GL00478

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA. 22092

In Reply Refer To:
Mail Stop 905

June 21, 1985

Dear Colleague:

The U.S. Geological Survey, (USGS) has initiated a new Regional Earthquake Hazards Assessments element as part of the National Earthquake Hazards Reduction Program. We are pleased to send you the proceedings of Conference XXVI, a workshop on "Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah," one of the first USGS activities sponsored by this program initiative.

The USGS, together with the Federal Emergency Management Agency, the Utah Geological and Mineral Survey, the Utah Division of Comprehensive Emergency Management, and the University of Utah sponsored the workshop in Salt Lake City, Utah, on August 14-16, 1984. One hundred and fifteen individuals with backgrounds in earth science, social science, planning, architecture, engineering, and emergency management participated in the workshop. They represented industry, volunteer agencies, and academic institutions from Utah, as well as local and State governments of Utah, other States, and the Federal Government.

The USGS Regional Earthquake Hazards Assessment element has two objectives: 1) to compile and synthesize geologic and geophysical data needed for evaluating the earthquake hazards of a region, including ground shaking, ground failure, surface fault rupture, and tectonic deformation, and 2) to foster an environment for implementation, creating partnerships, and providing high-quality scientific information that can be used by local governments to devise and implement earthquake-loss-reduction measures, such as building codes, zoning ordinances, and personal preparedness.

The October 1983 Borah Peak, Idaho, earthquake demonstrated that large earthquakes can occur in the Rocky Mountains. Many scientists believe that this earthquake was a "model" of what can happen along Utah's Wasatch front. The Wasatch fault zone (a major zone of active, young normal faulting within the intermountain seismic belt) is overdue for a damaging earthquake. A magnitude 7.0-7.5 earthquake nucleating at a depth of 10-15 km is now being considered in planning scenarios for Utah.

Sincerely yours,

Walter W. Hays

Walter W. Hays and Paula Gori
Office of Earthquakes, Volcanoes,
and Engineering

Enclosure

GLG0478

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROCEEDINGS OF CONFERENCE XXVI

A WORKSHOP ON "EVALUATION OF REGIONAL AND URBAN EARTHQUAKE HAZARDS AND RISK IN UTAH"

August 14-16, 1984
SALT LAKE CITY, UTAH

SPONSORED BY
U.S. GEOLOGICAL SURVEY
FEDERAL EMERGENCY MANAGEMENT AGENCY
UTAH GEOLOGICAL AND MINERAL SURVEY
UTAH DIVISION OF COMPREHENSIVE EMERGENCY MANAGEMENT
UNIVERSITY OF UTAH

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Compiled by
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Reston, Virginia
1984

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SUMMARY AND BACKGROUND

WORKSHOP ON "EVALUATION OF REGIONAL AND URBAN EARTHQUAKE HAZARDS AND RISK IN UTAH"

by

Walter W. Hays and Paula L. Gori

U.S. Geological Survey

Reston, Virginia 22092

INTRODUCTION

The workshop, "Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah," was held in Salt Lake City, Utah, on August, 14-16, 1984. The workshop is a part of the U.S. Geological Survey's (USGS) program element, "Regional Earthquake Hazards Assessments," and the Federal Emergency Management Agency's (FEMA) "Multihazards Project in Utah." The USGS, FEMA, the Utah Geological and Mineral Survey (UGMS), the Utah Division of Comprehensive Emergency Management (CEM), and the University of Utah (U of U) sponsored the workshop which is the 26th overall in a series of workshops and conferences that was devised in 1977 by USGS under the auspices of the Earthquake Hazards Reduction Act. The two primary objectives of the workshop were:

1) to strengthen the capability of the scientific and technical community of Utah to compile and synthesize geologic, geophysical, and engineering data needed for evaluating the earthquake hazards of ground shaking, seismically-induced ground failure, surface fault rupture, and tectonic deformation, and for assessing the risk from these hazards, and

2) to work with public officials in Utah to foster an environment for implementation of research results, creating partnerships and providing high quality scientific information that can be used by local governments to devise and implement loss reduction measures such as building codes, zoning ordinances, and community and personal preparedness plans and activities.

Three tasks were undertaken in the forum provided by the workshop: 1) assessment of the present state-of-knowledge of earthquake hazards in Utah including scientific, engineering, and societal-preparedness components, 2) determination of the need for additional scientific, engineering, and societal-response information to implement an effective earthquake hazards loss-reduction program in Utah, and 3) creation of action plans that scientific-technical-policymaker communities can use to implement research and loss-reduction measures.

The papers contained in this publication were presented at the workshop and are organized into three categories: 1) papers developing the session themes of the workshop, 2) papers providing supplementary scientific and technical information, and 3) papers defining the needs of the user communities in Utah. A glossary of technical terms used in earthquake engineering is contained in Appendix A to facilitate communication and understanding.

Prior to the workshop in October 1983, and January 1984 two planning meetings were held in Salt Lake City, Utah, to devise a draft workplan for the research and implementation activities along the Wasatch front. This plan, which follows this summary, was produced by representatives of UGMS, CEM, U of U, FEMA, and USGS. It was used as a framework for discussion in the workshop and is part of the Geological Survey's National Earthquake Hazards Reduction Program (NEHRP).

One hundred fifteen participants having varied backgrounds in earth science, social science, planning, architecture, engineering, and emergency management participated in the workshop. The participants (see Appendix B) represented industry, volunteer agencies, and academic institutions from Utah, as well as representatives of local and State governments of Utah, other States, the private sector, and the Federal Government. The participants represented a major part of the resources available to conduct research, to prepare for, to mitigate, and to respond to earthquake hazards in Utah.

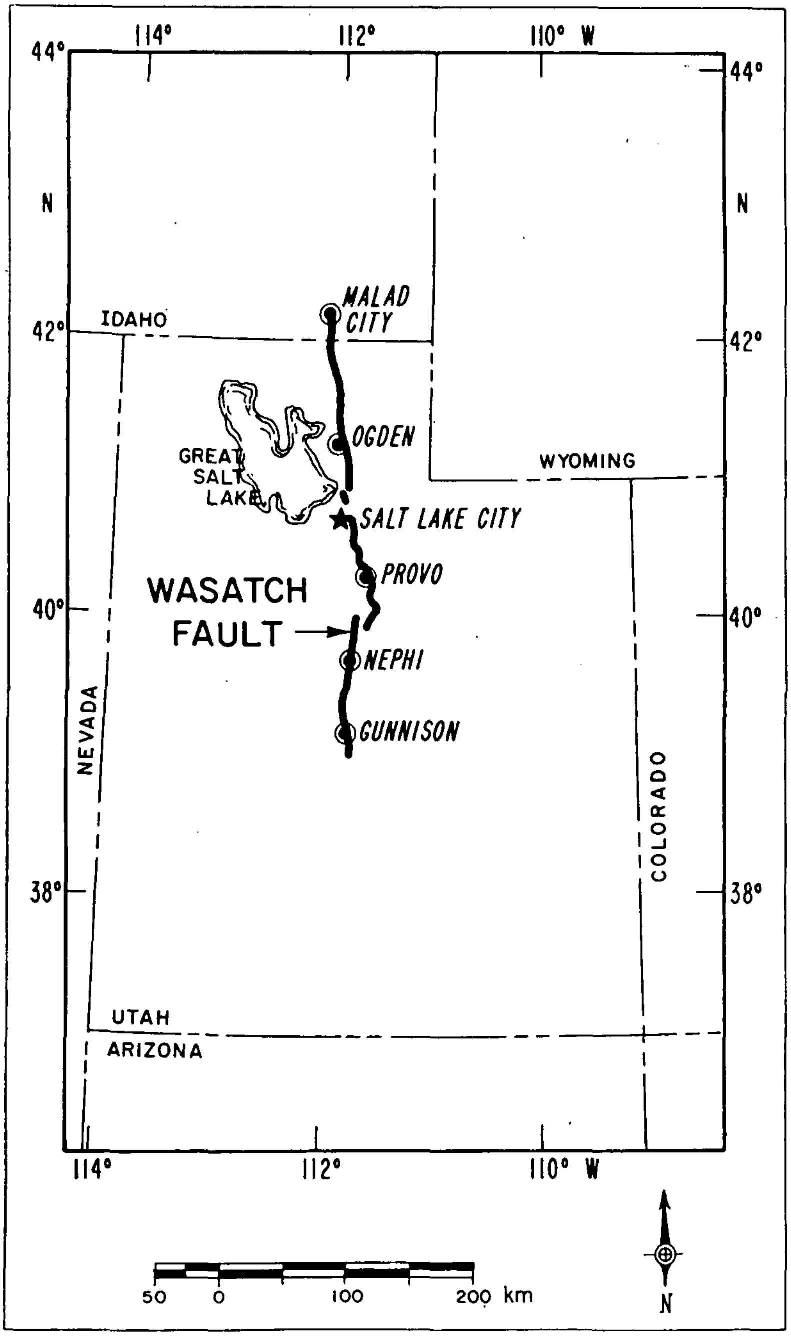

Figure 1.--Map showing the Wasatch fault zone, a major zone of young, active, normal faulting. The largest urban centers of Utah are located along the fault zone. Geologic and geomorphic evidence acquired primarily from paleoseismicity studies show that earthquakes having magnitudes of 7 or greater have occurred on the fault in the past 10,000 years. Current research is addressing questions such as: 1) Is the fault segmented? 2) If so, do individual segments generate a characteristic earthquake? 3) Does the fault become listric at depth? 4) Does the fault have seismic gaps? 5) What is the depth to the brittle-ductile transition zone in the crust where large magnitude earthquakes might be expected to nucleate? 6) Is the area along the Wasatch fault zone susceptible to enhanced ground shaking because of soil amplification? 7) Is the area susceptible to liquefaction and ground failure in a large earthquake?

The workshop followed by one year the Governor's Conference on Geologic Hazards which was held in Salt Lake City, Utah, in 1983.

JUSTIFICATION FOR STUDYING THE WASATCH FRONT

Some scientists believe that the Wasatch fault zone, a major zone of active, young normal faulting within the intermountain seismic belt, is overdue for a damaging earthquake. The fault extends approximately 370 km (220 miles) from Gunnison, Utah, to Malad City, Idaho (Figure 1). Studies by scientists at the University of Utah have shown that many small earthquakes have occurred in the past and are still occurring along the fault zone. However, no moderate or large earthquakes have occurred since Utah was settled in 1847 in spite of clear geologic and geomorphic evidence that large earthquakes (magnitude 7 or greater) have occurred repeatedly throughout the late Pleistocene (about 125,000 years B.P.) and Holocene (about 10,000 years B.P.) times.

The largest urban centers of Utah are located along the Wasatch front. Also, the largest growth in population is occurring in these centers. At present, Utah, like other parts of the nation, is not well prepared for a large damaging earthquake. On the basis of a damage study conducted in 1976 by the USGS for the Federal Disaster Assistance Administration (the predecessor of FEMA), a large earthquake centered near Salt Lake City would cause extensive damage to single family dwellings, buildings, lifeline systems, and public facilities. The level of ground shaking would probably be in the range of 0.2-0.4 g. Surface fault rupture and tectonic deformation would be expected. Landslides and liquefaction would occur in many areas. Deaths and injuries would be high, depending on the time of day and the season of year.

The October 1983 Borah Peak, Idaho, earthquake demonstrated that large earthquakes can occur in the intermountain seismic belt. Many scientists believe that this earthquake was a "model" of what can happen on the Wasatch front. A magnitude 7.0-7.5 earthquake nucleating at a depth of 10-15 km is now being considered in planning scenarios for Utah.

