shifts which can be used as Green's function corrections for relocating other events or as a quide to deriving new crustal models.

We will briefly introduce some of this data and discuss how it can be used to determine source characteristics. For example, the broadband displacements sampling three different azimuth of the Sierra Madre event is displayed in figure 1. These three stations are about 160 km away from the epicenter and show a clear separation between the early arriving P-waves (P_{nl} in the figure) and later arriving S-waves and surfaces waves. The three columns on the right display the vertical, radical and tangential motions with peak amplitudes given in cm. Displayed on the left are enlarged portions of the first ten secs of motion. The top trace of each set is the observed data. The lower two are synthetic motions predicted by Green's function appropriate for Southern California and a set of source parameters found by waveform matching Green's functions. The upper set of synthetics used the entire records in determining the source while the lower traces are based on the mechanism determined by the early P-wave portion (P_{nl}): The synthetics on the right than become predictions. The comparisons suggest that modeling the early portions of seismograms is sufficient in predicting later motions. Furthermore, if we have one TERRAscope station near an event we can do reasonably well at estimating the source parameters, for example see Dreger and Helmberger (1992 and 1993) and Zhao and Helmberger (1993). These studies show that in many situations one station solutions can be used to predict the observations at other stations. For example, using the LA Basin response such as derived by Craig and Helmberger (1993) and others we could predict the motions before they arrive and establish a Early Warning System.

b) Big Bear Earthquake

The June 28, 1992 Big Bear earthquake in southern California occurred at 15:05:21 gmt on June 28, 1992 and is considered to be an aftershock of the earlier $M_W = 7.2$ Landers earthquake. From overall aftershock locations and long-period focal studies, rupture is generally assumed to have propagated northeast. No surface rupture was initially found, however, and the mainshock locations determined from both strong motion and TERRAscope data are mutually consistent and do not lie on the assumed fault plane. Further, directivity analysis of records from the TERRAscope array suggest significant short- and long-period energy propagating northwest along the presumed antithetic fault-plane, as well as some long-period moment release in the direction of the presumed fault-plane. This observation is supported by significant early aftershocks distributed along both the presumed rupture plane and the antithetic plane to the northwest. An empirical Green's function approach using both the M = 5.2, June 28, 1992 14:43 gmt foreshock and M = 5.0 the August 18, 1992 aftershock produces results consistent between the two eGf's, and suggests that the Big Bear event comprised at least two substantial subevents. From the eGf results, we infer that the second, and possibly a third subevent occurred on the presumed (northeast striking) mainshock rupture plane, but that significant moment release occurred on the antithetic northwest striking plane. We present results from line-source finite-fault modeling for the Big Bear mainshock, which indicate that a two source or two fault event is necessary to produce the waveforms observed during the Big Bear mainshock. The constraint imposed by the directivity analysis required that the initial rupture be towards the northwest, striking 320^o. This was followed approximately 5 seconds later by bilateral rupture along a northeast-southwest trending fault, striking at 50^o east of north. The modeling was done in broadband displacement and involved summation of empirical Green's functions along a pair of finite, line-source faults.

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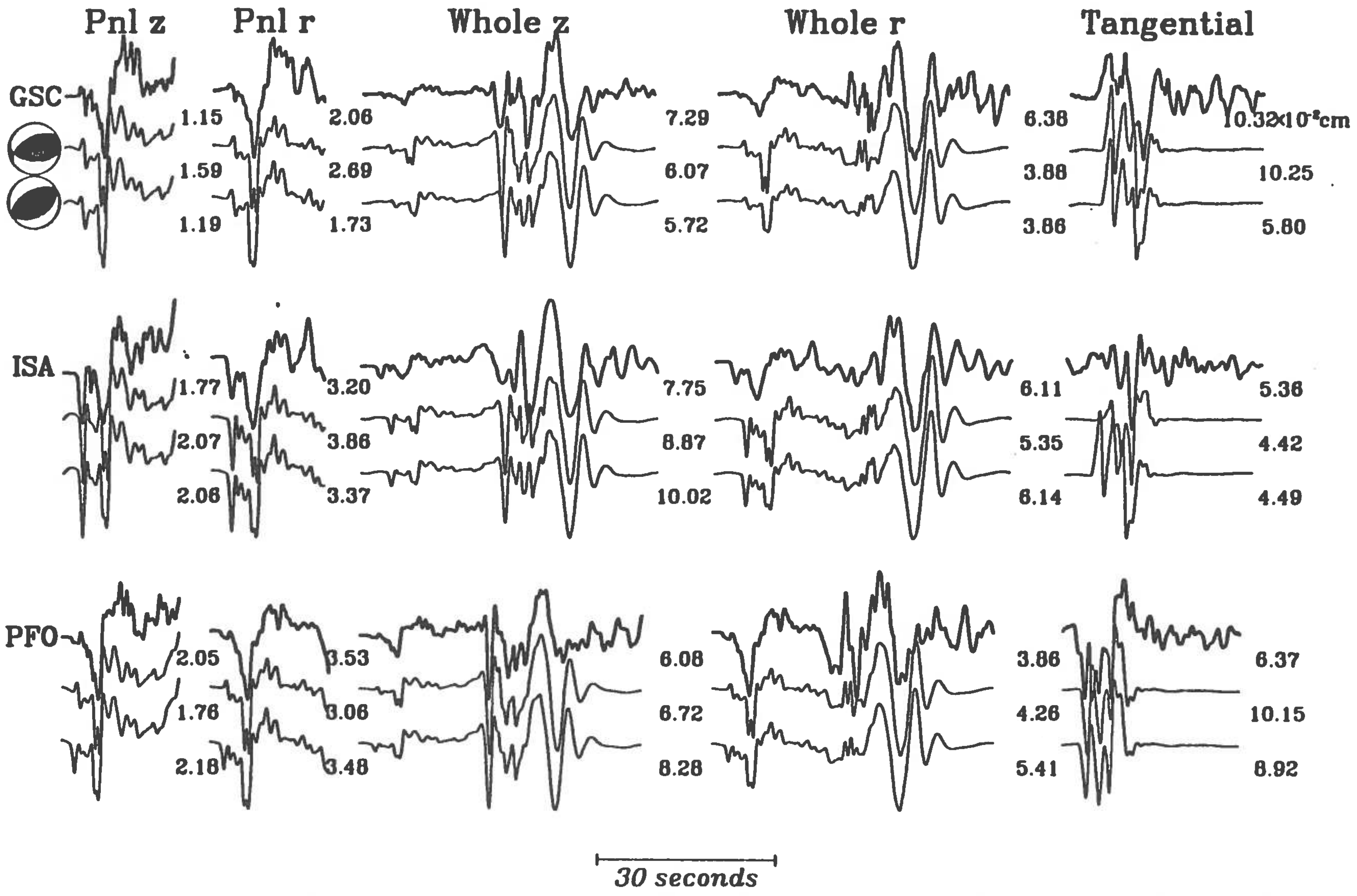

Figure 1. Comparison of Sierra Madre broadband observations at three stations (GSC, ISA, and PFO) with synthetics generated by estimating the fault parameters. Three windows of observed waveforms are used, namely the beginning portion P_{nl} (first two columns), the Raleigh waves (middle two columns), and the tangential (column on the right). The corresponding Green's functions are shifted in time for best alignment and used to estimate strike, dip and rake. The amplitude fits determine the moment (numbers indicate peak amplitudes in cm). The bottom trace of each set corresponds to the source estimation using only the P_{nl} columns and the middle traces correspond to using all 5 columns. Both solutions yield the same moment of 3. x10^{24} ergs. Single station solutions and various combinations of the datasets are discussed in Zhao and Helmberger (1993). The depth estimate is obtained by applying Green's functions at various depths and choosing the one with the smallest error (best fit). Several event sequences are considered in the above paper, some well outside the array (Yucca Mtn., Nev.) for example.

Report to SCEC, 1993

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In 1993 we have nearly completed our structural interpretation of southern California seismicity based on the data from the Caltech-USGS network. We have also started a systematic analysis of stress and stress changes using the same data. The abstract and 3 figures from a paper that deals with this work and that we are about to submit for publication are incuded here.

THE SAN ANDREAS FAULT SYSTEM THROUGH THE TRANSVERSE RANGES AS ILLUMINATED BY EARTHQUAKES: TRANSPRESSION AND TRANSTENSION BY STRAIN PARTITIONING

Abstract

The pattern of seismogenic faulting in the San Gorgonio Pass-San Bernardino basin area of the San Andreas fault zone is mapped from more than 4000 focal mechanisms. Key for exploiting high density of data in a structurally complex area is a new software to visualize and classify focal mechanisms. These units of structural data are represented by one of the two slip planes; a mechanism is associated with a given fault by "fixing" the corresponding nodal plane. Focal mechanisms are derived from 1981-92 phase data of the southern California seismic network via a single relocation procedure over most of the area covered by the network. This procedure accounts for three-dimensional velocity variations by ten distinct subregional 1-D velocity structures and by location-dependent station-corrections. A classical grid-search program yields focal mechanisms which are then quality-selected by multiple criteria, including a minimum number of first-motions and a maximum variance within the range of satisfactory fit.

One of the most prominent seismogenic features in the area of this study is a volume of diffuse, persistent, and unusually deep seismicity between the San Andreas fault (SAF) and the San Jacinto fault (SJF) from San Gorgonio Pass to a left-lateral cross fault corresponding to the Crafton Hills. Although individual faults are difficult to resolve within the zone, the dominant pattern of deformation appears to be dexteral shear parallel to the SJF. A mixture of thrusts and normal faults accomplishes both north-south shortening and east-west extension. This zone of seismicity has a sharp downward cut-off that defines a surface dipping gently (25°) northeast, toward the SAF, and is interpreted as a detachment. The dip of slip planes tends to decrease with depth suggesting listric faults that merge into this basal detachment. Right-lateral slip planes delineate a continuous fault with a steep northeast dip connecting the Coachella Valley segment of the Banning fault and the San Bernardino branch of the SAF. This transcurrent fault defined by geologic and earthquake data exhibits the simplest geometry of any structure through San Gorgonio Pass and is interpreted to be the main strand of the SAF. This fault intersects the proposed detachment along an asymmetrical trough in the lower boundary of the seismicity that marks the deepest well-defined seismic zone in southern California. From the southwest to the northeast side of the SAF, the floor of the seismicity steps up by as much as 10 km. Thrusting dominates the tectonic regime near the constricting bend of the SAF at San Gorgonio Pass. Gradually, normal faulting becomes dominant towards the northwest. In the San Bernardino Basin area, seismicity is concentrated along the SJF but is primarily generated by a system of normal faults. The SJF is currently seismogenic only below the intersection with an east-dipping normal fault. The transtensional regime in the San Bernardino Basin changes abruptly to a transpressional regime in the eastern San Gorgonio Mountains. A sharp stress boundary coincides with the merger of the SJF int the SAF and their intersection with the Cucamonga fault. This boundary projects into the Cajon Pass area and may account for the unexpected stress conditions inferred from deep borehole data.

The prominent Yucaipa cluster, centered on the Mill Creek fault near the intersection of the Crafton Hills cross fault and the SAF and about 10 km from the M=6.5, 6/28/92 Big Bear main rupture, has been very active since that earthquake, but was also active during the previous decade. Most of the ≈100 focal mechanisms in this ≈5km wide cluster can be associated with three intersecting structures: the Mill Creek fault, a northerly mapped branch of this fault, and a normal fault localized at the intersection of these steep right-lateral faults. Seismicity preceding the Big Bear main shock was almost exclusively on the Mill Creek fault; after this event, seismicity shifted to the other faults. The structural singularity represented by the fault intersection may be associated with a mechanical singularity responsible for the persistent and localized source of seismicity. The change in fault kinematics at the cluster may reflect static stress changes induced by the large nearby rupture of 1992.

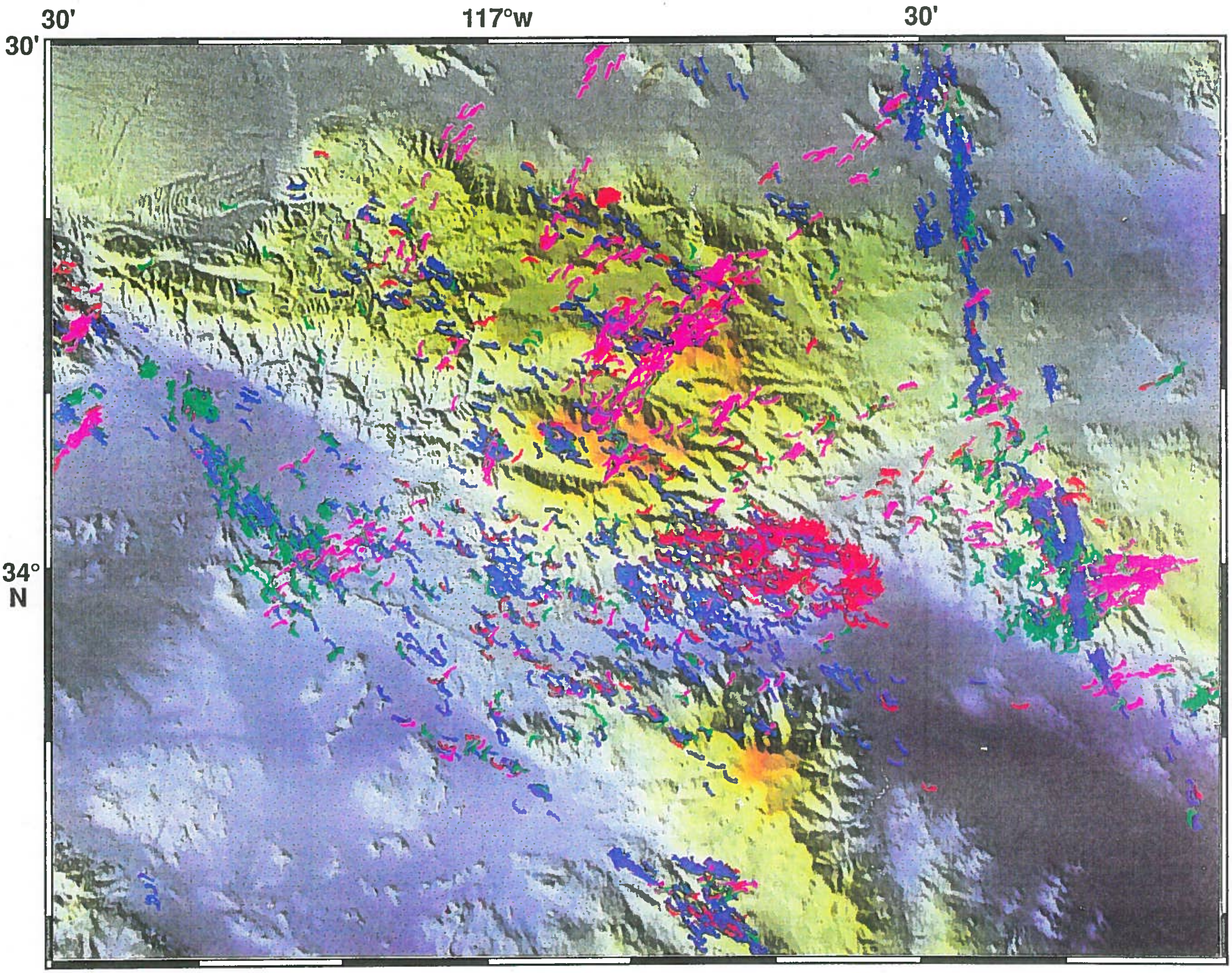


Figure 1: About 3500 slip planes (see Figure 2) from Jan 1981 to November 1992 superimposed on digital topographic data of the eastern Transverse Ranges (synthetic illumination from the southwest). These slip planes represent about 2/3 of our data base of focal mechanisms; they have been selected on the basis of structural interpretation and have been incorporated in our structural model of seismicity. They are color coded according to rake: purple=-45° to 45° (right-lateral); green=45° to 135° (normal); pink=135° to 225° (left-lateral); red=225° to 315° (reverse).