CUMMULATIVE IMPACT OF PRIOR WORKSHOPS

This workshop was designed to address the potential effects of earthquakes and other geologic hazards that might be triggered by earthquakes in Utah. Of the 26 prior workshops, it was the 13th in a series designed under the auspices of the NEHRP to define the threat from earthquakes in the United States and to improve earthquake preparedness. The program followed the format used in prior workshops. These workshops, which were sponsored by USGS, FEMA, other Federal agencies, and state and local agencies and institutions, have increased the state-of-knowledge about earthquake hazards throughout the Nation, increased the level-of-awareness and concern, and improved the state-of-practice in earthquake-resistant design. They have brought together more than 1,000 producers and users of geologic hazards information in almost every earthquake-prone part of the United States. They have fostered local-State-Federal partnerships and have enhanced the use of existing information networks as well as the creation of new networks. Seismic safety organizations have been created as a result of the workshops. Proceedings of past workshops have been dissiminated to the participants to use in their program development and to about 5,000 others who have requested them for the information they contained. A discussion of each of the 12 prior workshops follows this summary to provide a complete picture of the cummulative accomplishments. Proceedings are available from the USGS.

DECISIONMAKING AND EARTHQUAKE HAZARDS

The workshop on "Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah," emphasized the well known fact that understanding the geologic processes causing earthquake hazards is the most important step in devising practical methodologies for reducing future economic losses and social impacts from earthquakes. The potential losses in Utah are increasing annually as a consequence of factors such as: 1) increased population density and 2) increased building wealth exposed to potential geologic hazards as urban centers grow through construction of homes, schools, hospitals, high rise buidings, factories, utility systems, power plants, and public facilities.

The choices facing decisionmakers are difficult for three reasons: 1) future earthquake hazards occur at uncertain times and locations and have great variation in magnitude and probability of occurrence, 2) reduction of losses requires integration of technical information in the planning process and its use in the formulation of loss reduction measures, and 3) loss reduction measures cost money and require local-State-Federal partnerships having well conceived short- and long-term objectives in order to be cost effective. The variety of options for reducing losses from earthquake hazards includes:

1) Personal preparedness--prepare for the consequences of earthquake hazards that are expected to occur, taking advantage of efficiencies provided by preparation for other natural hazards such as floods and debris flows.

2) Avoidance--if maps and other technical information are available to answer the questions WHERE? and HOW OFTEN?, avoid the hazards by selecting the least hazardous area for construction.

3) Land-use planning and regulation--reduce losses to certain types of structures susceptible to a particular earthquake hazard either by reducing their density or by prohibiting their construction within parts of the area characterized by a relatively high frequency of occurrence or severity of effects.

4) Engineering design and building codes--require engineering design and construction that is appropriate in terms of the frequency of occurrence and the severity of the hazard.

5) Distribution of losses--use insurance and other financial methods to distribute the potential losses in an area susceptible to earthquake hazards.

6) Response and recovery--plan response and recovery measures that are appropriate in terms of past experiences, using scenarios based on damaging events in other parts of the Nation (e.g., the 1983 Borah Peak, Idaho earthquake) that provide specific lessons that can be transferred to Utah.

Decisionmakers have different perspectives about geologic hazards than scientists and engineers. These differences, which have been summarized by Szanton (1981), are the reason that implementation of loss reduction measures is difficult. They are:

1) The ultimate objective of the decisionmaker is the approval of the electorate; it is the respect of peers for the scientist/engineer.

2) The time horizon for the decisionmaker is short; it is long for the scientist/engineer.

3) The focus of the decisionmaker is on the external logic of the problem; it is on the internal logic for the scientist/engineer.

4) The mode of thought for the decisionmaker is deductive and particular; it is inductive and generic for the scientist/engineer.

5) The most valued outcome for the decisionmaker is a reliable solution; it is original insight for the scientist/engineer.

6) The mode of expression is simple and absolute for the decisionmaker; it is abstruse and qualified for the scientist/engineer.

7) The preferred form of conclusion for the decisionmaker is one "best solution" with uncertainties submerged; it is multiple possibilities with uncertainties emphasized for the scientist/engineer.

These differences in perspectives emerged in the workshop. They almost always emerge in discussions of the basic questions that form the basis for an earthquake hazards reduction program:

1) WHERE are the earthquake hazards of ground shaking, earthquake-induced ground failure, surface fault rupture, and tectonic deformation occurring? Where have they occurred in the past?

2) WHY are these hazards occurring?

3) HOW OFTEN do they occur?

4) WHAT physical effects are expected to occur from ground shaking, earthquake-induced ground failure, surface faulting, and tectonic deformation in a given period of time (for example, 50 years, the useful life of an ordinary building)? How severe are they expected to be?

5) WHAT are the viable options for reducing losses from these physical effects?

These seven differences in perspectives between decisionmakers and scientists are the main reasons that the effort to increase the capability of a region to reduce losses from earthquake hazards must involve the total community as a team and have well coordinated short- and long-term objectives for research and implementation.

WORKSHOP STRATEGIES

The strategies used in this workshop were designed to build on past and present activities in Utah, to enhance the interaction between all participants, and to facilitate achievement of the two primary objectives of the workshop. The strategies included:

1) A draft workplan "Regional Earthquake Hazards Assessments: Wasatch front, Utah," was prepared several months before the workshop (see "Draft Work Plan" following this summary). It was distributed in advance to all the particpants and used as a framework for discussion.

2) The workshop was scheduled to take advantage of heighted awareness and concern caused by debris flows, mud flows, landslides, and floods which struck numerous areas of Utah in the spring of 1983. Action plans were created in the Governor's Conference on Geologic Hazards held in Salt Lake City, on August 11-12, 1983, and were, to some extent, integrated into the discussions of this workshop.

3) Past experiences, accomplishments, and recommendations of the Utah Seismic Safety Advisory Council were integrated into the workshop. (See paper by Delbert Ward for council recommendations.)

4) Research reports and preliminary technical papers prepared in advance by the participants were distributed at the workshop and used as resource material. The papers comprised three categories: 1) papers developing specific themes of the workshop, 2) papers describing results of current research (presented in two special night sessions), and 3) papers describing the information needed by planners and decision makers in Utah (presented on the last day).

   The report and papers presented by the participants during the workshop and in the three special sessions were finalized after the workshop and are contained in this publication.

5) Scientists, social scientists, engineers, and emergency management specialists gave oral presentations in four plenary sessions. The objectives were to: 1) integrate scientific research and hazard awareness and preparedness knowledge, 2) define the problem indicated by the session theme, 3) clarify what is known about earthquake hazards in Utah and, 4) identify knowledge that is still needed to resolve specific problems. These presentations served as a summary of the state-of-knowledge and gave a multidisciplinary perspective.

6) A preliminary assessment of the effects of a hypothetical large earthquake in Utah was presented before the participants of the workshop and a committee of the Utah Legislature which was in session at the same time as the workshop.

7) Presentations of the speakers were discussed in small groups. These groups also suggested future research and implementation programs.

8) Ad hoc discussions on topics not addressed during the plenary and discussion group sessions were encouraged to add a spontaneous dimension and to foster creativity and networking.

PLENARY SESSIONS

Following the welcome and introductions, the overall theme of the workshop was developed in four plenary sessions. The themes, objectives, and speakers for each plenary session are described below:

WELCOME: Honorable Scott M. Matheson, Governor of Utah

OBJECTIVE: Description of the background of the workshop, its objectives, and goals.

SPEAKERS: Genevieve Atwood, Utah Geological and Mineral Survey
Paula Gori, U.S. Geological Survey

SESSION 1: EVALUATION OF EARTHQUAKE HAZARDS AND RISK ALONG THE WASATCH FRONT, UTAH

OBJECTIVE: An integrated series of overview-type presentations identifying important research results obtained in the past several years which are now being used to evaluate the hazards of ground shaking, earthquake-induced ground failure, surface fault rupture, and tectonic deformation in Utah and to assess the risk.

SPEAKERS: Ronald Bruhn, University of Utah
Robert Smith, University of Utah
David Schwartz, Woodward Clyde Consultants
Loren Anderson, Utah State University
Ted Algermissen, U.S. Geological Survey
Walter Hays, U.S. Geological Survey

OBJECTIVE: To produce a directory of the researchers working along the Wasatch front, the hazards information they have produced (or will produce), and procedures for acquiring information from the researchers.

SPEAKERS: Don Mabey, Utah Geological and Mineral Survey
Art Tarr, U.S. Geological Survey

SESSION 2: RESPONDING TO EARTHQUAKE HAZARDS IN UTAH

OBJECTIVE: Presentation of a hypothetical scenario of a damaging earthquake on the Wasatch front and simulation of a community response to it. (This presentation was made to a special committee of the Utah Legislature and to the participants. The participants took part in role playing afterwards to simulate some of the political processes that take place after a damaging earthquake).

SPEAKER: Charles Thiel, Telesis Inc.

OBJECTIVE: Special presentations to a committee of the Utah Legislature suggesting actions concerning existing buildings, lifeline systems, and preparedness planning that can be initiated now to mitigate hazards in Utah.

SPEAKERS: Genevieve Atwood, Utah Geological and Mineral Survey
Christopher Arnold, Building Systems Development, Inc.
Anshel Schiff, Purdue University
Jerry Olson, Federal Emergency Management Agency, Region VIII
Lorayne Tempest, Utah Divison of Comprehensive Emergency Management

OBJECTIVE: An overview of current preparedness planning along the Wasatch front for earthquakes and other natural hazards.

SPEAKERS: Jerry Olson, Federal Emergency Management Agency, Region VIII
Ralph Findlay, Utah Division of Comprehensive Emergency Management

SESSION 3: IMPLEMENTATION OF SPECIFIC ACTIONS TO REDUCE POTENTIAL LOSSES FROM EARTHQUAKE HAZARDS IN UTAH

OBJECTIVE: A series of integrated presentations describing the range of achievable actions that can be taken to reduce potential losses from earthquake hazards in Utah.

SPEAKERS: Genevieve Atwood, Utah Geological and Mineral Survey
Anshel Schiff, Purdue University
Delbert Ward, Structural Facilities, Inc.
Richard Olson, Arizona State University, Tempe, Arizona
Christopher Arnold, Building Systems Development, Inc.
Lawrence Reaveley, Reaveley Engineers & Associates
Charles Thiel, Telesis, Inc.
Jerold Barnes, Salt Lake County Planning Department
William Kockelman, U.S. Geological Survey

DISCUSSION GROUPS

The topical subjects of the plenary sessions were discussed in a small group setting. The goal was to stimulate interactive discussions between all the researchers. Some of the topics included:

1) Synthesis of geologic, geophysical, and engineering studies for evaluation of earthquake hazards and risk in Utah. (Ground failure hazards were also included.)

2) Ground motion modeling and loss estimation in Utah.

3) Information systems.

4) Implementation options available in Utah.

5) Legal issues relating to hazard mitigation policies in Utah.

SPECIAL SESSIONS: TECHNICAL SESSIONS ON EVALUATION OF EARTHQUAKE HAZARDS AND RISK ALONG THE WASATCH FRONT, UTAH, AND DETERMINATION OF THE NEEDS OF POLICYMAKERS

SESSION 1: GEOLOGICAL AND GEOPHYSICAL STUDIES IN THE WASATCH FRONT AREA

MODERATORS: Robert Bucknam, U.S. Geological Survey
Walter Arabasz, University of Utah

OBJECTIVE: To give details about current geological and geophysical research studies.