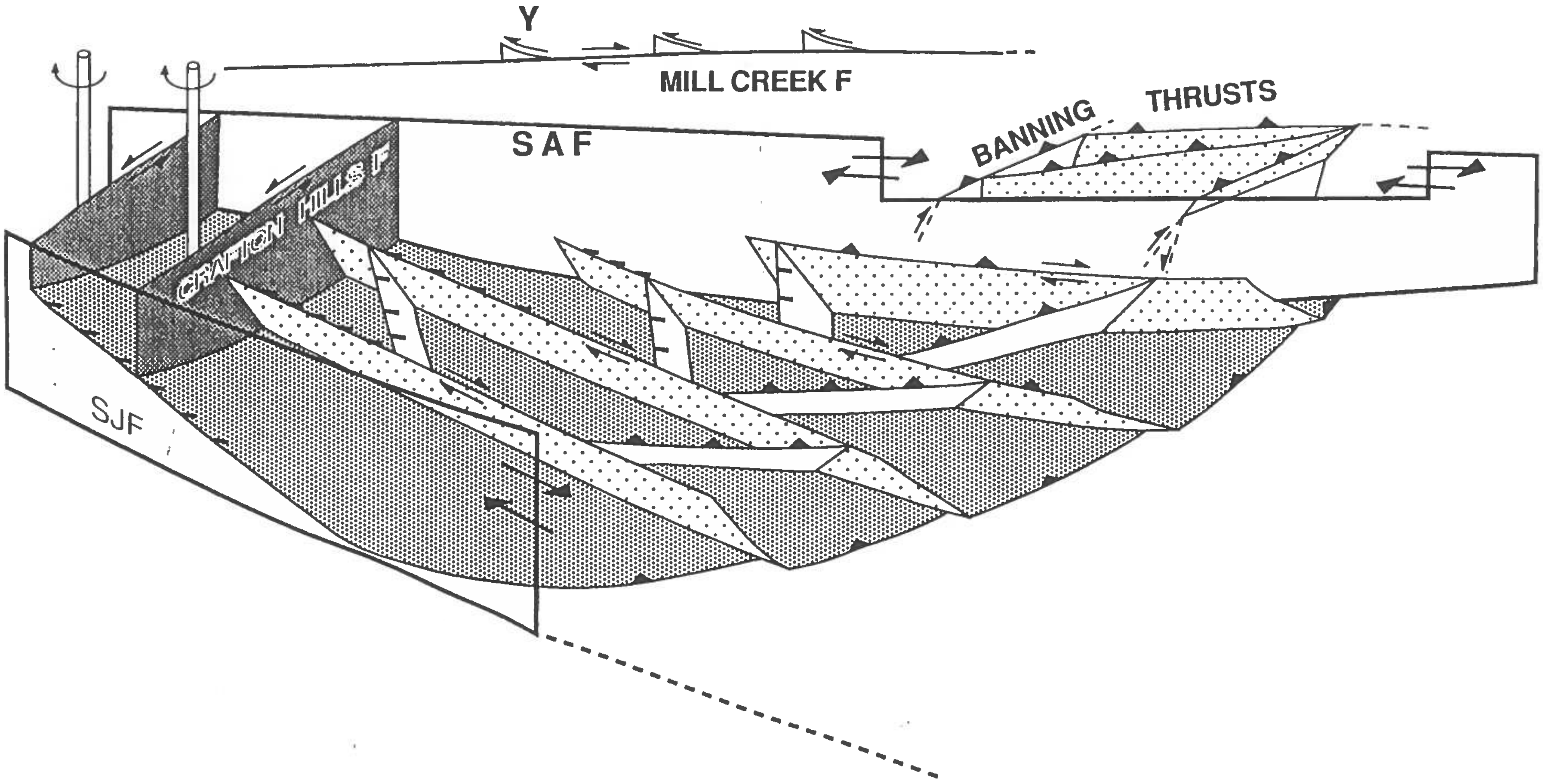


Figure 2. Tectonic sketch for the San Gorgonio Pass-San Bernardino Basin area. Oblique view from the southwest. Barbs on upthrown side of thrusts; short segments on downthrown side of normal faults. Y indicates approximate location of the Yucaipa cluster. SAF=San Andreas fault; SJF=san Jacinto fault.

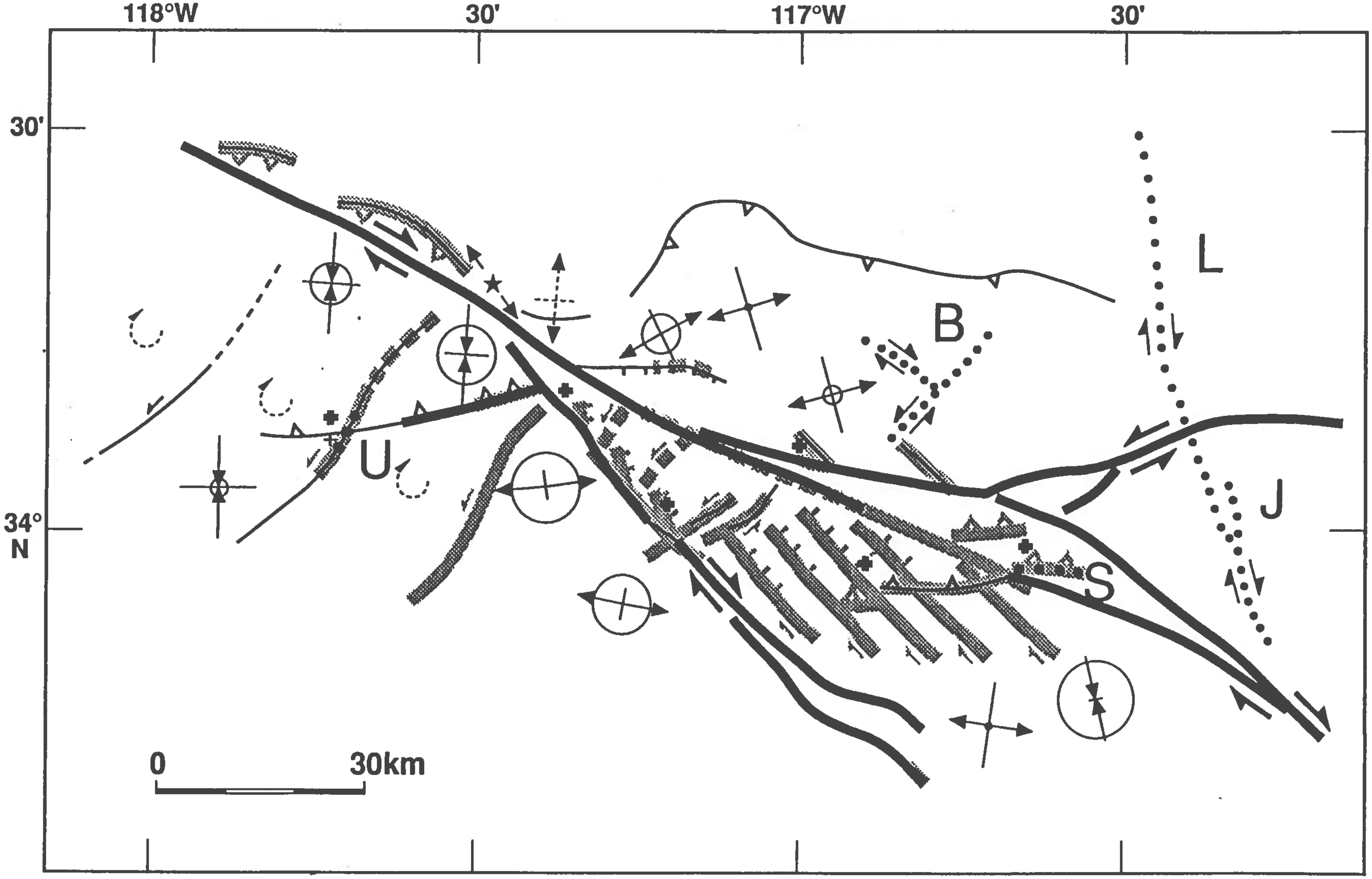


Figure 3. Tectonic sketch showing the main structural elements of the Cajon Pass-San Gorgonio Pass area. Solid lines are previously known faults (barbs of upthrown side of thrusts and short segments on downthrown side of normal faults); thick lines denote faults thought to play a primary role in the tectonic regime. Shaded strips denote some of the faults inferred from seismicity in this study. Dotted lines indicate faults delineaded by principlal aftershock sequences during data sampled in this study: S=1986 North Palm Springs; U=1990 Upland; J=1992 Joshua; L=1992 Landers; B=1992 Big Bear. Stresses calculated from slip planes are also shown. Principal stress axes tend to be either nearly horizontal (plotted as segments) or nearly vertical (plotted as circles). Lengths of segments and radii are proportional to the deviatoric component of the corresponding principal stresses; the polarity of the largest component is indicated by the arrows and is opposite to the polarity of the other two components. Of the nine stress symbols, the northern most four are centered in the areas pertaining to them, the others are drawn outside their areas which are centered at the plusses closest to each symbol. The dashed simbol refers to T and P axes of a single focal mechanism. The star indicates the scientific borehole site and the related arrows show the direction of maximum horizontal extension at the well.

Preparation of Seismic Data Collected on Portable Recorders from the Landers-Big Bear Aftershocks

Principal Investigator: Frank Vernon, UCSD

A collaborative study to record aftershocks was undertaken by several institutions following the June 28 Landers and Big Bear earthquakes. The M7.6 Landers earthquake occurred at 04:58 PDT approximately 6 miles north of Yucca Valley along the southern extension of the Johnson Valley fault. The earthquake produced over 70 km of ground rupture, with cumulative right-lateral offsets of 3 to 6.5 m along segments of the Homestead Valley, Emerson Lake, and Camp Rock faults, all of which were involved in the sequence. The primary aftershock activity occurred in a narrow band from 33.6N, -116.2W north to 34.5N, -116.6W, with a separate cluster at 35.0N, -117.0W. The M6.5 Big Bear earthquake occurred at 08:04 PDT approximately 35 km west of the Landers epicenter in the San Bernadino Mountains, involving left-lateral slip on a fault that strikes N45°W and dips 70°SE. The Big Bear aftershocks occur over an area of about 30 km long, extending northeast from 34.1N, -117.0W to 34.4N, -116.6W.

Personnel from Caltech, SDSU, UCSB, UCSD, and USC participated in the installation and maintenance of the portable stations. Within 12 hours, four portable instruments were installed and recording data, and an additional 18 were up and running within 48 hours. Approximately 10 Gb of raw data from thirty-one individual stations were acquired in the 2 months following the main shocks.

The processing scheme required several steps: raw data retrieval followed by formatting, quality control, timing corrections, and event association. A Sun Sparc field computer was set up in a motel room several days after the main shocks. Most of the data reformatting, quality control and timing corrections were performed on this field computer. The computer was operated for about three weeks and data collected afterwards were processed at one of the participating institutions.

Initially, a REFTEK Exabyte drive was used to dump the data at the station, but it was found to be more reliable to exchange hard discs and copy data via the SCSI bus on a Sun Sparc station. After the raw data were downloaded to disk, TAR backup tapes were made. Next the data were converted to PASSCAL SEGY format and reviewed using PASSCAL's quick look program PQL to evaluate the station performance. Data recorded on SSR-1s were brought back to SDSU, then copied to a Sun Sparc station and converted to PASSCAL SEGY format.

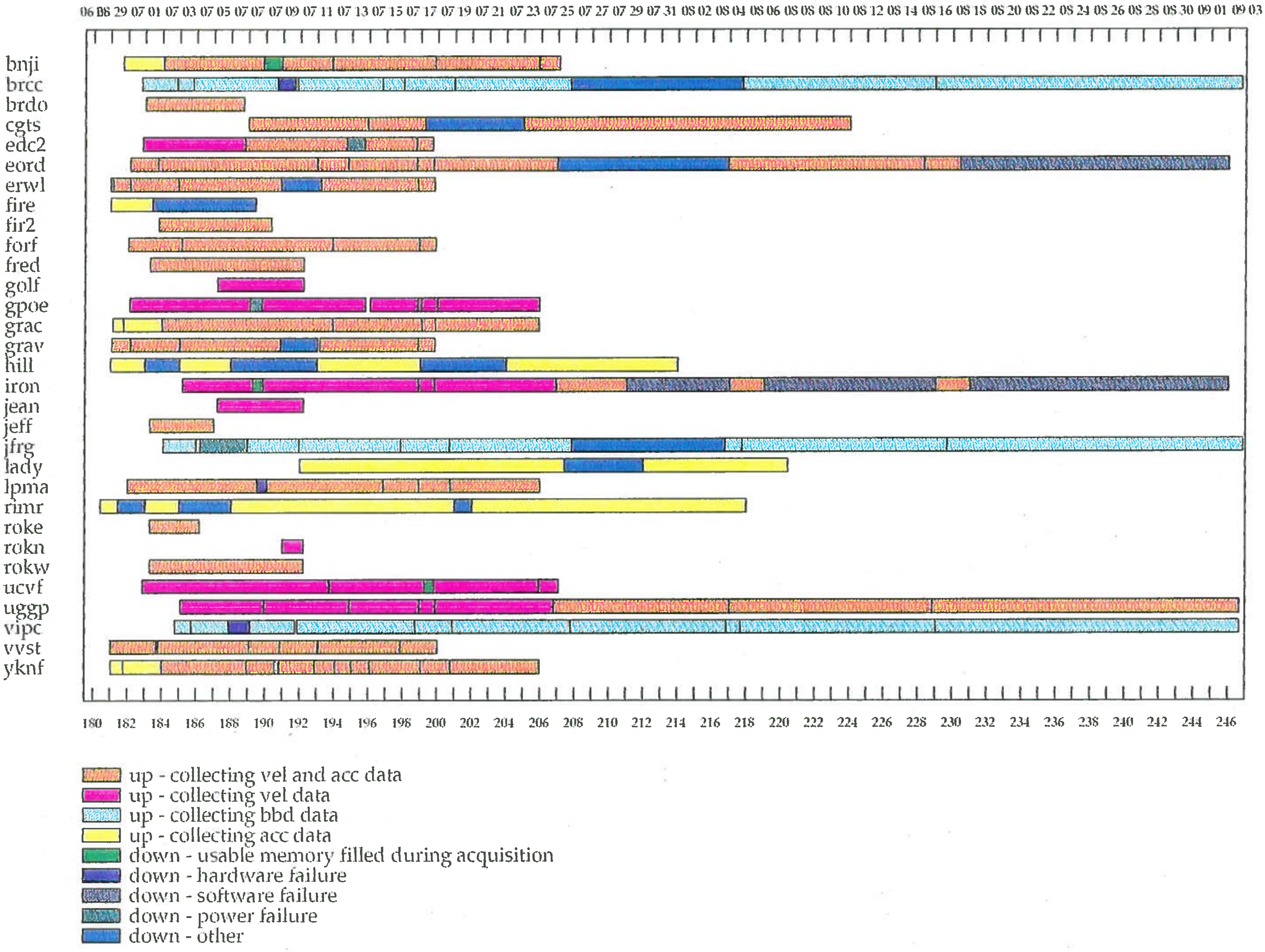
Errors in timing were also corrected at this point. The common timing errors that were present in the raw data resulted from improper leap second settings and unlocked Omega time clocks. Unfortunately, not all the RT72A-02 had the same firmware revisions. Firmware revisions 2.44, 2.45, and 2.46 were all used and each has a different leap second setting. To further complicate matters, an additional leap second was inserted on June 30 two days into the experiment. The timing shifts were accomplished by applying a shift to the trace start time via the TotalStatic field in the SEGY header. The program SEGYSHIFT was used to accomplish this.

The next step involved event association between the portable stations. This was accomplished by running the UCSB_TABLE and REAP programs. UCSB_TABLE creates a listing of event times, while REAP associates the data according to specified time and array parameters. Both the LDEO and SDSU datasets were then associated with the PASSCAL dataset based on event time windows. Figure 1 is a timeline showing the status of each station during the experiment.

At this stage all data meeting certain time criteria are organized into a sequence of events, and both P and S phases were picked. In order to determine event locations and magnitudes, two methods were used to associate the portable station records with the SCSN catalogue. An event-time association was performed, utilizing an ORACLE relational database, and an association between predicted arrivals and the P and S phase picks was performed, utilizing the CSS 3.0 database format.

All waveform record information, arrival information, station parameter information, and binary waveform files are ready to be converted into the SCEC database format and shipped to Caltech on DAT cartridges. A data report describing the field deployment, the data processing scheme, and the data itself will be included with this shipment.

Landers-Big Bear Earthquake Aftershock Deployment (28 June 1992 - 03 Sept 1992)



SCEC ANNUAL PROGRESS REPORT: FY1993

SCEC SCIENTIST: Craig Nicholson, Institute for Crustal Studies, University of California at
Santa Barbara, CA 93106-1100

This investigator did not receive any research support from SCEC in FY1993. Funds allocated to UCSB in FY1993 and assigned to this investigator were reimbursements for costs already incurred by ICS/UCSB in FY1992 during the portable instrument deployments for the April M6.1 Joshua Tree and June M7.4 Landers and M6.5 Big Bear earthquake sequences. Some additional SCEC funds were expended in FY1993 for initial data processing, organization, and event association. These funds completed the original process of data collection, and insured that the SCEC Data Center received properly time-corrected, useable, associated data; SCEC funding was not provided for data analysis or scientific research. Both 1992 deployments were successful, largely because of the tremendous cooperation between the various participating SCEC institutions involved. Participating institutions included Caltech, UCSB, UCSD, USC, USGS, PASSCAL, and SDSU.

22 April M6.1 Joshua Tree Earthquake

Five SCEC instruments were initially deployed within 6.5 hours of the April 22 M6.1 Joshua Tree mainshock. UCSB assisted in the deployment and maintenance of these sites. Six PASSCAL recorders were added to the deployment in the following days. The array was maintained until early June and collected about 5-6 Gbytes of raw digital data. At ICS, we corrected timing and performed event association on 3-4 Gbytes of data left after initial data processing and reduction. Over 10,700 events were associated, and the data were made available to the SCEC Data Center at Caltech.

28 June M7.4 Landers and M6.5 Big Bear Earthquakes

Nine PBIC DAS's were deployed for this aftershock sequence. PASSCAL supplemented the SCEC array with 10 DAS's in the days following the mainshock. SCEC member institutions, including UCSB, worked together to deploy and maintain the array. Once fully deployed, the array consisted of 18 sites including 3 STS-2 and 2 CMG-3 broadband sensors. A prototype field computer was used to perform initial field quality control of the data. Over 8 Gbytes of raw data were collected. Data processing, event association and timing corrections were performed at UCSD. Over 8,000 events were associated, and the data made available to the SCEC Data Center at Caltech.

FY1993 RESEARCH RESULTS

1. Changes in Attitude - Changes in Latitude: What Happened to the Faults in the Joshua Tree Area Before and After the M7.4 Landers Mainshock?

CRAIG NICHOLSON, RUTH A. HARRIS, AND ROBERT W. SIMPSON

The M6.1 Joshua Tree earthquake of 23 April 1992 occurred about 8 km northeast of the southern San Andreas fault and about 20 km south of the Pinto Mt fault. It was followed by over 6,000 M>1 aftershocks. No surface rupture for this sequence was found; although ground fractures were discovered in this area after the Landers earthquake on June 28. From the distribution of aftershocks and directivity effects, the mainshock ruptured unilaterally to the north along a fault about 15 km long. The focal mechanism indicated right-slip on a plane striking N14°W, dipping 80°W, with a rake of 175°. We relocated 10,570 events between 23 April and 24 July using the data from the regional network; and determined 3,030 single-event focal mechanisms with 15 or more first-motions. A large number of aftershocks occurred off the mainshock rupture plane on adjacent secondary structures that strike either sub-parallel to the Joshua Tree mainshock plane or on relatively short, left-lateral faults that strike at high angles to the mainshock plane. Aftershocks continued to migrate to the north and south following the mainshock, and ultimately extended from the southern San Andreas fault near the Indio Hills to the Pinto Mt fault. The northern 15-km section of the aftershock zone had a strike more nearly N10°E. Seismicity on this fracture network ceased in the hours prior to the 28 June M7.5 Landers event, and has not yet resumed. Instead, the Landers mainshock appears to have caused the activation of a new fracture network located farther west, that intersects the previous Joshua Tree activity in the area of the Joshua Tree mainshock, and is oriented more nearly N15°W. We investigate possible explanations for this change in the pattern of earthquake activity as a result of inferred stress changes induced by the Landers mainshock and some of its larger aftershocks.

2. Joint 3-D Tomography Using Seismic And Gravity Data Of The 1992 Southern California Sequence: Constraints On Dynamic Earthquake Ruptures?

JONATHAN M. LEES AND CRAIG NICHOLSON

Linear tomographic inversion of P-waves from the recent 1992 Southern California earthquakes is used to produce 3-D images of subsurface velocity. The 1992 dataset, augmented by 1986 M5.9 North Palm Springs earthquakes, consists of 6458 high-quality events providing 76,306 raypaths for inversion. The target area consists of a 104×104×32 km^3 volume divided into 52×52×10 rectilinear blocks. Laplacian regularization was applied and the residual RMS misfit was reduced by ~40%. Significant velocity perturbations are observed that correlate with rupture properties of recent major earthquakes. Preliminary results indicate a low-velocity anomaly separates dynamic rupture of the M6.5 Big Bear event from the M7.4 Landers mainshock; a similar low-velocity region along the Pinto Mt fault separates the April M6.1 Joshua Tree sequence from the Landers rupture. High-velocity anomalies occur at or near the nucleation sites of all 4 recent mainshocks (North Palm Springs-Joshua Tree-Landers-Big Bear). A high-velocity anomaly is present along the San Andreas fault between 5-12 km depth through San Gorgonio Pass; this high-velocity area may define an asperity where stress is concentrated. To test model reliability, a joint inversion of seismic and gravity data was performed. Gravity data can be used by assuming a linear relation between density and velocity perturbations. Gravity may be important to subsurface structure because the Landers rupture follows a strong gravity gradient. Gravity also helps constrain near-surface regions of the model where incident rays are nearly vertical and seismic resolution is poor. The joint 3-D model is required to fit both seismic data and isostatic gravity anomalies to a specified degree of misfit. A joint tomographic inversion in which 40% of seismic data residual misfit and ~80% of the gravity anomalies are explained does not differ significantly from previous models. These results suggest that high-resolution 3-D tomography may be a more effective means of segmenting active faults at depths than near-surface mapping.

3. The April 1992 M6.1 Joshua Tree Earthquake Sequence: Analysis of Portable Data and 3-D Tomographic Inversion

AARON MARTIN, CRAIG NICHOLSON, AND JONATHAN M. LEES

The M6.1 Joshua Tree earthquake of 23 April 1992 occurred about 8 km northeast of the southern San Andreas fault and about 20 km south of the Pinto Mt fault at a depth of 12–13 km. The mainshock was followed by over 6,000 M>1 aftershocks recorded by the permanent regional network and an 11-element portable array deployed by the Southern California Earthquake Center. No surface rupture for this sequence was found; although ground fractures were discovered in this area after the M7.4 Landers earthquake and its large aftershocks of June 28. We relocated 10,570 events between 23 April and 24 July using the data from the regional network; and determined 3,030 single-event focal mechanisms with 15 or more first-motions. A large number of aftershocks occurred off the mainshock rupture plane on adjacent secondary structures that strike either sub-parallel to the Joshua Tree mainshock plane or on relatively short, left-lateral faults that strike at high angles to the mainshock plane. The northern 15-km section of the aftershock zone had a strike more nearly N10°E. Seismicity on this fracture network ceased in the hours prior to the 28 June Landers event, and did not resume. Instead, the Landers mainshock appears to have caused the activation of a new fracture network located farther west, that intersects the previous Joshua Tree activity in the area of the Joshua Tree mainshock, and is oriented more nearly N15°W. This change in activity corresponds to a net tilt of about 30°–40° of the least-principal stress (σ_3) down to the northwest towards the Landers mainshock. Much of this later activity also coincides with a first-order discontinuity in 3-D velocity structure imaged by tomographic inversion of P-wave arrival times [*Lees and Nicholson,* 1993]. We investigate in more detail the structure of the Joshua Tree seismicity, changes observed before and after the Landers mainshock, and the local 3-D velocity structure using the portable digital data. Over 10,700 events were identified with recordings at 2 or more portable stations. Preliminary analysis of the portable data indicates that initial timing problems can be overcome and that the data are extremely useful for increasing model and structure resolution.

Group G: Physics of Earthquake Sources

Group Leader: Leon Knopoff

Group Leader: Leon Knopoff

REPORT OF WORKING GROUP G

Rice has shown that smooth, featureless, i.e. homogeneous, fault zones on a continuum model undergo repeated large earthquakes; the manifestations of chaotic behavior involving a Gutenberg-Richter spectrum of earthquake sizes is a consequence of the small scale disorder that is typical of the discrete lattice models on the scale of the lattice spacing. Xu and Knopoff have shown that there is no incompatability between the discrete and continuum models as long as both describe homogeneous systems that are scale-independent and have periodic end conditions; both lead to periodic large earthquakes; the chaotic behavior often ascribed to the lattice models is either a transient self-organizing state consequent on the initial conditions, or it is due to inhomogeneities that arise from healing pulses reflected from the ends of the model due to mismatched end (boundary) conditions. Both Rice and Knopoff argue that irregular fault system geometry is a major cause of chaotic seismicity. Shaw shows that the periodic state will not arise if it is possible to limit the size of the largest earthquakes; in this case the system organizes itself into a chaotic, non-repetitive state. The physical influence that limits the sizes of the largest events is a property of the models that resembles that of finite fault width; if an effective stiffness of a long section of a fault of finite width in Shaw's model exceeds the elasticity of the region, then fractures are limited in size. Thus the dichotomy between the homogenenists and the geometrists persists, and is reducible to the problem of the modeling of the fault in the direction perpendicular to it.