SPEAKERS: Anthony Crone, U.S. Geological Survey
Spencer Wood, Boise State University
Mary Lou Zoback, U.S. Geological Survey
Walter Arabasz, University of Utah
James Pechmann, University of Utah
William Parry, University of Utah

SESSION 2: EARTHQUAKE POTENTIAL AND GROUND MOTION/LOSS ESTIMATION MODELING

MODERATOR: Lawrence Reaveley, Reaveley Engineers and Associates

OBJECTIVE: To give details about current earthquake potential, ground motion, and loss estimation research studies and to report on the 1983 Borah Peak, Idaho, earthquake.

SPEAKERS: David Perkins, U.S. Geological Survey
Robert Smith, University of Utah
Martin McCann, Jack R. Benjamin and Associates, Inc.
Maurice Power, Woodward Clyde Consultants
Kenneth Campbell, U.S. Geological Survey
Don Steeples, Kansas Geological Survey
Ernest Anderson, U.S. Geological Suravey

SESSION 3: EARTHQUAKE-HAZARD INFORMATION NEEDED BY PLANNERS AND DECISIONMAKERS

MODERATORS: Genevieve Atwood, Utah Geological and Mineral Survey
William Kockelman, U.S. Geological Survey

OBJECTIVE: The purpose of this session convened especially for planners and decisionmakers was to identify the "special needs" for earthquake hazards information and to describe possible obstacles to its use after the information has been made available.

PANELISTS: Jerold Barnes, Salt Lake County Planner
Don Bennett, Vice President, Mountain Fuel Company
G. Allen Fawcett, Director, Richfield Community Planning
Don LeBaron, Utah House of Representatives
George Shaw, Sandy City Planner
Harold Tippetts, Davis County Commissioner

SPEAKERS: Patricia Bolton, Battelle Human Affairs Research Centers
Wesley Dewsnup, Utah State Division of Comprehensive Emergency Management
Merrill Ridd, Utah State University
Jeanne Perkins, Association of Bay Area Governments
Clark Meek, State of Idaho
Robert Alexander, U.S. Geological Survey
Stephen French, California Polytechnic State University

CONCLUSIONS, RECOMMENDATIONS, AND COMMITMENTS

Conclusions--The ultimate goal of the Wasatch front studies is the reduction of loss of life and property from the earthquake hazards of ground shaking, surface fault rupture, earthquake-induced ground failure, and tectonic deformation. This goal requires a long-term commitment; it is not likely to be achieved in a 3-year period. However, significant progress can be made in a 3-year period when effective partnerships are forged between scientists, engineers, architects, planners, social scientists, emergency managers, and public officials. The results of this workshop indicate that difficult goals are achievable.

Recommendations--The participants in the workshop produced a number of excellent specific recommendations (see the reports of the discussion groups). The recommendations encompass the following:

1) The earthquake potential of the entire Wasatch front should be assessed carefully. From a research perspective, the Wasatch front is a 3-dimensional volume, extending across the valley and to depths of about 20 km (12 miles). Such assessments require investigations of major faults, emphasizing mechanics, timing, geometry, stress, and other parameters. Additional trenching of major faults is needed to

determine the displacement history, segment definition, and statistical uncertainty. If resources can be made available, deep drill holes and seismic reflection lines should be deployed. Vertical and horizontal geodetic networks are needed to determine long term strain and deformation.

2) Improved deterministic and probabilistic estimates of the ground-shaking and ground-failure hazards are needed. Strong motion accelerometers need to be purchased and deployed at rock and soil sites and eventually in buildings to develop a "Utah" ground motion data base for use in earthquake-resistant design.

3) Vulnerability studies for buildings, other facilities, and lifeline systems are needed along the Wasatch front. The 1976 loss estimates produced by USGS need to be updated. The experience gained from the 1983 Borah Peak, Idaho, earthquake needs to be transferred to Utah.

4) User-friendly information systems are needed to make the information generated in the Wasatch front studies readily available. Such a system should be developed incrementally, using existing computer systems and carefully planned demonstration studies.

5) An extraordinary effort is needed to devise practical loss-reduction measures and to foster their implementation. In general, the progress of the scientific/technical investigations will drive the implementation activities; however, the cost is too great if Utah is unprepared for the next large earthquake because implementation of loss reduction measures has lagged behind the advances in scientific/technical knowledge.

Commitments--At the conclusion of the workshop, each partner in the "Regional Earthquake Hazards Assessments" program of the Wasatch front pledged their support of the goals of the program. U.S. Geological Survey renewed their commitment to the "Regional Earthquake Hazards Assessments" program and will continue to fund internal and external research projects. USGS will publish and disseminate the workshop proceedings and take responsibility for convening the 1985 and 1986 meetings and compiling a professional paper. The professional paper, tentatively scheduled for completion in 1986, will document the results of 3 years of focused research along the Wasatch front and recommend future research priorities. USGS plans to deploy strong motion accelerographs along the Wasatch front and will consider funding the "county geologists" proposal discussed in the workshop. The Federal Emergency Management Agency plans to assist in the implementation phase of the program, possibly by joint funding with USGS of some of the proposed implementation projects, training of land-use and emergency planners, and sponsorship of a working group of the agencies and universities involved in implementation. The Utah Division of Comprehensive Emergency Management plans to continue its efforts on the Multi-Hazards Project and active membership in the proposed working groups. The Utah Geological and Mineral Survey plans to continue work on projects to identify geologic hazards, create proposals for new projects, serve as a resource to other agencies and institutions, and make policy recommendations to the State Legislature to increase the capability of Utah to reduce losses from earthquakes and other geologic hazards. UGMS also plans to publish the "Wasatch Forum," a newsletter to communicate with the researchers and potential user groups.

ACKNOWLEDGMENTS

A special note of appreciation is extended to each of the following individuals for their contributions:

1) The Steering Committee of Walter Hays, Walter Arabasz, Genevieve Atwood, Jarold Barnes, Robert Bucknam, Paula Gori, Richard Hughes, Gary Johnson, Jerry Olson, Lawrence Reaveley, Ruth Ann Story, Lorayne Tempest, and Susan Tubbesing who planned and organized the workshop. Robert Smith provided encouragement and support throughout the endeavor.

2) Walter Arabasz, Robert Bucknam, and Lawrence Reaveley who planned and conducted the two special evening technical sessions.

3) William Kockelman and Genevieve Atwood who planned and conducted the special session on "Earthquake-Hazards Information Needed by Planners and Decisionmakers" on the last day of the workshop.

4) Utah Geological and Mineral Survey personnel who provided logistical support.

5) The participants who gave papers and joined in the plenary sessions and the discussion groups. They were the key to the success of the workshop. Their vigorous and healthy exchange of ideas made the workshop practical, interesting, and valuable.

5) Carla Kitzmiller, Lynne Downer, Wanda Seiders, Susan Kibler, Joyce Costello and Janine Jarva (UGMS) who provided strong and capable administrative support.

SELECTED REFERENCE

Szanton, Peter, (1981), Not well advised: Russell Sage Foundation and Ford Foundation, 81 p.

Utah Geological and Mineral Survey, (December 1983), Governor's Conference on Geologic Hazards: Utah Geological and Mineral Survey Circular 74, 97 p.

REGIONAL EARTHQUAKE HAZARDS ASSESSMENTS
WASATCH FRONT, UTAH
DRAFT WORK PLAN: FY 84-86

FOREWARD

This draft work plan describes the integrated goals, plans, and activities of the U.S. Geological Survey (USGS) and the Utah Geological and Mineral Survey (UGMS) for the program element, "Regional Earthquake Hazards Assessments: Wasatch front, Utah," a part of the Geological Survey's National Earthquake Hazards Reduction Program (NEHRP). The purpose of the work plan is to define research **GUIDELINES** and general **RESPONSIBILITIES** for 3-years, FY 84-86, the first phase of a focused effort on the Wasatch front. The work plan will be reviewed each year and revised, as appropriate, to reflect progress, new goals, opportunities for synergism, and more effective use of resources. The following persons participated in at least one of the two planning meetings held in Salt Lake City, Utah, on October 27-28, 1983, and January 26-27, 1984, and contributed to the formulation of the work plan:

Robert Alexander	U.S. Geological Survey (National Mapping Division)
Ted Algermissen	U.S. Geological Survey
Genevieve Atwood	Utah Geological and Mineral Survey
William M. Brown, III	U.S. Geological Survey
Robert Bucknam	U.S. Geological Survey
Russ Campbell	U.S. Geological Survey
West Dewsnup	Utah Division of Comprehensive Emergency Management
Ralph Findlay	Utah Division of Comprehensive Emergency Management
Douglas Gore	Federal Emergency Management Agency
Paula Gori	U.S. Geological Survey
Wendy Hassibe	U.S. Geological Survey (National Mapping Division)
Walter Hays	U.S. Geological Survey
Bruce Kaliser	Utah Geological and Mineral Survey
Floyd Toren Klinge	Utah Division of Comprehensive Emergency Management
William Kockelman	U.S. Geological Survey
Don Mabey	Utah Geological and Mineral Survey
Jerry Olson	Federal Emergency Management Agency
Albert Rogers	U.S. Geological Survey
Robert Smith	University of Utah
Arthur Tarr	U.S. Geological Survey
Lorayne Tempest	Utah Division of Comprehensive Emergency Management
Will Ulman	U.S. Geological Survey (National Mapping Division)

HISTORICAL BACKGROUND

The concept of the Regional Earthquake Hazards Assessments program element evolved out of discussions held at Asilomar Conference Center, Pacific Grove, California, in April 1982. At this meeting, 54 participants (27 USGS and 27 non-Survey) in the NEHRP were asked to debate the question "are changes in the NEHRP, now 5-years old, needed and if so what are they?" From these discussions, the 5 interrelated program elements constituting the current NEHRP were defined:

1) Regional Monitoring and Earthquake Potential--Perform geologic and seismological analyses of current earthquake activity including the seismic cycle of active faults and estimates of earthquake potential in earthquake-prone regions of the United States (23% of budget).

2) Earthquake Prediction Research--Conduct, field laboratory, and theoretical studies of earthquake phenomena with the goal of reliable prediction of the time, place, and magnitude of damaging earthquakes (44% of budget).

3) Data and Information Services--Provide data on earthquake occurrence to the public, other Federal agencies, State and local governments, emergency response organizations, and the scientific community (12% of budget).

4) Engineering Seismology--Operate a national network of strong motion instruments, disseminate the basic ground-motion information, and conduct research on the data (9% of budget).

5) Regional and Urban Earthquakes Hazards Evaluation--Compile and synthesize geologic and geophysical data needed for evaluating the earthquake hazards of ground-shaking, ground failure, surface fault rupture, and tectonic deformation and for assessing the risk in broad geographic regions containing important urban areas. Foster an environment for implementation, creating partnerships and providing high quality scientific information that can be used by local

governments to devise and implement loss-reduction measures (such as building codes, zoning ordinances, personal prepardness, etc.) (12% of budget).

COMPONENTS OF THE REGIONAL AND URBAN EARTHQUAKE HAZARDS PROGRAM ELEMENT

The Regional and Urban Earthquake Hazards program element has 5 **INTERRELATED** components:

1) Information Systems--The goal is to produce **QUALITY** data along with a comprehensive information system, available to both internal and external users for use in earthquake hazards evaluations, risk assessment, and implementation of loss-reduction measures.

2) Synthesis of Geological and Geophysical Data for Evaluation of Earthquake Hazards--The goal is to produce synthesis reports describing the state-of-knowledge about earthquake hazards (ground shaking, surface faulting, earthquake-induced ground failure, and tectonic deformation) in the region and to recommend future research to increase the state-of-knowledge required for the creation and implementation of loss-reduction measures.

3) Ground Motion Modeling--The goal is to produce deterministic and probabilistic ground-motion models and maps of the ground-shaking hazard with commentaries on their use.

4) Loss Estimation Models--The goal is to devise economical methods for acquiring inventories of structures and lifeline systems in urban areas, to create a standard model and commentary for loss estimation, and to produce loss and casualty estimates for urban areas.

5) Implementation--The goal is to foster the creation and implementation of hazard-reduction measures in urban areas, providing high-quality scientific information that can be used by local government decisionmakers as a basis for "calling for change."

Research focusing on one or more of the above components is presently being conducted in the following urban areas, ranked according to their respective priority:

1) Wasatch front, UT
2) Southern California
3) Northern California
4) Anchorage, AL
5) Mississippi Valley
6) Puget Sound, WA
7) Charleston, SC
8) Buffalo-Rochester area, NY

The Wasatch front is the only region where all 5 components are being conducted. In each region, the research is performed using the resources of the USGS's internal and external program (the external program is implemented through grants and contracts awarded annually following a request for proposals in cooperation with the resources of their "partners"). The goal is to achieve maximum synergism of State and Federal resources.

STRATEGIES FOR CONDUCTING RESEARCH IN THE WASATCH FRONT AREA

The strategies for the Wasatch front are:

1) Foster Partnerships--USGS and UGMS will seek to foster strong partnerships with the universities, private sector, units of local government, and other State and Federal agencies. Existing partnerships will be strengthened.

2) Take Advantage of Past Research Studies and Other Activities--Results of past research studies will be utilized to the fullest extent possible. Achievements of the Utah Seismic Safety Advisory Council, the USGS sponsored earthquake hazards workshop of 1980, and the Governor's Conference on Natural Hazards of 1983 will be used as building blocks for future activities.

3) Study 10 Counties Along the Wasatch Front--Although Salt Lake, Davis, Weber, and Utah Counties will receive the primary attention because of their population density, potential risk, and the availability of information from prior and ongoing research studies, Cache, Box Elder,

Summit, Wasatch, and Juab Counties will also be studied. The goal is to acquire a uniform, **HIGH QUALITY** data base on earthquake hazards.

4) Convene Annual Meetings to Review Progress and Recommend New Research- Each year, a workshop will be held in Salt Lake City to review: **WHAT HAS BEEN ACCOMPLISHED** and **WHAT IS STILL NEEDED TO ACCOMPLISH THE GOALS.** Participants from many different disciplines in the workshop will be asked to address the question "what changes, if any, are needed to accomplish the goals of the program element "Regional Earthquake Hazards Assessments: Wasatch front, Utah."

5) Publish Annual Reports and Communicate Findings--Proceedings of the workshops, which will include papers documenting results from all research projects in the Wasatch front, will be published as USGS Open-File Reports approximately 3- or 4-months after each meeting. In FY 86, the third year of the program, a USGS Professional Paper will be published. The workshops, their products, and the findings in the professional paper will be **COMMUNICATED** to policymakers whose task is to implement hazard-reduction policy.

6) Take Advantage of Earthquakes--Use knowledge gained from earthquakes such as the Borah Peak, Idaho, earthquake of October 1983 to improve the methodology that is currently used in the evaluation of earthquake hazards and the assessment of risk in the Wasatch front area. Many scientists consider the 1983 Borah Peak earthquake as representative of the type of earthquake that can occur along the Wasatch front. In addition, other parts of the World have a similar tectonic setting as the Wasatch front; earthquakes in these areas should be investigated to provide insight into the characteristics of ground-shaking and the physical effects that might occur in a major earthquake along the Wasatch front.

RESEARCH GOALS, OBJECTIVES, AND TASKS OF THE PROGRAM ELEMENT "REGIONAL EARTHQUAKE HAZARDS ASSESSMENTS: WASATCH FRONT, UTAH"

INTRODUCTION

The 5 **INTERRELATED** components comprising the program element "Regional Earthquake Hazards Assessments: Wasatch front, Utah" are described below to provide **GUIDELINES** for researchers who are either working now or planning to work in the Wasatch front area. Each component of the workplan will be reviewed annually and revised as appropriate, to meet the research goals of the program element. UGMS (and their partners) will focus primarily on tasks described in components 1, 2, and 5. USGS (and their partners) will focus on tasks described in components 1-5.

COMPONENT 1: INFORMATION SYSTEMS

Every research study will generate basic data which needs to be organized. A large but unorganized amount of data relating to the earthquake hazards along the Wasatch front already exists in published maps, reports, and computerized data sets. If these data were organized, the resultant data base would be an extremely valuable resource for a wide variety of user groups, including the participants in the NEHRP. In addition, the data base is expected to grow as research studies mature.

The objectives of this component are: 1) to make quality data readily available to meet the needs of researchers and policymakers, 2) to create a system that assures that new data will be available in the form most useful to meeting program objectives, 3) to devise a system whereby potential users will have easy access to data in media, scales, and formats that will be most useful to them, and 4) to provide continuing information on objectives and progress of the program element. Accomplishing these objectives will require: 1) inventorying existing data sets, 2) developing data standards for critical data sets, 3) identifying user groups and their needs, 4) developing strategies for data management and data dissemination, and 5) assuring that pertinent hazards data are available to the user community.

Priorities--The first priority is the creation of a directory of hazards information by the time of the 1984 annual workshop. Second priority is an inventory of existing data sets, perhaps using a standard questionnaire or form. Third priority is to test the capability for data interchange and communications.

Implementation--The objectives listed above will be accomplished primarily by USGS and UGMS. Tarr (USGS) and Mabey (UGMS) will provide leadership; however, others will be involved in the implementation of the tasks. To accomplish the above objectives, a leadership role is suggested for USGS and UGMS, as noted below in the task statements:

1) Inventory of Existing Data--UGMS lead. The UGMS is compiling a computerized bibliography of Utah geology that provides for keyword searches, including terms that are pertinent to the evaluation of earthquake hazards and the assessment of risk. The bibliography will be upgraded by the UGMS to meet the needs of the program element.

   USGS lead. USGS will compile a directory of hazards information to determine what data exists, what form the data are in, and the availability of the data. A determination will be made of each data set as to its adequacy for the needs of the research program.

2) Standardization--USGS lead. To the extent possible, the catalog of Utah earthquakes (especially the preinstrumental data) will be standardized because it is important, if not crucial, to several of the research studies. The catalogs of the University of Utah Seismograph Station and the USGS (National Earthquake Information Service, Algermissen) are the best starting point. Standards may need to be established for other major data sets, such as computer files of digitized geological data.

   UGMS lead. Part of this effort will be the selection of standard base maps and mapping scales for data compilation and publication by all participants in the program. Reproducible base materials must be available for rapid production of greenlines, paper copies, and film composites of maps. In addition, standards for computer storage of point data and line data will have to be established if automated computer mapping is to be realized.

3) Data Set Management--UGMS lead. A complete library of publications, reports, and a hard copy of data sets related to the Wasatch front studies are needed. These could be established as a part of the existing UGMS library.

USGS lead. The successful management of computerized data should expedite many research studies. Existing computer resources are the USGS VAX/VMS system in Golden, the Multics system in Lakewood, USGS PIO in Salt Lake City, and the Utah Department of Natural Resources Automatic Geographic Reference System in Salt Lake City. The University of Utah Computer Center and the NOAA data center in Boulder are other systems that may have to be accessed. Documented software to access and utilize the major data sets must also be available.

4) Information Transfer--UGMS lead. An earthquake information office is needed in Salt Lake City. Such an office would be concerned primarily with the dissemination of earth science information (e.g., in a quarterly newsletter) related to the earthquake hazards of ground-shaking, surface rupture, ground failure, and tectonic deformation, as well as earthquake preparedness. The Office would provide, to a wide variety of users: historic and current data on Utah earthquakes, information on current research, and advice on obtaining access to earthquake-related literature and data. The new earthquake information office could be established at the UGMS, with a close working relationship with the USGS Public Inquiries Office in Salt Lake City.

COMPONENT 2: SYNTHESIS OF GEOLOGIC AND GEOPHYSICAL DATA FOR EVALUATION OF EARTHQUAKE HAZARDS

Geologic and geophysical research aimed at a better understanding of the potential for the occurrence of large, damaging earthquakes in the Wasatch front region have been carried out since as early as 1970. These studies have provided a critical perspective on the level of the potential hazard for the region and have contributed, in large part, to the high priority given to this area in the Regional and Urban Earthquake Hazards program element. The geologic and geophysical data collected in these studies are essential in the evaluation of earthquake hazards and the assessment of risk from earthquakes occurring in the region. However, the results of these studies have been released primarily as discrete scientific papers in research journals or in the "gray" literature of USGS open-file reports and other publications. They have not been synthesized or integrated into a comprehensive evaluation of the potential for the occurrence of damaging earthquakes and the associated hazards of ground-shaking, ground failure, surface fault rupture, and tectonic deformation in the Wasatch front region.

Priorities--First priority will be given to collecting and synthesizing basic geologic and geophysical data required for evaluation of earthquake hazards. The second priority is to conduct additional research needed to achieve the goals of the program element.

Implementation--USGS and UGMS scientists (identified below) will provide leadership and perform the research tasks identified below. In addition, other researchers in universities and the private sector (e.g. University of Utah, Utah State University, and others) will participate under the auspices of the USGS's grants and contracts program.

1) Collection and Synthesis--Research initiated in prior years will be continued as well as new research, focusing on the collection and synthesis of those data needed for realistic deterministic and probabilistic calculations of hazard and risk for the region, as well as carrying out essential additional research. This effort will be integrated to provide: a) a broader understanding of the setting and

effects of active tectonic processes and rates of tectonic activity producing earthquakes in the region, and b) definition and study of specific geologic hazards of special significance to the Wasatch front area.

The objective of the above task is to develop synthesis reports and maps on four main topics. Project chiefs in USGS and UGMS are listed below for each topic:

a. Geologic/tectonic setting of current seismicity of the Wasatch front region:

Project Chief/Investigator	Project Topic
Anderson	Seismotectonic Studies, Eastern Great Basin
Wheeler	Structural controls of segmentation, Wasatch Front
Pakiser	Review and evaluation of crustal models Basin and Range Province
Diment	Geophysics of eastern Great Basin Transition Zone
Mabey (UGMS)	Interpretation of subsurface and geophysical data (Utah Valley to Ogden area)

2) Late-Quaternary tectonic activity of the Wasatch front region:

Project Chief/Investigator	Project Topic
Crone	Subsurface geometry of Late-Quaternary faults, Wasatch front region.
Machette/Rehis	Late Quaternary history of the Wasatch fault in the Santaquin-Nephi region.
Wood	Tectonic deformation, Wasatch front region
Kaliser (UGMS)	Documentation of evidence of Late-Quaternary faulting in Wasatch front urban area

3) Timing and character of Late-Quaternary ground failure events:

Project Chief/Investigator	Project Topic
Madole	Timing of ground failure events, Wasatch front region
Not assigned	Liquefaction potential mapping
Not assigned	Surface faulting
Not assigned	Slope stability mapping
Bucknam	Seismic source zone mapping

4) Information for local and regional use in hazard reduction:

Project Chief/Investigator	Project Topic
Not assigned (UGMS).......	Compilation of hazards information for local and regional use

COMPONENT 3: GROUND MOTION MODELING

This component is concerned primarily with the prediction of the effects of local geologic site conditions on ground shaking in the Salt Lake City region, although the effects of the source and the travel path will also be considered. Knowledge of the nature and severity of ground motion induced at a site is fundamental to sound earthquake-resistant design. Although the importance of local geologic conditions has been recognized for many years, the quantitative prediction of their influence on ground shaking using either empirical or theoretical models is still evolving. In this component, the application, extension, and validation of relevant research techniques will be continued in the Salt Lake City area and along the Wasatch front.