Rice's models are those of 2-D fracture surfaces imbedded in an elastic continuum. The Shaw and Knopoff models are 1-D reductions of these fault geometries. Chen and Knopoff constructed a dynamical plane-strain 2-D fracture model and applied it to an elongated fault structure designed to simulate a fault zone 15 km in depth and having a very long horizontal dimension. The applied stress is parallel to the long dimension of the fault. Faulting nucleates and grows initially in a more or less elliptical shape. Because of interaction with the upper and lower boundaries, the crack splits into two "Heaton pulses" that move in opposite directions with more or less constant velocity. If the crack encounters a near-surface asperity, a patch can be prolonged by growth around and below the asperity. There will be no slip at the surface at the asperity. This mimics the kink in the slip pattern in the Landers earthquake. Chen and Knopoff argue that inhomogeneities are important influences in pattern formation in seismicity.

One of the critical concepts in the models used in the simulations of seismicity, is that friction, in its static form inhibits the onset of the earthquake, and in its dynamic form inhibits sliding. The friction is usually modeled as a property of a point contact between the two blocks astride the fault. However, in the earth, the contact between the plates is a fault zone of finite width; explosion seismology and trapped-mode studies show that the fault zone has low seismic wave velocities, which is probably due to its being a zone of crushed rock of a possibly fractal distribution of sizes. Can we find equivalent rheological properties for a contact point that will model the properties of the extended fault zone? Sammis interprets the results of experiments on the deformation of gouge material as validating the rate-state dependent framework of precursory instability, but with a critical strain condition instead of a critical slip distance for the onset of the fracture instability;

the critical strain can be modeled as a critical slip distance if the width of the fault zone is taken into account, thereby allowing for the much larger critical slip distances that seem to be required to scale results from laboratory experiments up to dimensions appropriate to faulting.

The problem of precursory slip-weakening has been suggested as a mechanism for producing intermediate-term precursory effects. Landoni and Knopoff have shown that a comparison of results form modeling of inhomogeneous systems with and without precursory slip-weakening does not seem to produce significant changes in the space-time clustering of seismicity on any time scale. However a slow recovery of strength after fracture does produce significant clustering effects. Based on this observation it is suggested that much more experimentation is needed to understand slow recovery of strength in fault materials, as well as further numerical work on modeling these effects.

All investigators (Rice, Sammis, Shaw, Knopoff) agree that the understanding of the causes of the increase in the rate of intermediate magnitude seismicity before strong earthquakes, but not of the numbers of smaller earthquakes, is a major problem for the working group. Keilis-Borok and Levshina have shown that the precursory intermediate-magnitude seismicity for California earthquakes is distributed over several hundreds of km, which are distances many times greater than the classical fracture length of the strong earthquake that terminates the precursory episode. The termination of the increased activity is relatively abrupt, i.e. over a time scale probably of the order of one year or less. Thus modeling efforts should focus on long range effects.

RELATING FRICTION TO FAULT ZONE STRUCTURE

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Progress Report to the
Southern California Earthquake Center

1 December, 1993.

Earthquakes have traditionally been associated with frictional instabilities on preexisting faults. To a first approximation, frictional instabilities may be divided into dynamic instabilities and mechanical instabilities. Dynamic instabilities develop once the fault surfaces are moving and, as recently proposed by Brune and co-workers, may involve modes of vibration or waves which relieve normal stress on the fault. Mechanical instabilities develop if the initial displacement on a fault weakens the fault faster than that same displacement reduces the driving stress. The nucleation of earthquakes may be thus controlled by mechanical instabilities, while continued propagation may depend on dynamic instabilities.

Mechanical instabilities are commonly modeled using the Bowden-Tabor asperity model in which two sliding surfaces contact at a number of asperities. Asperities grow in strength with time, but their lifetime is limited by their size and the sliding velocity. A sudden increase in sliding velocity produces an instantaneous strengthening of the existing asperities "a" due to the increase in strength associated with the higher loading rate. However, as sliding proceeds at the higher velocity, the average asperity lifetime decreases which results in a decrease in asperity strength by an amount "b" over a characteristic sliding distance D_c which, in the Bowden-Tabor model is interpreted as the sliding distance required to completely change the population of asperities to ones having the new shorter lifetime. If $b > a$, then the material velocity weakens and, depending on the unloading rate of the fault, a stick-slip instability is possible. Stability is determined by comparing the apparent stiffness of the fault-zone:

$(b-a)\,\sigma_n / D_c$ with the elastic stiffness of the fault walls which, for a circular dislocation patch of radius r may be approximated as: $7\pi G/24r$ where G is the shear modulus of the wall rock.

Because fault zones generally contain a layer of crushed rock between the wall rocks, the direct application of the Bowden-Tabor model is problematical in terms of the identification of asperities and characteristic displacements. Experimental studies of friction in which a layer of crushed rock is introduced between the sliding rock surfaces have observed the same rate- and state-dependent phenomenology. Step changes in velocity still produce a signal which can be parameterized using a, b, and D_c as discussed above, but the values of all three parameters are significantly larger than those observed in rock-on-rock experiments. We interpret the larger values of both "a" and "b" observed for rough surfaces as being due to a velocity dependent dilatancy commonly observed in granular layers and show that the observed dilatancy produces instantaneous and evolutionary signals indistinguishable from those produced by the asperity model. The large increase in "b" and slight decrease in "a" which produce the transition from velocity strengthening to velocity weakening observed in gouge layers are produced by a transition from fracturing particles which has no lifetime effect to slip between particles which does. This work has been accepted for publication in a special issue of PAGEOPH on fault-zones and friction to be published in early 1994.

Sammis, C.G. and S.J. Steacy, The micromechanics of friction in a granular layer, PAGEOPH, in press, 1993.

The significance of the above observations is as follows: if the rate and state parameters in a fault zone depend on dilatancy, then they may not depend directly on fault displacement, but on strain within the fault-zone. This result is predicted by both soil mechanics and damage mechanics models for the strength of a crushed rock layer. The stiffness of the wall rock still depends on the displacement as discussed above, but the stiffness of the fault-zone now depends on strain=displacement/width. The immediate result is that wider fault zones should be more stable in the sense that a larger sliding patch is required to nucleate an instability. There are indeed hints that the creeping segment of the San Andreas fault has a wider crush zone than locked portions, and that small characteristic quasi-stable creep events also occur in these regions.

A second problem we have begun to work on is a physical model for the patterns of seismicity which are observed to precede large earthquakes: namely an increase in intermediate sized events (M>5) with no corresponding increase in smaller (M<4) events. These events do not occur in the rupture zone of the impending mainshock, but on other faults in the broader surrounding region. We have developed a heterogeneous bond-breaking model to test our working hypothesis that the precursory seismicity is a consequence of regional heterogeneity in that small events are more likely to break barriers and become large events late in the seismic cycle when the stresses are higher. A typical result is shown in Figure 1 where we have plotted the maximum event size at each strain increment. This figure clearly shows precursory activity; however we find that this is only the case when strength heterogeneities overwhelm stress fluctuations, and the strength of the barriers is proportional to the size of the fault. We are presenting this model at the Fall AGU meeting in San Francisco this month and at a workshop on geological hazards at the Santa Fe Institute for the Study of Complexity in January.

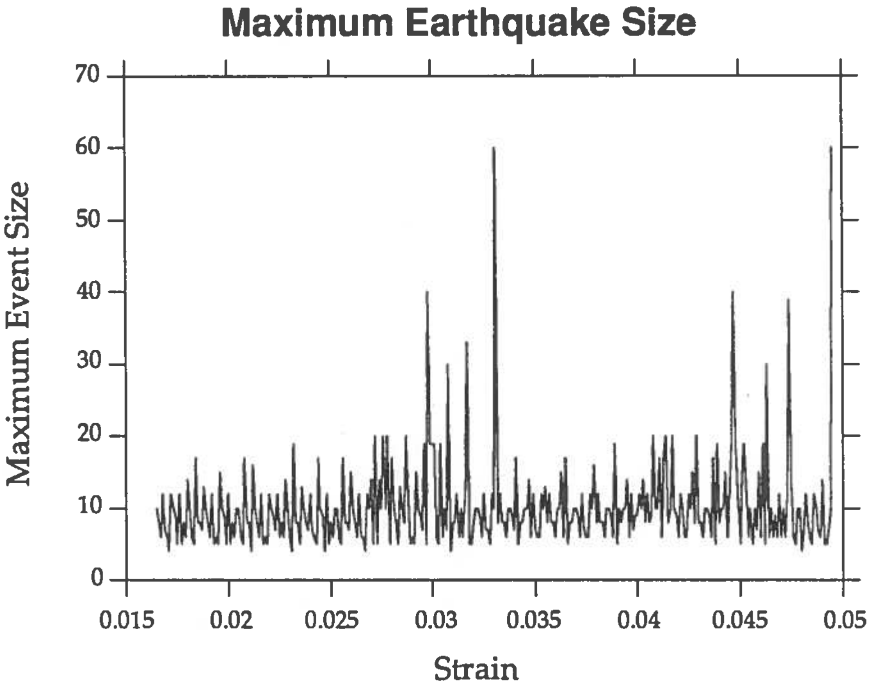

Figure 1: The largest event in each strain increment is plotted as a function of strain for a typical realization of a heterogeneous bond-breaking model for regional seismicity. Note the increase in intermediate-size events prior to each of the two largest events, consistent with observations of natural seismicity.

Annual Summary Report, Southern California Earthquake Center, USC P.O. 569928

Rupture heterogeneity and evaluation of the characteristic earthquake concept (seismicity in relation to geometric complexity, rheology and rupture dynamics of fault zones)

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November 1993

Our aim is to relate seismic response to the geometric disorder of fault zones, as represented by segmentation with kinks and jogs, and to the rheology of the frictional seismogenic region and its ductile surroundings. The studies were initiated under the title *Rupture Heterogeneity and Evaluation of the Characteristic Earthquake Concept*. They attempted to identify physical origins of characteristic earthquake response and to examine limitations to the concept by addressing inter-relations between fault zone property variations, geometric disorder, and heterogeneity of seismic response. An initial focus, retained in current work, was on modeling recurrent earthquakes along fault surfaces embedded in 3D (or sometimes 2D) elastic solids with a specification of physically based fault zone constitutive response of a kind that could lead to spontaneous failures. Additional themes added in the current grant year are: (1) Seismicity correlations and precursory patterns suggested by catalogs from our 3D fault models, and their relation to model assumptions, and (2) Interaction of stress heterogeneity, resulting from the elastodynamics of rupture propagation and arrest, with recurrent seismicity.

An understanding is emerging of which class of earthquake models will give repeated large events, which will show a spectrum of earthquake sizes, and when such a size distribution has Gutenberg-Richter self-similarity out to the largest events on a given fault segment [Rice (JGR, 1993; Fall AGU Abstract, 1992), Ben-Zion and Rice (JGR, 1993; USGS Redbook, in press, 1993)]. For example, our work suggests that smooth, featureless fault zones undergo repeated large earthquakes, principally because the stress concentration at a spreading rupture tip is too compelling for arrest by other than extraordinarily large variations in driving stress or toughness. However, geometrically disordered zones, so far simulated only approximately in our work by the finite size fault cells of a, then, inherently discrete model, have some probability of stopping sufficiently small ruptures, and give a Gutenberg-Richter spectrum of earthquakes over at least some small size range. We have described theoretical reasons (Ben-Zion and Rice, JGR, 1993), and confirmed from our numerical modeling, that a single size of heterogeneities could induce self-similar failure sequences only over a limited size range (e.g., 1 to 200 cell areas). In recent work (Ben-Zion and Rice, USGS Redbook, in press, 1993) we have been able to verify from numerical modeling our conjecture that the introduction of additional, stronger, heterogeneities at larger scale, but not necessarily with any self-similar of fractal features of their own, suffices to extend a simple Gutenberg-Richter power-law scaling to larger event sizes.

More importantly, these studies are helping to understand how one should interpret small-event seismicity statistics for an individual fault zone in terms of the largest probable events there. The large-event occurrence rate can generally be expected to coincide with power-law extrapolation of the instrumental record for small events only when strong disorder extends to the largest event scales; otherwise, the region is enriched in large "characteristic" events. Such considerations seem consistent with what is known from the statistics of instrumentally detected events and from the historical recurrence record at Parkfield, as we have noted. Also, preliminary results from S. Wesnousky (draft manuscript, 1993), who is comparing instrumental statistics with paleoseismic and geologic recurrence evidence for various fault zones in Southern California, lead us to believe that our considerations are on the right track. He finds that high geometric complexity, as characterized by the number of fault jogs or step-over distance per unit length along strike, is a feature which distinguishes fault zones such as the Newport-Inglewood and San Jacinto, whose paleoseismic rates are approximately coincident with extrapolation of the instrumental statistics, from zones such as Whittier-Elsinore, Garlock and San Andreas which seem to respond more nearly like the characteristic earthquake model.

Our work on theoretical models of recurrent seismicity has begun to search model catalogs for precursor patterns, based on time variations of minor seismicity, and to relate the presence or absence of such effects to model features. A focus is the statistical relation between small and slightly larger events, including any evidence that the probability of a small rupture growing into a larger one increases as stresses gradually build in time in and near the focal region. Additionally, we have developed an understanding of features that can lead to repetitions of similar small earthquakes at a given location; this is a response mode that can occur in some types of heterogeneous fault models at a border between locked and creep-slipping zones. Results from other groups (e.g., W. Foxall, T. McEvily and co-workers) suggest that such repeated events are common at Parkfield but rare at Anza.