Priorities--The first priority is to install strong motion accelerographs in the Salt Lake City area and to acquire and use the mini-Sosie portable reflection system in ground-response research. (Utah only has one strong motion accelerogram from past earthquakes.) The second priority is to prepare a synthesis report of the ground shaking data available from prior studies in Utah. The third priority is to extend the results of these studies, performing deterministic and probabilistic hazard analysis and utilizing new equipment (mini-Sosie, strong motion accelerographs, etc.) to acquire basic data.

Implementation--The research will be conducted primarily by Algermissen, Campbell, Hays, Rogers, and King (USGS). Non-USGS researchers will be invited to participate through the Survey's external grants and contract program. The tasks are described below:

1) Synthesis Report--The research by Hays, King, and Miller, which used nuclear-explosion ground-motion data to derive ground response in the Salt Lake City-Ogden-Provo-Logan-Cedar City area, has been published

in several journals (e.g., Proceedings of Third International Conference on Seismic Microzonation), but has not been synthesized and published in a reference that is more readily available. Such a report will be produced in FY 84. A USGS Open-File report describing the nuclear-explosion ground-motion data will also be produced.

2) Deterministic and Probabilistic Hazard Analysis--Research on deterministic and probabalistic hazard analysis, applied in 1982 on a national scale by Algermissen and others, will be applied in the Wasatch front urban areas, and extended by using time-dependent models of earthquake occurence. A regional seismic wave attenuation function for Utah will be derived. These analyses, combined with the inventory and vulnerability studies discussed below in the loss estimation component, will form the basis for estimates of economic loss (risk) and casualties.

3) Research on Attenuation and Ground Response--Beginning in late FY 84, the methodology developed by Rogers and others to zone the ground-shaking hazard in Los Angeles will be applied to the Wasatch front. This empirical technique uses several generally available geotechnical factors to predict how site conditions will influence ground motion during an earthquake. Sites are classified into site types or clusters according to their geotechnical factors, and a mean ground shaking factor (dependent on the site's cluster type) is assigned to the site in three separate period bands. The classification scheme developed for Los Angeles will be applied to Salt Lake City. Validation of this technique for Salt Lake City will be accomplished by comparing ground motions recorded by Hays and others in Salt Lake City with the predictions. By combining and comparing the cluster results at selected sites throughout the city with mapped near-surface geology, maps of the ground-shaking response relative to rock can be constructed for each of the three period bands on a regional basis. These results will also be used to construct intensity maps for a maximum-magnitude earthquake. Ground-response research is still in the early stages, and as noted by Rogers and others, some sites outside of Los Angeles can not be classified using the scheme

developed for that city. Additional site types may have to be developed in this study; these clusters might possibly be based on the data of Hays and others. Additional ground motion data, however, may have to be collected, as well as the development of new correlation techniques and the collection of new site properties.

Regional seismic-wave attenuation functions for the Wasatch front will be derived using the best available data.

4) Zoning Research--Beginning in FY 85, research with high frequency techniques (e.g., mini-Sosie) will be initiated to determine subsurface conditions within the study area that are known to exhibit high ground response. For example, in the Los Angeles study near-surface velocity contrasts in the depth range of 10-20 meters were found to cause the highest levels of ground response for buildings that are in the 2- to 5-story class. Buildings having more than 5-stories were also found to be at greatest risk when located at sites where the depth to basement is the greatest. Because reflection techniques may provide the only means to define the important subsurface factors controlling site response in some urban areas, experiments will be conducted in Salt Lake City and Los Angeles at sites where measured site response can be correlated with reflection data.

5) Probabilistic Ground Shaking Hazard Maps Incorporating Ground Response--Following tasks 1-4, described above, revised estimates of the probabilistic ground-shaking hazard in the Salt Lake City region will be made. Maps of the peak acceleration and intensity will be prepared for exposure periods of 10, 50, and 250 years. These maps will incorporate the effects of local geologic conditions.

COMPONENT 4: LOSS ESTIMATION MODELS

In this component all available hazards data will be used in the development of economic loss (risk) and casualty estimates. Estimates of probable losses and casualties in an earthquake are important results. Loss estimates provide a scientific basis for land-use planning, an economic basis for the implementation of suitable building codes, and form the framework for disaster mitigation, preparedness, and relief programs. A considerable amount of research on loss estimation (seismic risk) has already been done in the Wasatch front area by USGS and its consultants. An earthquake vulnerabilty study was completed in 1976 (Rogers, et al 1976) to provide planning guidance for earthquake preparedness and mitigation. Preliminary estimates of economic losses using three different loss models for Salt Lake City have recently been published (Algermissen and Steinbrugge, 1984).

Priorities--The first priority is to update the existing building inventory in Salt Lake City (especially considering high rise buildings) and to create an inventory for lifeline systems. The second priority is to establish building inventories and lifeline system inventories in other parts of the study area, seeking to achieve uniformity with the Salt Lake City inventories. The third priority is to reassess the vulnerability relationships for Utah.

Implementation--The research will be conducted primarily by Algermissen (USGS). Non-Survey researchers will be invited to participate through the USGS's external grants and contract program. The tasks are described below:

1) Loss Estimation, Salt Lake City-Ogden-Provo--Begining in FY 84, the primary emphasis will be placed on research concerning earthquake loss (risk) studies is the Salt Lake City, Ogden, and Provo metropolitan areas. The data requirements are: 1) update the existing building inventory in Salt Lake City, 2) develop an inventory of buildings in other parts of the study area, 3) reassess vulnerability relationships for Utah, utilizing new data from the 1983 Coalinga, California, earthquake and data obtained from additional review and analysis of the 1971 San Fernando, California, earthquake, and 4) develop additional data on the distribution and vulnerability of lifeline systems in the Salt Lake City-Ogden-Provo areas.

   Deterministic loss and casualty estimates will be made for magnitude (M_s) 6.5 and 7.5 earthquakes having various locations on the Wasatch fault. Probabilistic loss and casualty estimates will be computed for exposure times of interest of 10, 50, and 250 years at the 90 percent probability level. Both deterministic and probabilistic loss estimates will be based on appropriate ground motion hazard maps which, where possible, will include site response (see above discussion of ground motion modeling). The loss estimates will also include, where possible, losses associated with the geologic effects of earthquakes such as liquefaction. Total economic losses will be estimated and, in addition, losses by class of construction and the vulnerability. In general, the classes of construction used will be based principally on their framing system. Casualty estimation will require additional data on building occupancy.

2) Loss Estimation, Other Parts of the Study Area--To the extent possible, the same data identified in task 1 above will be acquired in other counties in Utah and used to perform loss estimates.

COMPONENT 5: IMPLEMENTATION

The goal of this component is effective use of scientific information to reduce loss of life and damage to property caused by earthquake hazards as well as by other geologic and hydrologic hazards. Successful achievement of the goal requires **COMMUNICATION** of **TRANSLATED SCIENTIFIC INFORMATION to RESPONSIBLE OFFICIALS** and **INTERESTED PARTIES** seeking to **REDUCE HAZARDS** by use of one or more **REDUCTION TECHNIQUES.** These aspects of the problem and its solution will be discussed below, providing a framework for an integrated work plan involving all concerned parties and guidelines for proposals to the USGS's external grants and contracts program.

Priorities--The first priority is to determine the needs of users in Utah for earthquake hazards information. The second priority is to produce translated (i.e., interpreted information derived from basic scientific data) scientific information that meets the needs of these user groups. The third priority is to foster an environment for implementation of research results by local governments, utilizing workshops, training classes, questionnaires and other procedures to communicate the scientific information.

Implementation--Leadership for the implementation components will be provided by Atwood and Mabey (UGMS) and Gori, Hays, and Kockelman (USGS). One objective of this component is to make it easy for local government, engineers, architects, planners, emergency preparedness planners, and emergency responders to use the technical information generated in this program. A key strategy is to build on past successful activities such as the Utah Seismic Safety Advisory Council (1977-1980) and the "Governor's Conference on Geologic Hazards" (August 1983). Partnerships between the research community (USGS, UGMS, universities, and the private sector) and those who will ultimatly use the information to implement hazard-reduction plans are necessary for success, and the strongest possible effort will be made to achieve these partnerships within the initial three years. However, implementation activities, described below, must continue after the Wasatch front is no longer receiving first priority in the Survey's "Regional Earthquake Hazards Assessments program element".

1) Scientific Information--This task began before FY 84 because many prior studies (e.g., conducted by the University of Utah, Utah State University, Woodward Clyde Consultants, USGS, UGMS, and others) have produced considerable high-quality information. Translated scientific information is a prerequisite to its transfer to a user and its use in a loss-reduction measure or technique. While a great deal of scientific information can be used directly by engineers or other scientists, some information must be translated to enhance its understanding and effective use by nonscientists. Such translated information includes: fault-rupture location with forecasts of recurrence intervals and anticipated displacement, liquefaction with levels of susceptibility, areas of landslide hazard with levels of susceptibility, areas of inundation caused by hypothetical dam failures, and areas of building failures caused by ground shaking. The following actions are likely to improve use of scientific information by nonscientists:

-- Identify and catalog existing hazard maps and reports.

-- Identify the hazard maps and reports needed for hazard-reduction measures.

-- Estimate cost and determine responsibility, funding, and delivery of the information that can be provided.

-- Assure that new information is prepared in detail and at the scales needed by the users (see Table 1).

-- Make special efforts to present the information in a format and language suitable for use by engineers, planners, and decisionmakers.

-- Assure that information (including discoveries, advances, and innovative uses) is released promptly through appropriate communicators and communication techniques (see Tables 2 and 3).

2) Communication--This task is also a continuation of past activities. Communication of scientific information consists of both its transfer and its effective use for hazard reduction. Examples of communicators and communication techniques are listed in Tables 2 and 3. The following actions are likely to improve effective use of the technical information:

-- Design the communications program after an assessment of potential users' needs and capabilities.

-- Select the most effective educational, advisory, and review services (Table 2) appropriate to the targeted users.

-- Design the communications program so that information can be effectively disseminated (including use of the scientists and investigators to help communicate).

3) Determine Users' Needs--The past work by the Utah Seismic Safety Advisory Council (1977-1980) and the August 1983 Governor's Conference

on geologic hazards succeeded to some extent in determining the needs for earthquake hazards information in Utah. Use of scientific information by nonscientists requires a considerable effort on the part of both the producers and the users to communicate with each other, and although a variety of users exist, effective use depends upon the users' interests, capabilities, and experience in hazard reduction. Examples of users are listed in Table 1. The following actions will ensure effective transfer of the information to potential users:

-- Identify and target users (Table 1) that have urgent needs and who could be expected to use the information most effectively.

-- Consult with those users about their needs and priorities and prioritize the information needed.

-- Monitor and analyze the enactment of local, State, and Federal hazard-reduction laws or regulations and the issues that affect users in order to anticipate and respond to their needs.