A major new initiative in our work has been on developing truly elastodynamic models of unstable ruptures [Perrin and Rice (Spring AGU Abstract, 1993), Rice (Fall AGU Abstracts, 1993)], and on beginning the study of their consequences for some of the issues on complex response mentioned above. [Previously, our studies of recurrent events have been done with quasistatic models which only approximate to dynamic effects by inclusion of a radiation damping term (Rice, JGR, 1993) or provision for dynamic overshoot (Ben-Zion and Rice, JGR, 1993).] This elastodynamic work has begun with the simple setting of 2D anti-plane deformation. We have developed an efficient and stable computational technique, based on spectral representations of the stress and slip histories, that includes velocity weakening friction in the now standard rate- and state-dependent framework. The spectral representations are truncated at short (and very long) period, with rapid FFT techniques used to evaluate the interrelation between the stress and slip histories. The methodology is open to generalization to 2D problems of in-plane slip and general 3D problems, and we are exploring such as time allows. Further, its spectral basis leads to results that are apparently free of numerical oscillation problems that have plagued previous work based on related boundary integral formulations, but whose basis is instead stress (e.g., Das, Kostrov, Andrews) or slip (Madariaga and Cochard) over cellular domains.

We are currently studying dynamic models of rupture scenarios, in the anti-plane elastic setting, to begin to understand issues such as the following: How does the heterogeneous stress state along a fault, as created in the wave-mediated elastodynamics of arrest of slip, set the initial conditions for the next earthquake(s) there? Can such stress heterogeneity be regenerating from event to event, in that strong but heterogeneous dynamic overshoots provide under-stressed regions that can stop future ruptures, and thus provide a basis for sustained spatio-temporal complexity of faulting? Along the way, we are gaining an understanding of the remarkably complex sequences of slips that occur in the elastodynamics of starting of rupture along a suddenly loaded fault segment that carries a highly heterogeneous pre-stress.

Also, we have rewritten the quasistatic computer coding with radiation damping (Rice, JGR, 1993), used for the modeling of recurrent events, converting to a new code with fully explicit procedures and adopting a similar framework and spectral basis for slip as in the elastodynamic code. Thus we will soon have a 2D code which can properly switch to an elastodynamic mode when response requires, but which can nevertheless simulate the 100's to 1000's of years of seismic history and recurrence statistics that we now routinely study using the quasistatic models; that approach should ultimately be extendable to our 3D fault modeling.

Leon Knopoff

PROGRESS REPORT 1993, UCLA SEISMICITY MODELING GROUP

Chen and Knopoff have constructed a program to simulate plane strain fracture on a two-dimensional fault structure. The model is a fusion of the Mikumo/Miyatake plane strain model of fracture and the Burridge/Knopoff model of recurrence. The model is a 2-D particulate model in which each lattice site is coupled to nearest and next-nearest neighbors by 16 springs in the plane plus the usual transverse spring that drives the model. The 16 springs simulate the pure shear, pure compression and coupled shear/compression modes of deformation (the latter term presents some computational difficulties when applied near free surfaces.) We have simulated dynamical stress transfer in the elastic medium astride the fault by means of an equivalent vector dynamical friction proportional to the particle velocity. We have applied the model to an elongated 15x500 fault lattice in dimension; we imagine that the grid spacing is 1 km, with obvious implications for California faulting. The driving stresses are parallel to the long dimension the fault, and are applied through the transverse springs that extend from the anvils to the lattice sites.

The ends of the fault structure have periodic boundary conditions, the upper surface is free and the lower surface has a viscous boundary condition, i.e., it is unbreakable during the rupture event but any stress stored by the fracture is dissipated in the slow time interval between earthquakes. In these simulations we have considered a case of homogeneous friction and prestress with nucleation at a point in the interior. The fracture grows in a more or less elliptical shape until the fracture surface encounters the upper and lower boundaries. Healing is initiated as a reflection from both boundaries; an observation of healing initiated at the free surface was unexpected, but is now understood to be a consequence of the energy loss due to transport by elastic waves away from the faults. The fracture event then splits into two patches, which we identify as Heaton patches, and which then travel away from each other with constant velocity and constant shape for a given transverse (driving) spring constant. When a patch encounters a small asperity in its path, the fracture wraps around it and the patch continues to travel in a relatively unperturbed state. If the asperity is located at the surface it yields a kink in the surface slip, not unlike the observations in the Landers earthquake.

Rice has recently pointed out an incompatability between the homogeneous discrete lattice models of the B-K type and continuum models of faulting. While this does not directly impact on our focus on inhomogeneous systems, the discrepancy between our lattice system and the homogeneous continuum casts a shadow of unease on our use of the discrete lattice systems in the inhomogeneous cases. Xu and Knopoff have therefore considered a homogeneous version of the B-K 1-D system, with a dynamical friction adjusted to simulate the stress concentrations in the elastic medium adjoining the fracture surface, and with periodic boundary conditions in 1-D. We find that, for arbitrary initial conditions, the finite periodic lattice system at first undergoes a transient state in which it generates a Gutenberg-Richter power law distribution of earthquake sizes. After the G-R transient, it settles into a permanent state of periodic runaway events, in which the entire chain ruptures; in the permanent or steady state there are no smaller events. The periodicity leads us to agree with Rice that inhomogeneity must be introduced into these systems: it also restores our confidence in the relevance of our version of the B-K model. This result also indicates that reports of G-R distributions on finite homogeneous discrete lattice systems are due either to observations of a transient state, i.e., the computations were not carried out for a long enough time, or due to internal scale sizes not considered in our scale independent model, or due to hidden inhomogeneities in the system, such as reflections of healing stresses at incompatible end conditions, such as free or open end conditions.

Landoni and Knopoff have pursued the interaction between the long-term organization of seismicity implicit in model systems without viscous, e.g. creep effects, and the influences of viscous processes on intermediate-term clustering. Non-elastic deformation such as strain-hardening or slip-weakening obviously advance the times at which fractures take place. We have compared synthetic seismicity on a 1-D B-K model with an inhomogeneous distribution of critical fracture thresholds, and without other non-elastic effects, with the results from these same models with a precursory viscous rheology in the inter-earthquake interval. The viscous effects are assumed to be strongest immediately before or after the rapid fracture event. Although we have performed experiments on several forms of weakening of fracture strength prior to rupture, in general we find no significant influences on the seismicity patterns whether slip-weakening is present or absent. However if we introduce a slow restoration of fracture strength after rapid rupture, we find a significant change in pattern away from the irregular space-time organization of the instantaneous healing model and toward a localized periodic organization of events on all scales. We argue that postcursory creep is a potentially potent influence on organization of seismicity and hence if present in the real earth, could play an important role in contributing to the earthquake prediction enterprise. We urge that more attention be paid to postfracture anelastic effects both in the field and in the laboratory.

Keilis-Borok, Knopoff and Levshina have studied the space-time relationships between strong earthquakes and intermediate-magnitude earthquakes both before and after the strong earthquakes. Seventeen out of the 18 strong earthquakes in California with magnitudes greater than 6.4 in the interval 1941 to 1993 were preceded by an increase in intermediate-magnitude precursory activity (defined as events with magnitudes greater than about 4.7) over times ranging from a few months to several years. The precursory activity is concentrated in well-defined regions having linear dimensions of the order of a few hundred kilometers; these dimensions are significantly larger than the estimated fracture lengths of the ensuing strong earthquakes. Earthquakes with magnitudes less than about 4.4 or so, do not exhibit a similar increase in rate prior to strong earthquakes. The precursors to the largest of these strong earthquakes may occur over a longer precursory time interval and have larger magnitudes than do the precursors to smaller ones. Most frequently, the strong earthquake is located at the edge of a boundary between a zone of increased activity and a quiescent zone. All of the 18 strong earthquakes either switch off the increased activity abruptly, or are themselves part of a precursory pattern of continued activity before soon-to-occur additional strong earthquakes. the most remarkable of these observations is the long-range of these interrelationships as well as the fact that the decrease in seismicity over these long distances is relatively abrupt. We have developed a skeletal theory for the long range, intermediate-term, intermediate-magnitude interactions that invokes only the elasticity of the seismogenic plates and the distribution of fractures.

Progress report for Bruce Shaw for 1993

Two papers appeared in print this last year [Shaw, 1993a; Shaw, 1993b]. Two other papers were accepted for publication [Pepke, Carlson, and Shaw, 1993; Carlson, Langer, and Shaw, 1993]. A fifth paper was completed and submitted for publication [Shaw, 1993c]. Below, some of the results from these papers are briefly summarized.

"Moment Spectra in a Simple Model of an Earthquake Fault" recently appeared in *Geophysical Research Letters*, [Shaw, 1993a]. In this paper, the dynamics of the Burridge-Knopoff model was studied on the timescale of the rupture process. Large events were seen to consist of narrow pulses of slip propagating down the fault. The pulses of slip roughly inverted the displacement field, with places that were more retarded moving more, and places that were less retarded moving less. The moment release rate fluctuated as the pulses of slip passed over the rough displacement field. 'Subevents' were seen in the large events, with fluctuations in the moment release rate being of order the rate itself. A quantitative characterization of the motion was given by measuring the average moment spectra in the far field. Power laws in the spectral amplitudes were seen. A bend in the spectra of large events was seen, at a frequency corresponding the the length scale marking the transition from small to large events.

"Generalized Omori Law for Aftershocks and Foreshocks from a Simple Dynamics" recently appeared in *Geophysical Research Letters*, [Shaw, 1993b]. In this paper, I present a simple dynamical explanation for the time delay associated with aftershocks and foreshocks, and then present a series of measurements of aftershocks and foreshocks of small magnitude mainshocks, using the USGS catalogue for Central and Northern California from 1969-1990. The derivation of the Generalized Omori Law is based on the response to sudden forcing of a nucleation dynamics of self-driven acceleration to failure. The physical idea the dynamics is meant to represent is subcritical crack growth. One of the most interesting aspects of the derivation, is that an Omori law decay exponent of 1 is seen to be a generic value for strongly accelerating systems. Next, the simplest explanation of foreshocks is supposed– that they are events that happened to have an afterevent that was bigger. From this hypothesis, and the time dependence of aftershocks, the time dependence of foreshocks is derived. The last half of the paper involves the measurements from the USGS catalogue to see whether they are consistent with the simple theory. First, the time dependence of aftershocks as a function of mainshocks magnitude is examined; the exponent of the Omori law decay is seen to be independent of mainshock magnitude. Second, the spatial and temporal dependence of aftershocks is examined; it is observed that the dependence is separable into a dependence on space and a dependence on time. The figure from the paper showing this is reproduced in Figure 1. This is an important simplification, and allows for explanations which only consider temporal dynamics to be possible. A third measurement examined the number of aftershocks and foreshocks as a function of mainshock magnitude, and observed that the number of aftershocks approaches the number of foreshocks as the mainshock magnitude becomes smaller. This observation is expected by the simplest explanation of the relationship of foreshocks to aftershocks.

"Prediction of Large Events on a Simple Dynamical Model of a Fault" [Pepke, Carlson, and Shaw, 1993] was accepted for publication in *Journal of Geophysical Research*. The paper presents results for long term and intermediate term prediction algorithms applied to a catalogue generated by the Burridge-Knopoff model. The idea in this paper is to study issues related to algorithm optimization and the intrinsic limitations of algorithms, in a situation where we have well controlled, intrinsically complex catalogues. The catalogues generated by the model are of arbitrary length, and arise from a model which is deterministically chaotic. Here, we seek not to show that any particular complex seismicity pattern generated by the model matches the Earth, but rather to study how algorithms based on intrinsically complex patterns work, and how algorithm optimization works on such catalogues. Some of our results are as follows.

One methodological question we address is the evaluation of the performance of a prediction algorithm. For this purpose, we introduce a linear cost-benefit function Q, which quantifies the tradeoffs that necessarily must be made between the different goals of the prediction scheme. It measures the extent to which an algorithm is able to fulfill all of the prediction goals ($Q = 1$) relative to the option of doing nothing at all ($Q = 0$). In the cases we consider, the goals are to predict the future event, with the alarm time on for as little time as possible, and with the minimum of false alarms.

As a benchmark for evaluating the results of the intermediate predictions, we first evaluated long term predictability. Three commonly used methods were examined: the time-predictable and slip-predictable models, as well as a prediction based on recurrence intervals. Neither the time-predictable nor the slip-predictable models described the behavior very well, though the time-predictable model did slightly better. Interestingly, for either the time or slip-predictable models, it was possible to find good correlation over just a few subsequent large events. At any point, however, such a short time "pattern" could be broken, with the next event differing dramatically from the proposed model.

Intermediate term prediction, based on individual precursor measures of the small event activity, produced forecasts with much smaller time windows than the long term predictors. Four predictors were considered. In order of best performance, they were active zone size, activity, rate of change of activity, and finally, fluctuations in activity, which did much worse than the other three.

Finally, we considered the effect of finite catalogue lengths. We measured the average and standard deviation of Q as the catalogue length was increased. The average Q rose rapidly to its maximum, and the standard deviation dropped rapidly to its minimum in less than a repeat time. This is relevant for the question of the stability of the learning process for algorithms. In the model, we find that catalogues containing one large event are sufficient for stability in learning. If these results also apply in the Earth, one would expect continued improvement in algorithm performance as catalogue lengths reach the repeat times of large events, with a much slower improvement after that.

"Dynamics of Earthquake Faults" [Carlson, Langer, and Shaw, 1993] has been accepted for publication in *Reviews of Modern Physics.* In this paper, we review the variety of results that have been found concerning the behavior of homogeneous fault models with stick-slip friction and inertial dynamics. This paper was solicited by the editors, due to widespread interest in the physics community in the work our group has been doing on these fault models.

"Complexity in a Spatially Uniform Continuum Fault Model" [Shaw, 1993c] was completed and submitted for publication in Geophysical Research Letters. This paper addressed the question raied by Rice [JGR, 1993; a "top ten" on the SCEC list] of whether faults with a continuum limit could generate complex nonperiodic sequences. Here, I show that the introduction of a viscous term to the Burridge-Knopoff model provides a small lengthscale cutoff which allows a well defined continuum limit, and which continues to generate complex nonperiodic sequences. The figure from the paper demonstrating this is reproduced in Figure 2. Thus spatial heterogeneity or inherent discreteness is shown to not be a necessary condition for complex sequences. Rice has shown that long range quasistatic interactions appear not to give complex sequences in the continuum limit; here I show that short range interactions with inertial dynamics do. The big question for seismology– what happens with both long range and fully dynamic interaction remains an open question.

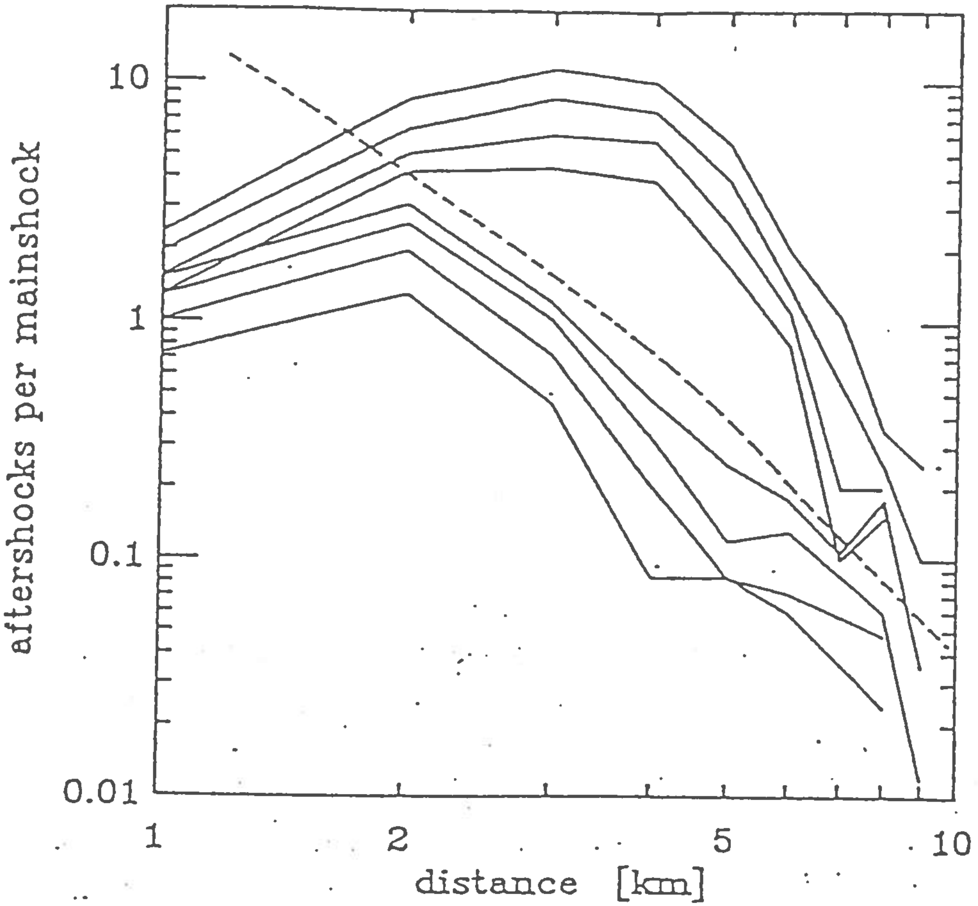

FIG 1. The spatial distribution of aftershocks for real earthquakes. The number of aftershocks per mainshock as a function of distance is plotted, for events happening up to a given time following the mainshock. Distance is measured between hypocenters, in units of kilometers. The four solid curves are for mainshocks with magnitudes between 4 and 5, while the four dotted curves are for mainshock magnitudes between 5 and 6. The long dashed curve is a theoretical curve (see Eq.(15)). The times of the four curves in each set are all the events before 1/3, 1, 3, and 9 days. Observe that the spatial distribution appears stationary in time; it does not broaden, and only the rate of events changes. The finite size of the source can be seen in the drop in events at small distances.

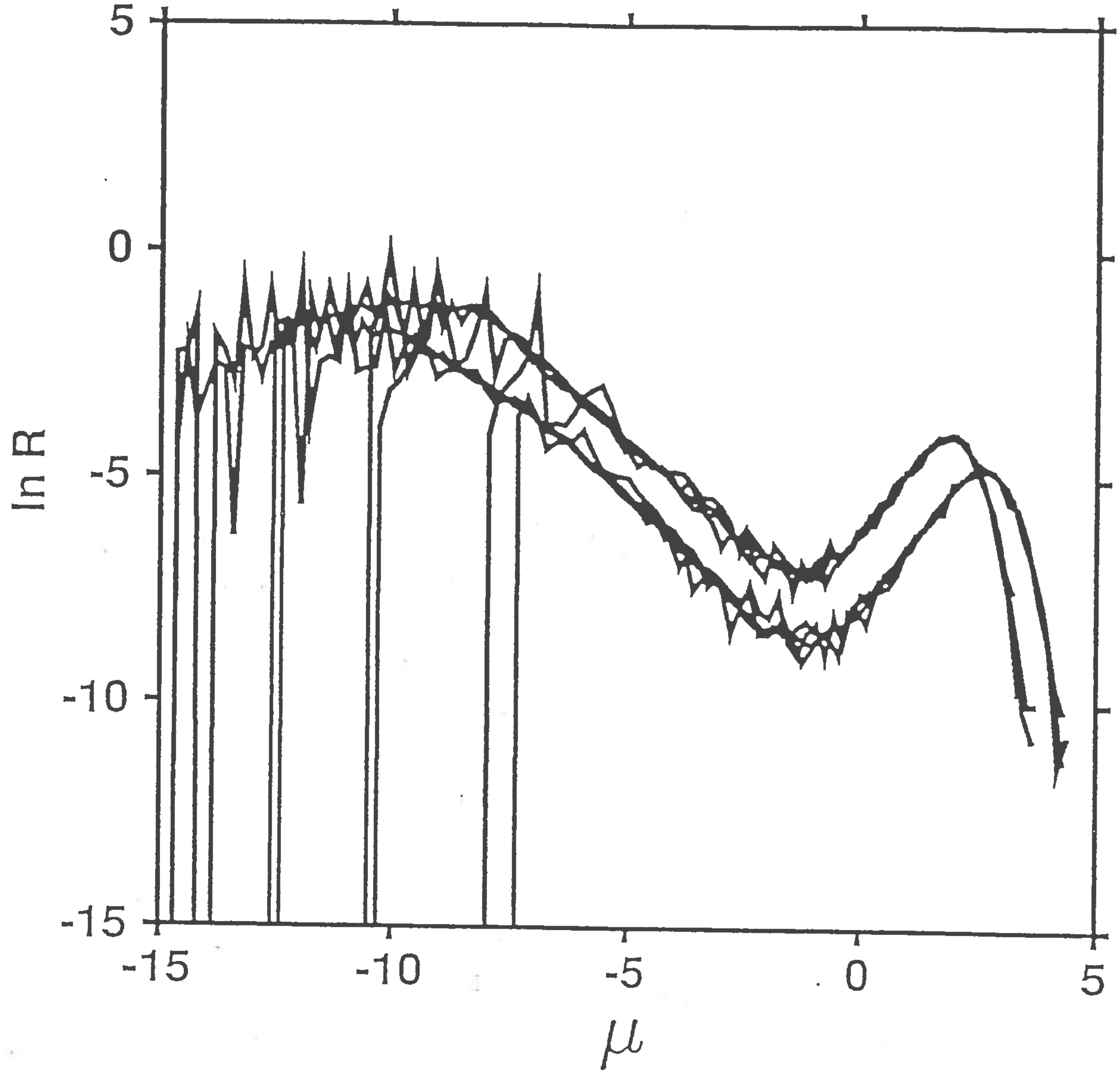

FIG 2. The distribution of sizes of events for a homogeneous continuum fault model. The relevant small lengthscale is set by a viscous term. There are eight different curves on the plot, with four different values of the numerical resolution for two different viscous lengths. The eight different curves collapse onto two sets, corresponding to the two different values of the viscous term. The important thing to see in the figure is that the distributions that are obtained are independent of the numerical resolution, and depend instead on the viscous term. Thus, we have obtained a complex nonperiodic sequence of events with a spatially uniform continuum fault model.

3-D DYNAMIC MODELING - EFFECTS OF FAULT GEOMETRY ON EARTHQUAKE RUPTURES IN SOUTHERN CALIFORNIA

FY93 PROGRESS REPORT TO THE SCEC

Ruth A. Harris
(U.S.G.S., Menlo Park)

In FY 1993 I was a Visiting Scientist at the SCEC and received $16,500.00 of financial support for my research on '3-D Dynamic Modeling-Effects of Fault Geometry on Earthquake Ruptures in Southern California'. My tenure was at the USGS in Menlo Park and my sponsor was Ross Stein.

This has been a very exciting year for my research on dynamic rupture propagation. For the past 2 years, with the generous collaboration of Steve Day, I have been using a 2D finite-difference computer code to numerically simulate earthquake ruptures jumping between fault segments [Harris et al., 1991; Harris and Day, 1993]. In 1992 I started using a 3D code and extended my modeling efforts to the more realistic 3D case. The 3D simulations have been specifically applied to the scenario of an earthquake which nucleates on the Anza segment of the San Jacinto fault zone [Harris et al., 1992; Harris et al., manuscript to be submitted]. The results of my numerical modeling efforts have been presented to the scientific community at a number of meetings, workshops, and seminars, but the implications of my results were not widely appreciated at first (as is the usual case for new research). Then, on June 28, 1992 the M7.4 Landers earthquake occurred. This earthquake jumped previously defined segment boundaries [Wesnousky, 1986], rupturing 5 southern California faults, and evolved into the largest earthquake to strike California in the past 40 years.

Since the Landers earthquake, detailed analyses of the strong motion data [e.g. Kanamori et al., 1992; Wald and Heaton, submitted; Campillo and Archuleta, 1992] have revealed that the Landers earthquake did indeed follow many of the patterns predicted by the Harris and Day [1993] numerical models. The predicted and observed patterns include time delays at the stepovers, and 'bilateral slip' after the rupture jumped to another fault segment. Most significantly, the numerical models were able to predict that jumps between fault segments spaced only 1-2 km apart are very reasonable. The Landers earthquake has demonstrated that at least for some strike-slip faults in the eastern Mojave shear zone, my numerical modeling results can be directly applied to real cases of earthquakes jumping between fault segments. With this insight I am enthusiastically continuing the 3–D modeling effort and plan to tackle the case of non–parallel strike-slip faults, with the collaboration of Steve Day.

As part of my dynamic numerical modeling efforts, I am also working with David Pollard on a project which aims to determine if it is possible to distinguish between dynamic and static effects of earthquakes when studying the geological record of paleoearthquakes. The results of our study [Pollard and Harris, in press] will be presented at a special session of the annual GSA meeting in October 1993.

On a final note, during my tenure as an SCEC visiting scientist I have also had the opportunity to investigate detailed models of the effects of the Landers earthquake's static stress changes on nearby faults in southern California. The beginnings of this study were published as a paper in the journal Nature in 1992 [Harris and Simpson, 1992], and contributed heavily to the Phase I Landers report. In FY 1993 we (Bob Simpson and I) have extended our previous study to encompass all of the known active faults in southern California. This work [Simpson and Harris, submitted] has been submitted to the BSSA Landers special issue. The paper also investigates the effects of the Landers earthquake relative to two great (M8) California earthquakes, the 1906 San Francisco earthquake and the 1857 Ft. Tejon earthquake. The investigation into the impressive effects of the 1857 earthquake on southern California faults will be discussed at the 1993 Fall AGU Meeting in San Francisco [Harris and Simpson, submitted].

I would like to thank the SCEC for the financial support during FY93. I definitely plan to continue my collaboration with the SCEC in the months and years to come.

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Southern California Earthquake Center

Summary Report on the Research Contract

Sponsored by

The State of California Department of Transportation
The Los Angeles County Department of Public Works
The City of Los Angeles Department of Public Works

on

The Characteristics of Earthquake Ground Motions for Seismic Design

Principal Investigators: Geoffrey R. Martin
Assistant Director for Engineering Applications
Keiiti Aki
Science Director

I. Tasks

The three year contract was initiated in April, 1992. The research tasks complement ongoing SCEC research, and have as their general objective the development and completion of seismological and geotechnical data relevant to State, County, and City programs in seismic design of bridge and buildings. The research program is presently subdivided into eight asks as listed below.

Task H-1: Characteristics of Earthquake Response Spectra in Southern California See H4
V. Lee and M. Trifunac, University of Southern California

The goal of Task H-1 is to develop improved empirical models for scaling the amplitudes of smooth elastic earthquake response spectra characteristics of the Southern California region, for use in design. These empirical scaling equations can be used directly for prediction of site-specific spectrum amplitudes given the earthquake magnitude, the distance from the source, and the geological and local site conditions at a particular site. The scaling equations also provide the means for providing improved attenuation relationships for use in probabilistic earthquake hazard analyses. The new scaling equations will be developed by regression analyses of a large number of strong motion records. During the first year of work of this task, the focus was on preparation of earthquake data for analysis and on developing functional relationships to guide critical parameters for the regression analyses.

Task H-2: Southern California Fault and Earthquake Parameters See Group C
K. Sieh, California Institute of Technology

Research supported by Task H-2 has focused on identifying sources of destructive earthquakes in the Los Angeles metropolitan region, particularly in the northern Los Angeles basin. Results of research have been extremely productive in delineating the seismic hazards posed by the Santa Monica and Hollywood faults and has provided a major contribution in the understanding of potential earthquake behavior of the blind thrust faults that underlie much of urban Los Angeles.

Task H-3: Effects of Local Site Characteristics on Ground Accelerations — See H5
K. Aki and G. Martin, University of Southern California

The goal of Task H-3 is to evaluate the extent of amplification of ground motions arising from the presence of site specific soil profiles. This task becomes complex for very strong ground motion as amplification factors depend on the level of ground shaking, that is, site effects are nonlinear. As part of the first year activities, a preliminary GIS based map of weak motion amplification factors for Southern California has been constructed. To further pursue questions related to weak motion amplification factors and nonlinear effects, several portable broad band seismometers have been installed close to existing sites of strong motion seismographs in the Los Angeles basin. Data acquisition is in progress utilizing regularly occurring small earthquakes. Analysis of data recorded on the portable instruments is continuing together with evaluation of methods to correct for nonlinear effects.