-- Encourage users--both public and private--to develop an in-house capability to obtain and apply the information (including risk assessment).

-- Orient or train targeted users in order to enable them to understand and to use the information effectively.

4) Reduction Techniques--This task must also build on past activities. Many opportunities are available for reducing geologic and hydrologic hazards. Examples of hazard-reduction techniques are listed in Table 4. The following actions will increase the likelihood of an effective reduction of hazards:

-- Identify the most effective reduction techniques that are either being used by the targeted users or are available to them.

-- Review existing State programs or laws that could incorporate such reduction techniques and recommend changes or new programs and laws.

-- Devise and test innovative reduction techniques.

5) Evaluation--Continuing systematic evaluation will be a part of this program and is a key to any successful State-local hazard reduction program. An inventory of uses made of the scientific information, interviews with users, and an analysis of the inventory and responses will result in identifying new users, and any obstacles to communication of the information or its effective use. The following actions will make evaluation easier and enhance implementation:

-- Inventory uses of information (Table 4) to identify and document the type and number of uses of each hazards map or report.

-- Analyze uses of the hazards information and any problems identified and suggest improvement to the information or to the communication techniques.

-- Identify problems with and suggest improvements to reduction techniques by the monitoring of land-use decisions.

-- Interview users of information (Table 1) to evaluate the adequacy of the information and the communication techniques and to identify obstacles to their effectiveness.

Proposed-Selection Criteria--Numerous combinations of scientific information, communication techniques, users, and reduction techniques exist. Consideration of the following factors will be helpful in the selection of proposals for grants and contracts in support of the above implementation tasks:

-- User is an applicant.

-- Experienced communicator is an applicant.

-- A high probability exists for successful transfer and effective use of the information.

-- A communicator is in place and communication technique are in operation.

-- Translated scientific information is immediately available to the user.

-- Minimum time is required for translation and transfer of the information.

-- A large number of people or numerous critical facilities are at risk in the targeted area.

-- Rapidly urbanizing areas are located in the targeted area.

-- An opportunity exists for innovative or prototypical communication or reduction techniques.

-- Sponsor, convene, and coordinate at least one workshop each year designed to foster an environment for implementation of loss reduction measures at the local level.

-- Evaluate proposals and fund selected projects that will enhance implementation.

-- Enlist Federal partners.

Suggested Roles for UGMS--Initially, the role of the UGMS would be to:

-- Advise the USGS on the selection of projects that will enhance implementation.

-- Serve as a technical advisor and reviewer of funded implementation projects.

-- Enlist partners in Utah.

Table 1

Some Potential Users of Geologic and Hydrologic Information for Earthquake-Hazard Reduction along the Wasatch Front, Utah

City, County, and Areawide Government Users

City building, engineering, zoning, and safety departments
County building, engineering, zoning, and safety departments
Mayors and city council members
Multicounty planning, development, and preparedness agencies
Municipal engineers, planners, and administrators
City and county offices of emergency services
Planning and zoning officials, commissions and departments
Police, fire, and sheriff's departments
Public works departments
County tax assessors
School districts

State Governments Users

Department of Community and Economic Development (Community Services Office, Economic and Industrial Development)
Department of Business Regulation (Contracts Division, Real Estate Division)
Department of Financial Institutions
Department of Health (Environmental Health, Health Care Financing)
Department of Natural Resources
Department of Transportation
Division of Comprehensive Emergency Management
Division of Water Resources
Division of Water Rights
Facilities Construction and Management
Geological and Mineral Survey
Governor's Office
Legislative Fiscal Analyst
Legislative Research and General Counsel
National Guard
Planning and Budget Office
Public Service Commission
Science Advisor
State Tax Commission

Federal Government Users

Army Corps of Engineers
Bureau of Land Management
Bureau of Reclamation
Congress and Congressional staffs
Department of Agriculture
Department of Energy
Department of Housing and Urban Development
Department of Interior
Department of Transportation
Environmental Protection Agency
Farmers Home Administration
Federal Emergency Management Agency
Federal Housing Administration
Federal Insurance Administration
Federal Power Commission
Forest Service
General Services Administration
Geological Survey
National Bureau of Standards
National Oceanic and Atmospheric Administration
National Park Service
National Science Foundation
Nuclear Regulatory Commission
Small Business Administration
Soil Conservation Service

Other National Users

Applied Technology Council
American Association of State Highway and Transportation Officials
American Public Works Association
American Red Cross
Association of Engineering Geologists
Association of State Geologists
Council of State Governments
Earthquake Engineering Research Institute
International Conference of Building Officials
National Academy of Sciences
National Association of Counties
National Association of Insurance Commissioners
National Governors' Association
National Institute of Building Sciences
Natural Hazards Research and Applications Center
National League of Cities
Professional and scientific societies (including geologic, engineering, architecture, and planning societies)
United States Conference of Mayors

Private, Corporate, and Quasi-public Users

Civic and voluntary groups
Concerned citizens
Construction companies
Consulting planners, geologists, architects, and engineers
Extractive, manufacturing, and processing industries
Financial and insuring institutions
Landowners, developers, and real-estate persons
News media
Real-estate salespersons
Utility companies
University departments (including geology, civil engineering, architecture, urban and regional planning, and environmental departments).

Table 2

Typical Communication Techniques

Educational services

Assisting and cooperating with universities and their extension divisions in the preparation of course outlines, detailed lectures, casebooks, and display materials.

Contacting speakers and participating as lecturers in regional and community educational programs related to the application of hazard information.

Sponsoring, conducting and participating in topical and areal seminars, conferences, workshops, short courses, technology utilization sessions, cluster meetings, innovative transfer meetings, training symposia, and other discussions with user groups, e.g. 1983 Utah Governor's Conference on Geologic Hazards, UGMS Circular 74.

Releasing information needed to address critical hazards early through oral briefings, newsletters, seminars, map-type "interpretive inventories," open-file reports, reports of cooperating agencies, and "official use only" materials.

Sponsoring or cosponsoring conferences or workshops for planners and decisionmakers at which the results of hazard studies are displayed and reported on to users, e.g. scheduled USGS workshop, August 1984.

Providing speakers to government, civic, corporate, conservation, and citizen groups, and participating in radio and television programs to explain or report on hazard-reduction programs and products.

Assisting and cooperating with regional and community groups whose intention it is to incorporate hazard information into school curricula.

Preparing and exhibiting displays that present hazard information and illustrate their use in hazard reduction.

Attending and participating in meetings with local, district, and State agencies and their governing bodies for the purpose of presenting hazard information.

Guiding field trips to potentially hazardous sites.

Preparing and distributing brochures, TV spots, films, and other visual materials to the news media.

Advisory services

Preparing annotated and indexed bibliographies of hazard information and providing lists of pertinent reference material to various users.

Assisting local, State, and Federal agencies in designing policies, procedures, ordinances, statutes, and regulations that cite or make other use of hazard information.

Assisting in recruiting, interviewing, and selecting planners, engineers, and scientists by government agencies for which education and training in hazard information collection, interpretation, and application are criteria, e.g. pending proposal to fund county geologists.

Assisting local, State, and Federal agencies in the design of their hazard information collection and interpretation programs and in their work specifications.

Providing expert testimony and depositions concerning hazard research information and its use in reduction techniques.

Assisting in the presentation and adoption of plans and plan-implementation devices that are based upon hazard information.

Assisting in the incorporation of hazard information into local, State, and Federal studies and plans.

Preparing brief fact sheets or transmittal letters about hazard products explaining their impact on, value to, and most appropriate use to local, State, and Federal planning and decisionmaking.

Assisting users in the creation, organization, staffing, and formation of local, State, and Federal planning and planning-implementation programs so as to assure the proper and timely use of hazard information.

Preparing and distributing appropriate user guides relating to earth hazard processes, mapping, and hazard-reduction techniques, e.g. UGMS fliers.

Preparing model State safety legislation, regulations, and development policies.

Preparing model local safety policies, plan criteria, and plan-implementation devices.

Review services

Review of proposed programs for collecting and interpreting hazard information.

Review of local, State, and Federal policies, administrative procedures, and legislative analyses that have a direct effect on hazard information.

Review studies and plans based on hazard information.

Table 3

Representative Communicators of Hazard Information

American Institute of Architects/Research Corporation
American Institute of Certified Planners, Utah Chapter
American Institute of Professional Geologists, Utah Chapter
American Society of Public Administrators, Utah Chapter
American Society of Civil Engineers, Utah Chapter
Association of Engineering Geologists, Utah Chapter
Bear River Association of Governments
Children's Museum
Church groups, church organizations, and church-sponsored events
Circuit riders (regional or project area)
City Management Association
Civic and voluntary groups
Community planning assistance programs
Council of State Governments
County extension agents
Educators (univerity, college, high school, and elementary school levels)
Governor's Advisory Council on Local Governments
Hansen Planetarium
Hazrd-information clearinghouse (national, regional, or project area)
Hazard researchers, interpreters, and mappers
International Conference of Building Officials, Utah Chapter
Journalists, commentators, and editors, and their professional associates
Local seismic safety advisory groups
Mountain Lands Association of Governments
Museum of Natural History
National Council of State Legislators
National Governor's Conference
Neighborhood associations
Public information offices (Federal and State)
Researchers, engineers, and planners
Speakers bureaus (regional or project area)
Society of American Foresters, Wasatch Front Chapter
Urban and Regional Information Systems Association
University of Utah Seismograph Stations
Utah Association of Counties
Utah Geological Association
Utah League of Cities and Towns
Utah Geological and Mineral Survey
United States Conference of Mayors
U.S. Bureau of Land Management
U.S. Forest Service
U.S. Geological Survey
U.S. Soil Conservation Service
Wasatch Front Regional Council
Western Governor's Policy Office

Table 4

Some Opportunities for Using Geologic and Hydrologic Information to Reduce Earthquake Hazards along the Wasatch Front, Utah

Preparing development studies and plans

Circulation of transportation studies or plans
Community facility and utility inventories or plans
Environmental impact assessments lnd reports
Land-use and open-space inventories or plans
Land subdivision lot layouts
Multi-hazards inventories, risk analyses, and response capabilities
Natural-hazards reduction plans
Redevelopment plans (pre- and post-earthquake)
Seismic safety and public safety plans

Discouraging new or removing existing unsafe development

Capital-improvements expenditures
Costs of insurance
Disclosing hazards to real-estate buyers
Financial incentives and disincentives
Governor's executive orders
Policies of private lenders
Non-conforming use provisions in zoning ordinances
Posted warnings of potential hazards
Public acquisition of hazardous areas
Public facility and utility service policies
Public information and education
Recording the hazard on public records
Removing unsafe structures
Special assessments or tax credits

Regulating development

Building ordinances
Design and construction regulations
Grading regulations
Hazard-zone investigations
Land-use zoning districts and regulations
Special hazard-reduction ordinances
Subdivision ordinances

Designing and building structures

Strengthening or retrofitting of unsafe structures
Critical facilities, siting, design, and construction
Engineering, geologic, and seismologic reports
Public-facility or utility reconstruction or relocation
Reconstruction after earthquakes
Repair of dams
Site-specific investigations and hazard evaluations

Preparing for and responding to disasters

Anticipating damage to critical facilities
Damage inspection, repair, and recovery procedures
Dam and reservoir supervision
Disaster training exercises
Earthquake-prediction response plans
Earthquake-preparedness plans
Emergency response plans
Monitoring and warning systems
Relocating occupants of exceptionally hazardous buildings

SUMMARIES OF WORKSHOPS AND KNOWLEDGE UTILIZATION ACTIVITIES CONDUCTED UNDER THE AUSPICES OF THE NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM

WORKSHOPS

The first workshop, "Communicating Earthquake Hazards Reduction Information," was held in Denver, Colorado, in May 1978, 65 participants attended the workshop which had two objectives: 1) to evaluate the process of information flow, examining critically the characterists of the information producer and the information of the user communities, the communication procedures that work, and the lessons that have been learned, and 2) to recommend procedures for improving communication of earthquake hazards reduction in the NEHRP. The workshop (described in USGS Open-File Report 78-933) identified the key factors that must be accommodated in order to achieve effective communication: 1) publication of a "report" does not constitute communication, 2) there are many publics, each one has specific needs for earthquake hazards reduction information, 3) there is no consistency between the provision of scientific information to a user and how it is used, and 4) communication is enhanced when the user has a stake in the process.