Task H-4: Duration of Strong Motion Shaking in Southern California — See H8
M. Trifunac and V. Lee, University of Southern California

The goal of Task H-4 is to develop improved empirical models by scaling the duration of strong ground motion of the Southern California region by utilizing regression analyses of recorded data. The developed regression equations describe the duration of strong ground motion in terms of the seismic energy available to excite the structures. As all the processes effecting duration are frequency dependent, analyses of duration have been performed in twelve narrow frequency bands with a central frequency between 0.1 to 25 Hz. The developed functional relationships and scaling models have been verified by currently available strong motion data in California.

Task H-5: Geotechnical Site Data Base for Southern California — See H10
M. Vucetic, University of Southern California

The objective of Task H-5 is to compile a geotechnical database for the Los Angeles Basin for use in strong ground motion site characterization. Such a database will be particularly valuable in assessing questions related to site amplification and site stability during strong ground motion. The program TECHBASE (a mining and geotechnical oriented three-dimensional GIS software package with capabilities of generating soil and geologic profiles and boring logs is being used. Collection and digitization of relevant geotechnical and geologic data, particularly shear wave velocities, is continuing.

Task H-6: Evaluation of Bridge Damage in Recent Earthquakes — No Report
J. Hall and R. Scott, University of Southern California

The objective of this task is to study the earthquake performance and damage to bridges in the magnitude of 7.8 Lugos, Philippines earthquake (July, 1990) and the magnitude 7.5 Costa Rica earthquake (April, 1991). Research activity to date has largely focused on completion of a report on the Costa Rica earthquake. In the second year, research is focusing on the Philippines earthquake.

Task H-7: Probabilistic Evaluation of Acceleration Response Spectra and Earthquake Time Histories for Southern California (Year Two)
G. Martin and K. Aki, University of Southern California

The initiation of this task in year two of the research program has the objective of developing a consensus among the scientific and engineering earthquake community in Southern California, regarding the critical input data needed for proposed probabilistic analytical studies planned in year three.

A series of four mini-workshops to develop a consensus regarding the database are planned. These mini-workshops will bring together earthquake engineers, geologists, and seismologists (from both the consulting and academic environment) and will include input from Southern California Earthquake Center scientists working on related studies. The workshops will encompass the following areas:

1) The seismotectonic characterization of Southern California.

2) Attenuation relationships required for probabilistic analyses.

3) Probabilistic computer codes.

4) Methodologies available to develop earthquake time histories.

Task H-8: Liquefaction Characteristics and Liquefaction Potential of Southern California Sites (Year Two) See H13
G. Martin, University of Southern California

The objectives of this task are to:

1) Digitize available liquefaction potential maps as part of our developing GIS database.

2) Re-assess and improve the database used to develop the above maps by taking advantage of the developing database of borehole data being compiled as part of Task H-5.

3) Develop a more quantitative approach for assessment of post liquefaction ground deformation potential suitable for mapping.

Task H-8 is in effect an extension of Task H-5. The two tasks together have the overall objective of providing a comprehensive geotechnical site database, including seismic hazard assessments in a form suitable for both planning and engineering design purpose.

Brief progress summaries of individual tasks follow with the exception of Tasks H-6 and H-7. Progress on Task H-6 has been limited due to the rescheduling of planned travel to the Philippines. The Task H-7 workshops have been initiated, the first two-day workshop on "Seismotectonic Characterization of Southern California," being held on November 8-9, 1993. The workshop was attended by about 40 leading scientists and engineers in various disciplines, and provided a forum for a critical evaluation of the SCEC seismotectonic model.

TASK H-1 CHARACTERISTICS OF EARTHQUAKE RESPONSE SPECTRA IN SOUTHERN CALIFORNIA

CO PI's: TRIFUNAC, LEE AND TODOROVSKA

SUMMARY

The empirical equations for scaling Fourier and Response amplitude spectra in the frequency band from ~ 0.1 to 25 Hz can be extrapolated to describe the long and short period strong motion amplitudes. The results of this extrapolation agree with (1) the seismological and field estimates of permanent ground displacement (near field), and with (2) the independent estimates of seismic moment and the observed corner frequencies of far field Fourier spectrum amplitudes.

At high frequencies ($f > 25$ Hz) the spectral amplitudes can be described by $\exp(-\pi \tau f)$, where τ ranges from .02 (near the source) to about .06 at epicentral distance of ~ 200 km.

The amplification of strong motion amplitudes by local soil and geologic site conditions can be defined to apply in the same broad frequency range.

To propose the final generation of empirical scaling equations, we are at present working on the refinement of the frequency dependent attenuation equations, and on the more detailed classification of the local soil and local geologic site conditions.

The work completed to date is summarized in the following publications:

Trifunac, M.D. (1993). Fourier Amplitude Spectra of Strong Motion Acceleration: Extension to High and Low Frequencies, Earthquake Eng. and Structural Dynamics, (in press).

Trifunac, M.D. (1993). Long Period Fourier Amplitude Spectra of Strong Motion Acceleration, Soil Dynamics and Earthquake Eng. (in press).

TASK:H-3

Effects of Local Site Characteristics on Ground Accelerations

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University of Southern California

The well established separability of source, path and site effects on coda waves of local seismic events offers the most effective means for determining the site amplification factor empirically. Many studies have confirmed that the coda amplification factor represents those of S waves averaged over various directions of wave approaches. A systematic relation has been found between the coda amplification factor and the age of surface geology at the recording site in California, and has been used to interpolate coda amplification factors observed at selected sites to construct maps of amplification factors in California.

We found that, in general, the coda amplification factor is applicable to strong ground motion at rock sites. It is also applicable to soil sites, if the basement acceleration level is lower than about 0.1 g. We found, however, the coda amplification factor overestimates the observed strong motion amplification at soil sites when the basement acceleration level exceeds 0.1-0.2 g. These discrepancies can be explained by the increased absorption due to the non-linear histeresis in soil response. A preliminary method by M. Mahdyiar and others (1993) for correcting the coda amplification factor for the non-linear effect is also being tested. This method is based on the following two assumptions.

(1) The non-linear effect attenuates the coda amplification factor as a function of frequency f in the form exp($-\alpha$f), where α is a constant. This assumption is consistent with the interpretation that the non-linear soil response is primarily due to stress-strain histeresis. In that case, the fractional loss of energy is independent of frequency (constant Q), and the frequency dependence of attenuation will be of the form exp($-\alpha$f).

(2) We assume the existence of a universal relation between the peak ground acceleration observed at the surface of a soil site and that at the basement rock beneath the site. This is a drastic, and probably oversimplifying assumption, but is supported from several studies.

Fig 1 shows comparison between observed and predicted 5% pseudo relative velocity response at various stations from the Landers earthquake of 1992. Also shown are the expected values with the 84% confidence interval based on regression analysis of strong motion data by Trifunac and Lee (1989). The applicability and uncertainty of predicted response spectra for our calculation is compatible with the one calculated from regression analysis of strong motion data as shown in Fig 2. Similar results can also be found for the 1989 Loma Prieta earthquake.

We are currently measuring the coda amplification factor, at the site of strong motion seismographs where strong motion data from past earthquakes are available, and where subsurface shear wave velocities have been estimated for geotechnical studies in order to develop the non-linear correction.

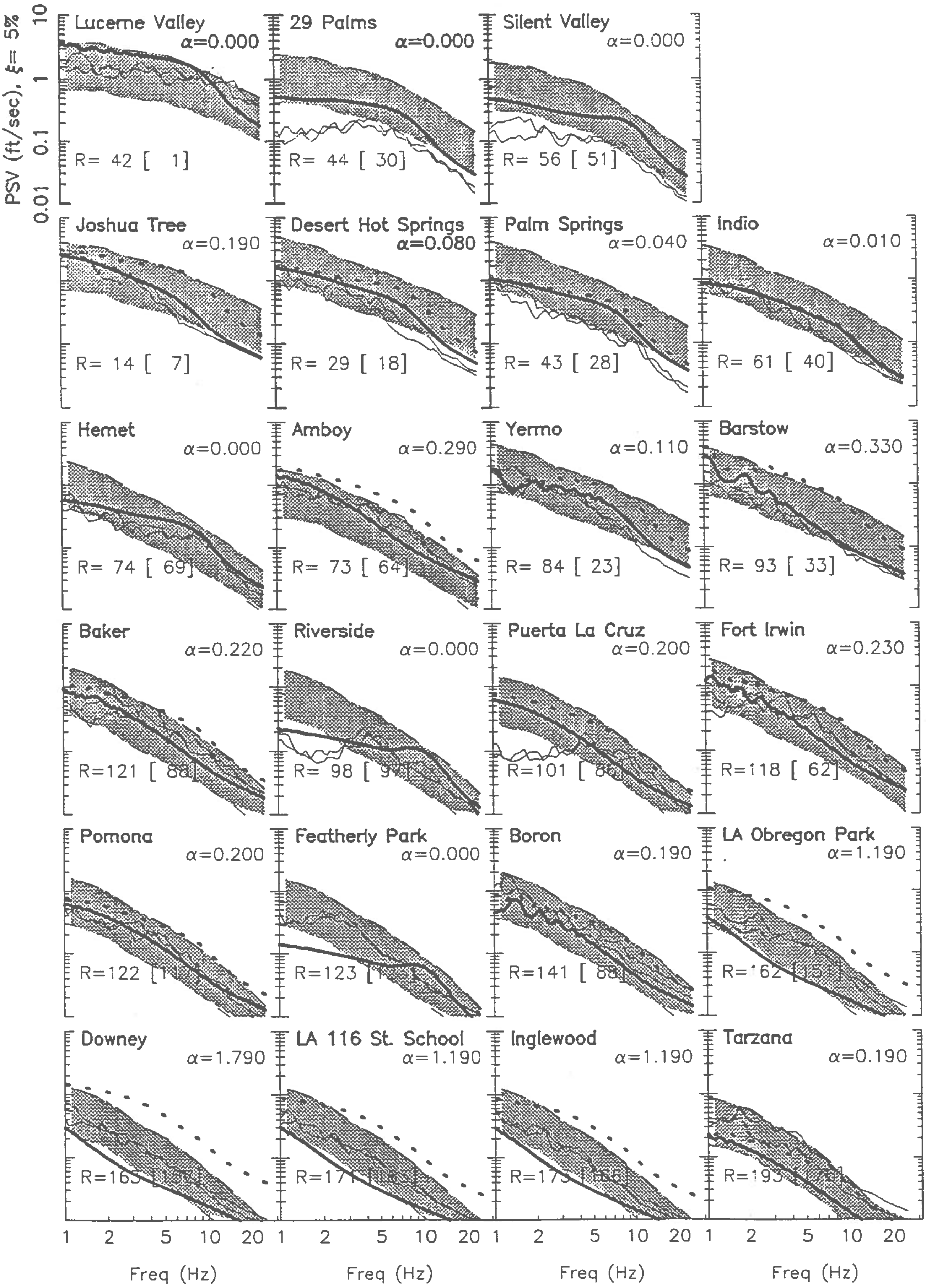

Fig. 1. The comparison between observed (thin lines) and predicted (thick lines) 5% pseudo velocity response spectra correct by the factor exp(-αf). The thick dashed line indicates the predicted spectra for α=0. The shaded region represents the expected values with the 84% confidence interval based on regression analysis of strong motion data by Trifunac and Lee (1989).

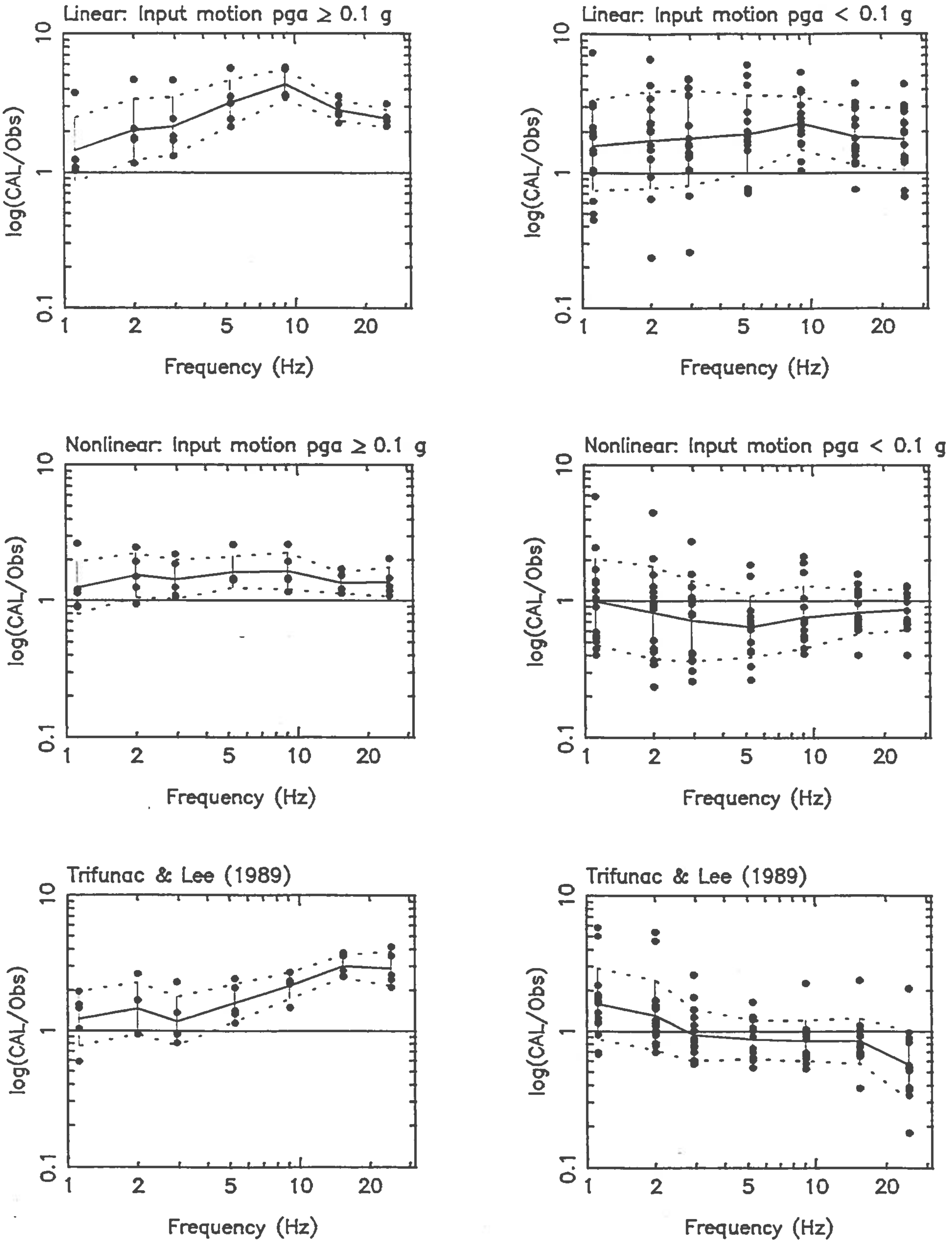

Fig. 2. The response spectral ratio of predicted to the observed as a function of frequency based on our calculation and empirical equation derived from regression analysis for the strong motion data (Trifunac and Lee, 1989). At high basement acceleration level (pga>0.1 g) as shown on the left hand side of the figure, the calculation based on the linear model (for $\alpha=0$), nonlinear model and the Trifunac and Lee's empirical equation are shown at the top, middle and bottom, respectively. The same results shown on the right hand side are for lower basement acceleration level (pga < 0.1 g).