The second workshop, "Information Needs for Producing National and Regional Seismic Hazards and Risk Assessments," was held in Vail, Colorado, in October 1979. The workshop had two objectives: 1) to define the needs of users in local-State-Federal government, researchers, land-use planners, building code organization, the financial sector, and others for hazards and risk maps and information, and 2) to identify the concerns of users with regard to: a) the physical parameters that are mapped, b) the usefulness of the map products, c) how to depict uncertainity, d) how to minimize conservative tendencies, and e) how to disseminate the information effectively. Six maps depicting the ground shaking hazard on a national scale in terms of exposure times, peak acceleration and velocity, and a 10% probability of nonexceedance have been published since the workshop and the recommendations of the workshop (described in USGS Circular 816) have been incorporated in both the internal and external programs of the USGS.

The third workshop, "Communicating Earthquake Prediction Information," was held in Los Angeles, California, in January 1980. The workshop was cosponsored by USGS, FEMA, and California State government agenices. It provided a forum for presenting basic information on earthquake prediction and for identifying constructive responses before and after the actual prediction of an earthquake. One hundred and five participants attended this meeting. The results are published in USGS Open-File Report 80-843. Two prediction councils, the California Earthquake Prediction Council and the National Earthquake Prediction Council, began to function in an integrated way as a result of this meeting.

The fourth workshop, "Evaluation of Regional Seismic Hazards and Risk," was held in Santa Fe, New Mexico, in August 1980. Forty scientists and engineers participated in the meeting which had three objectives: 1) to identify the technical issues associated with the evaluation of regional earthquake hazards, 2) to assess the current state-of-knowledge for evaluating regional earthquake hazards and risk and 3) to recommend future research for resolving the technical issues for improving the state-of-knowledge. The recommendations of the workshop, which are described in USGS Open-File Report 81-437, are now being implemented in the USGS's "Regional Earthquake Hazards Assessments" program element, a part of the NEHRP.

The fifth workshop, "Preparing for and Responding to a Damaging Earthquake in the Eastern United States," was held in Knoxville, Tennessee, in September 1981. The Knoxville workshop (described in USGS Open-File Report 82-220) demonstrated that policymakers and members of the scientific-engineering community can assimilate a great deal of technical information about earthquake hazards and work together to devise practical work plans. The workshop resulted in the creation of a draft 5-year work plan to improve the state-of-earthquake-preparedness in the Eastern United States and the birth of the South Carolina Seismic Safety Consortium.

The sixth workshop, "Continuing Actions to Reduce Losses from Earthquakes in the Mississippi Valley Area," was held in St. Louis, Missouri, in May 1982. It resulted in the identification of specific actions with high potential for reducing losses that could be implemented immediately and the formation of the Kentucky Governor's Task Force on Earthquake Hazards and Safety. The workshop provided a basis that eventually led in 1984 to FEMA's Central United States Earthquake Preparedness Project. The results of the workshop (described in USGS Open-File Report 83-157) reaffirmed that practical work plans can be created efficiently by a diverse group of scientists, engineers and decisionmakers.

The seventh workshop, "The 1886 Charleston, South Carolina, Earthquake and Its Implications for Today," was held in the Charleston area of South Carolina, in May 1983. The Charleston workshop had multiple objectives including: interpretation of scientific information and its use in the siting of critical facilities and preparedness measures. The most important outcome of the workshop (described in USGS Open-File Report 83-843) was the definition of a comprehensive integrated research program on eastern seismicity.

The eighth workshop, "Continuing Actions to Reduce Potential Losses from Future Earthquakes in the Northeastern United States," was held at Massachusetts Institute of Technology, Cambridge, Massachusetts, on June 13-15, 1983. The workshop (described in USGS Open-File Report 83-844) identified a need for at least one regional seismic safety organization in the Northeastern United States to deal with earthquakes in the context of natural hazards. A seismic safety organization for New York was created in 1984; formation of a New England Seismic Safety Organization is currently being considered.

The ninth workshop, "Site Specific Effects of Soil and Rock on Ground Motion and their Implications for an Earthquake-Resistant Design," was held in Santa Fe, New Mexico, in July 1983. Forty scientists and engineers attended this workshop which was sponsored by USGS and the Nuclear Regulatory Commission. The objective was to identify the technical issues concerning the effects of soil and rock on ground motion and the consequences of these issues on current design practice. The workshop (described in USGS Open-File Report 83-845) produced recommendations for experiments that would address the concerns of both scientists and engineers; these are now being implemented.

The tenth workshop, "Continuing Actions to Reduce Potential Losses from Future Earthquakes in Arkansas and Nearby States," was held in North Little Rock, Arkansas, in September 1983. The workshop was designed to accelerate the ongoing work of the Arkansas Office of Emergency Services, providing a forum for discussion of their activities to prepare for and respond to a major earthquake such as a recurrence of the 1811-1812 New Madrid earthquakes. The results of this workshop (described in USGS Open-File Report 83-846) reiterated the fact that no State or region of the United States is adequately prepared to cope with the effects of a major earthquake. Corrective measures are now being taken throughout the United States.

The eleventh workshop, "Geologic Hazards in Puerto Rico," was held in San Juan, Puerto Rico, in April 1984. The workshop was designed to strengthen the short- and long-term activities of the Department of Natural Resources of Puerto Rico to reduce losses from earthquakes and other geologic hazards. The results of this workshop (described in USGS Open-File Report 84-761) pointed out that Puerto Rico is potentially vulnerable to landslides, large earthquakes, and tsunamis. A vulnerability study is currently underway to be incorporated into preparedness measures and emergency plans.

The twelfth workshop, "Earthquake Hazards in the Virgin Islands Region," was held in St. Thomas, Virgin Islands, in April 1984. The workshop was designed to identify the earthquake hazards in the Virgin Islands Region to report on the status of geologic mapping and a vulnerabilty study, and to recommend specific research and loss reduction measures. The workshop (described in USGS Open-File Report 84-762) called for continuation of geologic mapping and the vulnerability study.

KNOWLEDGE UTILIZATION

In order to enhance the utilization of knowledge about earthquake hazards generated in the workshops, a new series of publications was created in 1984. The first two publications in the series are:

"Primer on Improving the State of Earthquake Hazards Mitigation and Preparedness," (USGS Open-File Report 84-772).

"The New Madrid Seismic Zone," (USGS Open-File Report 84-770).

EVALUATION OF THE WORKSHOP ON REGIONAL AND URBAN EARTHQUAKE HAZARDS AND RISK IN UTAH: ANALYSIS AND RESPONSE OF PARTICIPANTS

by

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At the conclusion of the two-and-a half day gathering, participants were asked to evaluate the success of the workshop in reaching its goals, to rate various sessions, to list one or two possible actions to increase earthquake hazard awareness and concern of others, and to identify one or two positive and negative aspects about the workshop.

The workshop was designed to define the regional and urban earthquake hazards and risk in Utah: to inform participants about the potential from earthquakes; to outline some of the unresolved technical problems surrounding the hazard which require more research; to identify some of the scientific-legal-political-social issues that might result from a damaging earthquake in Utah; to highlight the possibility for present action to mitigate future potential losses; and to identify relative priorities, program options and strategies for future research to improve the evaluation of the earthquake hazard in Utah.

Responses were elicited on a five-point scale: 1 and 2 representing the lowest level of agreement, 3 moderate agreement, and 4 and 5 highest agreement, or a "yes" response (see Figure 1). Since not all respondents answered all the questions, percentages are based only on those who submitted evaluations (see Figure 2).

Evaluations returned by 48 participants indicate that the workshop was successful in increasing knowledge about various aspects of the earthquake hazard in Utah. Almost all or 98% came away from the workshop with more information about earthquake hazards and 80% with an increased understanding of Utah's potential risks from earthquakes.

In other key areas respondents indicated that their earthquake hazard awareness had been increased. Specifically, 92% felt they had learned more about some of the unresolved technical problems that require more research. Eighty-nine percent felt they had improved their understanding of the scientific-legal-political-social issues accompanying a damaging earthquake. A majority, or 85%, gained a better grasp of mitigation actions that can be implemented now to reduce future earthquake losses in Utah. Another 85% felt that they had increased their understanding of the relative priorities, program options, and strategies for future research that would improve evaluation of the earthquake hazard in Utah.

Ninety-four percent of those evaluating the workshop attended the plenary session finding them to be both informative (89%) and valuable (96%). Similarly, highly positive responses were elicited from the 95% who attended the interactive group discussions, as over 85% found them to be both informative and valuable.

The special evening technical sessions were attended by over three-quarters of the respondents. Again, evaluations were highly positive as the respondents found the technical sessions also to be informative and valuable (92%).

There seems to have been some confusion regarding the evaluation of the special session on the "Determination of the Needs of Policy Makers in Utah". This session was held <u>after</u> the respondents had completed their evaluations. Consequently, the responses are, at best, misguided and should probably be ignored.

Responses related to earthquake hazard awareness before and after the workshop indicated that three-quarters of the respondents already had substantial knowledge of the earthquake threat in Utah. While 77% indicated that their pre-workshop awareness was high, this figure increased by 17% to render a post-workshop count of 96%. The challenge is, of course, to attract greater numbers of participants who are less aware of the significance of the earthquake risk. U.S. Geological Survey (USGS) has demonstrated a strong commitment to identifying concerned policymakers through whom other influential officials can be identified for future involvement. Finally, almost all respondents would welcome the opportunity to repeat the workshop experience and support the planning of future workshops of this type.

Another important judgement of the success or failure of a workshop can be made by looking beyond the impacts it had on attitudes, to ways in which it may affect behavior. In order to determine whether the workshop had any long-term effect on the behavior of participants, the final questions on the evaluation sheet asked respondents to consider actions they might take to improve the awareness and concern of others in Utah. Responses to those questions were varied and reflect a wide range of experience and knowledge.

In the home, plans included educating family members and adopting basic household safety measures such as tying down water heaters, latching cupboards and installing fire alarms. At work, plans included both baisc safety measures, such as bolting bookshelves and protecting computerized data bases, as well as more ambitious actions such as orgaizing workshops.

Several respondents indicated that education was the key to increasing community awareness of earthquake hazards. The media, church groups and local advisory boards were suggested as instuments to convey the earthquake message. With reference to colleagues, several respondents suggested the use of professional workshops to increase earthquake hazard awareness in Utah.

When asked to identify one or two items of value about the workshop, respondents' answers were varied. Most frequently mentioned were the mix of both technical and policy persons and issues and the interdisciplinary nature of the workshop. Other items mentioned included the informal contacts made and discussions held, the opportunity to focus on needs and objectives and the interactive discussion sessions.