TASK H-4 DURATION OF STRONG MOTION SHAKING IN SOUTHERN CALIFORNIA

CO PI's: TRIFUNAC, LEE AND TODOROVSKA

SUMMARY

The physical bases and empirical equations for modelling the duration of strong earthquake ground motion in terms of the earthquake magnitude, the epicentral distance and the geological and local soil site conditions are investigated. At 12 narrow frequency bands, the duration of a function of motion $f(t)$, where $f(t)$ is acceleration, velocity or displacement, is defined as the sum of time intervals during which the integral $\int_0^t f^2(\tau)d\tau$ gains a significant portion of its final value. All the records are band-pass filtered through 12 narrow filters and the duration of strong ground motion is studied separately in these frequency bands. It is shown that the duration of strong motion can be modeled as a sum of the source duration, the prolongation due to propagation effects and the prolongation due to the presence of the sediments and local soils. It is shown how the influence of the magnitude on the duration of strong ground motion becomes progressively stronger, in going from low to moderate frequencies, and that the duration is longer for "soft" than for "hard" propagation paths, at low and at moderated frequencies. At high frequencies, the nature of the broadening of the strong motion portion of the record with increasing distance is different, and is most likely related to the diffraction and scattering of the short waves by the velocity inhomogeneities along the wave path. It is also shown that the geological and local soil conditions should both be included in the model. The duration can be prolonged by 3.5 sec at the site on a deep sedimentary layer at frequencies near 0.5 Hz, and by as much as 5 $\div$ 6 sec by the presence of soft soil underneath the station, at frequency of about 1 Hz. Empirical equations for probabilistic estimates of the discrepancies of the predictions by our models relative to the observed data (distribution function of the residuals) are presented.

To date, the following papers have been completed:

Novikova, E.I and M.D. Trifunac (1993). Duration of Strong Ground Motion in Terms of Earthquake Magnitude, Epicentral Distance, Site Conditions and Site Geometry, Earthquake Eng. and Structural Dynamics (in press).

Novikova, E.I. and M.D. Trifunac (1993). The Modified Mercalli Intensity and the Geometry of the Sedimentary Basin as Scaling Parameters of the Frequency Dependent Duration of Strong Ground Motion, Soil Dynamics and Earthquake Eng. (in press).

Novikova and Trifunac (1993). Modified Mercalli Intensity Scaling of the Frequency Dependent Duration of Strong Ground Motion, Soil Dynamics and Earthquake Eng. (in press).

Novikova, E.I. and M.D. Trifunac (1993). Influence of the Geometry of Sedimentary Basins on the Frequency Dependent Duration of Strong Earthquake Ground Motion, Earthquake Eng. and Eng. Vibration (in press).

Novikova, E.I. and M.D. Trifunac (1994). Duration of Earthquake Fault Motion in California, (submitted for publication).

TASK H-5: GEOTECHNICAL SITE DATA BASE FOR SOUTHERN CALIFORNIA

by
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During the first 1.5 years of this three-year project the following tasks have been achieved: (i) the geotechnical parameters related to earthquake damages that are most relevant for mapping were selected, (ii) suitable computer hardware and GIS software were acquired and installed, (iii) basic and advanced seminar training with the selected GIS geotechnical software "Techbase" was taken, (iv) digitized maps comprising base layers of GIS (coastline, highway and freeway system, earthquake faults, etc.) have been acquired and transformed into a desired format, (v) the collection of relevant geotechnical and geological data, their organization and evaluation has started and continues, and (vi) the digitization of relevant geotechnical and geological data has started.

During the last several months the following progress has been made:

(i) Learning of more advanced "Techbase" tasks and computer data manipulations continues with help from "Minesoft" company, which is the author of "Techbase"
Manipulations with large data bases and utilization of their relations have been studied. The most efficient ways to generate boring logs and associated data are explored. The boring logs can now be plotted automatically using data organized in various "Techbase" fields and tables.

(ii) The boring log format has been generated
The selected boring log format is given in appendix along with the legend of symbols and terms used. There will be two boring log forms, one in *SI* units and the other in *British* units. The transformation between the two forms will be automatic. There will be one boring log for each location on the map, regardless of the data available. This means that not all of the information will be included in all boring log forms. The information included in the boring logs in digitized form will be subsequently manipulated to obtain different GIS maps.

(iii) Organization and digitization of data
The soil properties data, shear wave velocity distribution data and Standard Penetration Test results are being digitized, as specified in the boring log form. Undergraduate students are also being trained to help with this task. To date, approximately 40 boring logs have been digitized. The rest of the second year will be spent mainly on further digitization.

BORING LOG PATTERN AND SOIL TYPE

⁙	GRAVEL	GR
▩	SAND	SA
▤	SILT	SI
▦	CLAY	CY
▓	SANDY CLAY OR CLAYEY SAND	SA.CY CY.SA
▓	SANDY SILT OR SILTY SAND	SA.SI SI.SA
▤	SILTY CLAY	SI.CY
▤	CLAYEY SILT	CY.SI
✱	PEAT/ORGANIC MATTER	PO
▒	FILL MATERIAL	FM
▧	IGNEOUS ROCK	IR
☰	SEDIMENTARY ROCK	SR
▥	METAMORPHIC ROCK	MR

UNIFIED CLASS. SYMBOL

ACCORDING TO UNIFIED SOIL CLASSIFICATION

PLASTICITY DESCRIPTIVE

NON LOW MEDIUM HIGH

ACCORDING TO FIELD IDENTIFICATION, VISUAL INSPECTION OR LABORATORY CLASSIFICATION

PLASTICITY INDEX (PI)

PI = LIQUID LIMIT – PLASTIC LIMIT

SILT CONTENT

% OF FINES PASSING THROUGH STANDARD SIEVE NO.200 WITH OPENINGS 0.075 mm

STIFFNESS OR DENSITY

ACCORDING TO THE STANDARD PENETRATION TEST

PENETRATION INDEX (BLOWS/FT)	GRANULAR	COHESIVE
0–4	VERY LOOSE	VERY SOFT
5–9	LOOSE	SOFT
10–19	SLT COMPACT	STIFF
20–34	COMPACT	VERY STIFF
35–69	DENSE	HARD
>70	VERY DENSE	VERY HARD

NOTE: SLT COMPACT = SLIGHTLY COMPACT

MOISTURE DESCRIPTIVE

DRY

SLT MOIST

MOIST

WET

ACCORDING TO FIELD VISUAL INSPECTION

NOTE: SLT MOIST = SLIGHTLY MOIST

SPT BLOWS PER FOOT

THE SPT VALUES ARE UNCORRECTED

SCEC GEOTECHNICAL DATA BASE BY UCLA-USC

PREPARED BY: MACAN DOROUDIAN
DATE: 10/05/93

EASTING: 1981787.19
NORTHING: 530001.68
LONGITUDE: -118.1966
LATITUDE: 33.7703

ELEVATION: 7.3 (m)
DEPTH TO GW: 25.0 (m)

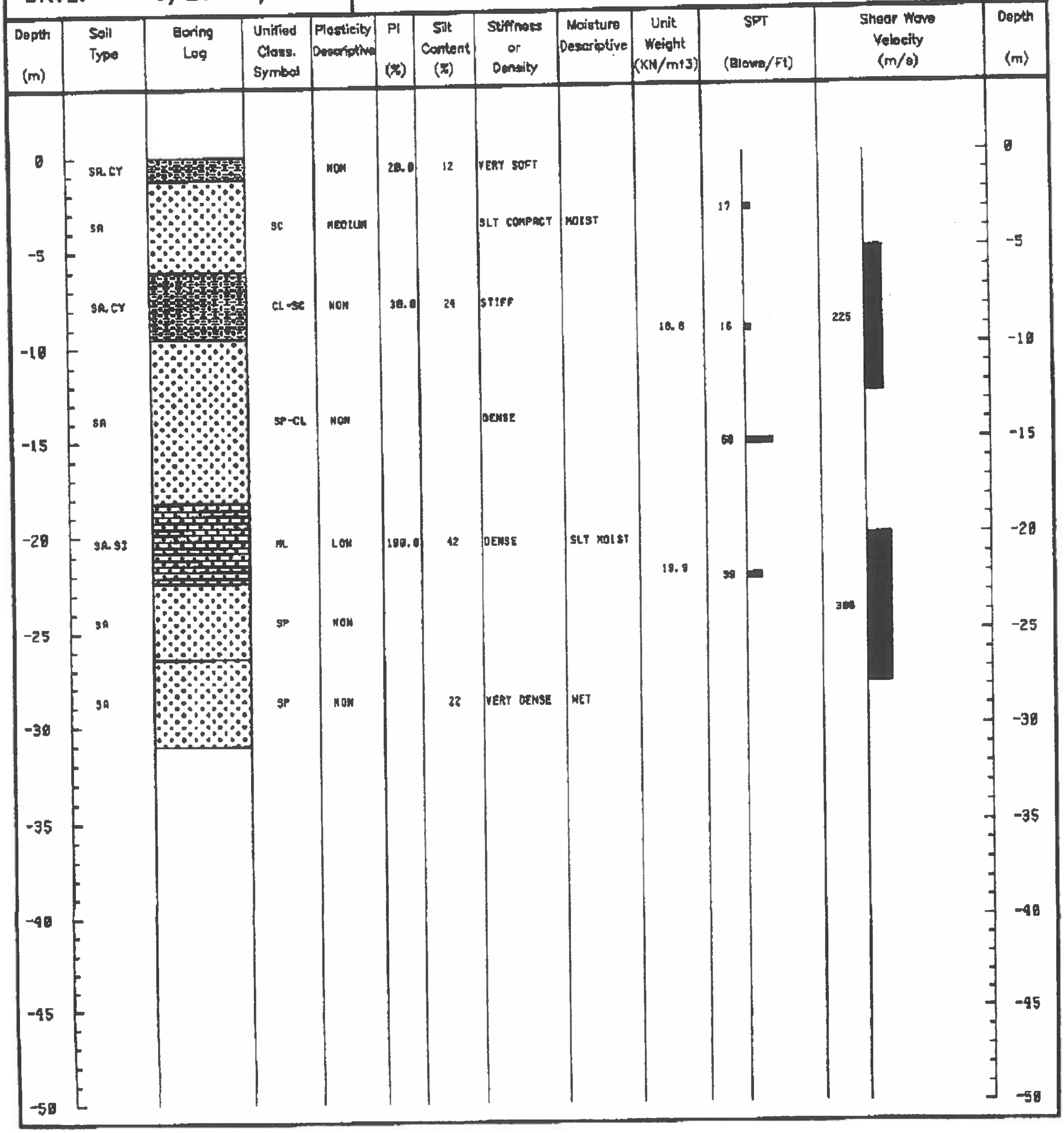
HOLE ID: usgs-1

SOURCE: usgs

LOCATION: LONG BEACH,CA (MAGNOLIA)

DATE: 3/20-22/78

COMMENTS:



TASK H-8: Liquefaction Characteristics and Liquefaction Potential of Southern California

PI: Geoffrey Martin
University of Southern California

Past earthquake induced liquefaction of saturated cohesionless soils has resulted in major damage to man-made structures and facilities. Maps showing areas of liquefaction potential have been produced, and are used by authorities to both prepare for and help mitigate any possible damage. The objective of this new research task is to reassess and improve the Southern Californian database used to develop liquefaction potential maps, and develop a more quantative approach for assessment of post liquefaction ground deformation potential, suitable for mapping.

A review of the literature concerning methods of evaluating potential liquefaction induced ground displacements has been carried out in the last few months. Although this work is of prime importance for assessing potential damage, and thus determining for development and planning purposes the amount of ground remedial work necessary, relatively little research has been carried out in this area to date. One of the objectives of this task is to improve on the current methods, which are mainly empirically based.

Compiling, manipulation and mapping of data is being performed using "Techbase", a GIS software package from MINEsoft Ltd, with special geotechnical capabilities. A Sun SPARC 10 workstation capable of storing and manipulating the large amount of data needed for this project has been purchased, along with a HP color inkjet plotter for use in producing high quality 24" x 36" maps. Delivery of a GTCO 24' x 36" digitizer is expected within the next few days. This will be used to transform geological, lifeline, and other surface map data to digital form, suitable for use in future analysis and presentation.

Work to be carried out in the near future includes digitizing data from available maps, transfering into the database raw data and previously digitized data from various sources, including USGS, CDMG, and LA County. This data will later be manipulated in order to develop liquefaction potential maps and approaches for assessment of post liquefaction ground deformation potential. A long term goal is to transfer Techbase data to the Arc Info database at UC Riverside. Development of the overall database will be coordinated with the geotechnical database being compiled as part of TASK H-5.