When identifying items that needed improvement, what one respondent perceived as a weakness, almost invariably, another saw as a strength. However, there were several items that were repeatedly perceived as weaknesses. Prominent among them was the complaint that the technical presentations were too technical and that these seemed to take precedence over planning issues.

Overall, the evaluations were indicative of a high level of interest in and concern about the earthquake hazard in Utah. Clearly, a majority of the respondents found the workshop to be of great benefit and were intent on translating an increased awareness on the earthquake hazard in Utah into action at home, at work, in the community and among professional associates.

FIGURE 1
Evaluation of the Workshop by Individual Participants

	Low 1&2	3	High 4&5
1. Did you find the workshop to be useful to you or your organization by increasing you knowledge of:			
a. earthquake hazards in Utah?	2	16	30
b. the potential risk from earthquake hazards in Utah?	10	18	20
c. some of the unresolved technical problems requiring additional or more focused research?	4	10	34
d. some of the scientific-legal-political-social issues that might result as a consequence of a damaging earthquake in Utah?	5	8	34
e. achievable actions that can be taken to reduce potential losses from earthquake hazards in Utah?	7	21	17
f. relative priorities, program options, and strategies for future research to improve the evaluation of earthquake hazards in Utah?	7	17	22
2. Did you attend the plenary sessions?	0	45	
If yes, did you find them to be:			
a. informative?	5	9	33
b. valuable?	2	12	33
3. Did you attend the interactive group sessions?	2	41	
If yes, did you find them to be:			
a. informative?	6	8	32
b. valuable?	5	10	30
4. Did you attend the special evening technical sessions where details of individual research projects were discussed?	10	34	
If yes, did you find them to be:			
a. informative?	3	9	35
b. valuable?	3	13	21
c. presented clearly and in an understandable manner?	7	8	22
d. reinforced by the handout material?	3	9	25
5. Did you attend the special session on "Determination of the needs of policymakers of Utah"?	28	17	
If yes, did you find it to be:			
a. informative?	2	2	11
b. valuable?	2	1	11
c. reinforced by the handout material?	1	5	8
6. Before this workshop, I would rate my level of earthquake hazard awareness and concern as	3	8	36
7. Now I rate my level of earthquake hazard awareness and concern as	2	1	45
8a. If the clock were turned back and the decision to attend this workshop were given to you again, would you want to attend?	2	44	
8b. Should future workshops of this type be planned?	1	45	

FIGURE 2

Evaluation of the Workshop by Percentages Participants

	Low 1&2	3	High 4&5
1. Did you find the workshop to be useful to you or your organization by increasing you knowledge of:			
a. earthquake hazards in Utah?	4%	33%	63%
b. the potential risk from earthquake hazards in Utah?	21%	37%	42%
c. some of the unresolved technical problems requiring additional or more focused research?	8%	21%	71%
d. some of the scientific-legal-political-social issues that might result as a consequence of a damaging earthquake in Utah?	11%	17%	72%
e. achievable actions that can be taken to reduce potential losses from earthquake hazards in Utah?	15%	47%	38%
f. relative priorities, program options, and strategies for future research to improve the evaluation of earthquake hazards in Utah?	15%	37%	48%
2. Did you attend the plenary sessions?	0%		94%
If yes, did you find them to be:			
a. informative?	11%	19%	70%
b. valuable?	4%	26%	70%
3. Did you attend the interactive group sessions?	5%		95%
If yes, did you find them to be:			
a. informative?	13%	17%	70%
b. valuable?	11%	22%	67%
4. Did you attend the special evening technical sessions where details of individual rêsearch projects were discussed?	23%		77%
If yes, did you find them to be:			
a. informative?	8%	24%	68%
5. b. valuable?	8%	35%	57%
c. presented clearly and in an understandable manner?	19%	22%	59%
d. reinforced by the handout material?	8%	24%	68%
5. Did you attend the special session on "Determination of the needs of policymakers of Utah"?	62%		38%
If yes, did you find it to be:			
a. informative?	12%	13%	73%
b. valuable?	14%	7%	79%
c. reinforced by the handout material?	7%	36%	57%
6. Before this workshop, I would rate my level of earthquake hazard awareness and concern as	6%	17%	77%
7. Now I rate my level of earthquake hazard awareness and concern as	4%	2%	94%
8a. If the clock were turned back and the decision to attend this workshop were given to you again, would you want to attend?	4%		96%

SUMMARY AND RECOMMENDATIONS OF DISCUSSION GROUP 1:
SYNTHESIS OF GEOLOGICAL, GEOPHYSICAL, AND ENGINEERING DATA
FOR EVALUATION OF EARTHQUAKE HAZARDS AND RISK IN UTAH

Moderator: Walter J. Arabasz, University of Utah
Recorder: Russell L. Wheeler, U.S. Geological Survey

FOREWARD

These draft plans and recommendations were developed by the participants of the workshop on "Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah." They are intended to serve as a guide for scientists, engineers, social scientists, public officials, and emergency managers. Representatives of these disciplines can use the plans and recommendations in several ways: 1) to evaluate the present state-of-knowledge of earthquake hazards in Utah including scientific, engineering, and societal preparedness components, 2) to determine if additional scientific, engineering and societal-response information is needed to implement an effective earthquake-loss reduction program in Utah, and 3) to create action plans to implement such a program as soon as possible.

Messers. Keaton, L. Anderson, and Youd prepared the recommendations for the ground failure program. Phillip Wright prepared recommendations for geodetic and subsurface studies. Craig Taylor provided the preliminary results of his study on seismic risk.

The membership of the discussion group included:

Loren Anderson	Utah State University
Ernest Anderson	U.S. Geological Survey
Walter Arabasz (Moderator)	University of Utah
Lynn Barnhard	U.S. Geological Survey
Ronald Bruhn	University of Utah
Robert Bucknam	U.S. Geological Survey
Russell Campbell	U.S. Geological Survey
Patricia Cashman	Weber State College
Robert Conlon	Consultant
Anthony Crone	U.S. Geological Survey
Mark Jadkowski	Utah State University
Bruce Kaliser	Utah Geological and Mineral Survey
Jeffery Keaton	Dames and Moore
Richard Martin	Bureau of Reclamation
James Pechmann	University of Utah
Loren Rausher	Utah Department of Transportation
Robert Schuster	U.S. Geological Survey
David Schwartz	Woodward-Clyde Consultants
Richard Shea	The Church of Jesus Christ of the Latter Day Saints
Robert Smith	University of Utah
Craig Taylor	National Technical Systems
Bergthora Thorbjarnardottir	University of Utah
John Tinsley	U.S. Geological Survey
Russell Wheeler (Recorder)	U.S. Geological Survey
Spencer Wood	Boise State University, Idaho

Phillip Wright — University of Utah Research Institute
Leslie Youd — Brigham Young University
Mary Lou Zoback — U.S. Geological Survey

INTRODUCTION

The primary charge given to this discussion group was to "focus on the task of synthesizing geological, geophysical, and engineering data for evaluating earthquake hazards and to identify achievable actions that can be taken within the next 2 or 3 years to foster an environment for implementation of loss reduction measures in Utah." For a number of reasons, the scope of discussion was very broad. The discussion group included a large number of participants who are working on fundamental studies of earthquakes and fault behavior along the Wasatch front, and this meeting was their first forum for open discussion within the framework of a new USGS Wasatch front initiative. Because members of the group had strong convictions about how much we do not know about earthquakes and fault behavior in the Wasatch front area, there was a natural hesitancy to address only short-term, implementation-oriented programs and plans.

The recommendations contained in this report reflect, in part, the participants' many-sided scientific and engineering interests. Participants were invited to submit correspondence to form part of this report, and edited versions of three such submissions are included. However, the recommendations of the group are more than a patchwork of individual interests; they represent first-order concerns of experts who are deeply involved and committed to resolving earthquake problems along the Wasatch front.

Because the discussion topic is broad, covering many disciplines, diverse activities, and a complex of challenging problems with varying susceptibilities to being solved, recommendations are divided according to whether they apply to the long or short term. For each of the two time scales, discussion and recommendations are concentrated around one problem or goal. Many useful suggestions were put forth during the discussion, however, all could not be included in this report because of the scope and diversity of the topic.

Short-term efforts cover fiscal years 1985 and 1986 (Oct. 1, 1984 to Sept. 30, 1986). The general recommendation of the group is that adequate priority be given during the next two years to filling gaps in the data base and to understanding what is needed for probabilistic risk assessment. The reason for this general recommendation is that experience elsewhere demonstrates that the results of probabilistic risk assessment are likely to have considerable technical and societal impact, can provide a focus and guide for later work, and probably can be achieved using data and understanding that are available now or can be obtained in the next two years. This sharply focused work will increase our ability to produce implementation-oriented products in the short term.

Long-term efforts should start now, but extend beyond FY 1986. Such efforts should aim at increasing understanding of earthquake occurrence and of the earthquake process. A useful and challenging focus for such work is to anticipate the most likely areas for the next large earthquake in Utah. Both short- and long-term efforts are necessary, and it is important not to concentrate resources unduly on either one to the detriment of the other. Short term efforts can quickly provide a foundation for planning and preparedness; long-term efforts are necessary for refinement and specification of hazard estimates, and for eventual forecasting and prediction. The short-term work will allow some actions to be taken in the near future, but the long-term work will eventually allow the most focused and, therefore, cost-effective estimation of hazard and risk and provide a technical basis for loss reduction measures.

RECOMMENDATIONS

Short term--The following investigations are considered likely to produce the most effective results in the next 2 or 3 years.

1) Expanded geodetic studies--These studies include collection of new data and investigation and extension of existing data bases. Development of a working rapport with the National Geodetic Survey (NGS) and coordination of efforts would increase the usefulness of their results for our purposes. Two or three decades ago the Civil Engineering

Department of the University of Utah, together with the NGS, established local geodetic networks in the area of Salt Lake City; the feasibility of reobserving these networks is worth investigating. Expected results of geodetic studies include characterization of present crustal deformation on active faults, possible detection of preseismic deformation, and ability to model strain. The costs of geodetic studies are comparatively low, the benefits should appear quickly, and the results would guide other research.

2) Accelerated investigations of active faults--These investigations include:

   a) Detailed investigations of the Quaternary record to determine elapsed time since the last large earthquake and to estimate the average interevent time for such earthquakes.

   b) Shallow reflection and other geophysical work to determine subsurface fault geometries and properties and to extend the results of work on the Quaternary record.

   c) Investigations to evaluate the proposed segmentation of the Wasatch fault.

Long term--Long term investigations should start now and extend beyond FY 1986: The following investigations are recommended:

1) Investigations of subsurface fault geometries throughout the seismogenic layer of the crust: Activities should include drilling, specially designed seismic reflection surveys, reprocessing of existing seismic reflection data, and geological investigations of exposed analogues.

2) Accelerated seismological research--A key factor is stable funding to support the seismograph networks and the analysis and application of the data obtained from them. In addition, consideration should be given to submitting a proposal through the Incorporated Research

Institute for Seismology (IRIS) for an experiment to image the upper crust at the Wasatch fault. Support from the USGS would improve the chances of success for the proposal.

3) Investigations of ground failure--The most important and urgent priority is the development of a comprehensive model that synthesizes characteristics of the several kinds of ground failure in Utah. To assess the hazard from specific kinds of ground failure and to combine them into an overall hazard assessment requires consistent criteria, data formats, and map scales. The tasks are mainly long term because so much needs to be done. They include:

   a) Improve the methodology for the probabilistic assessment of ground failures such as liquefaction-induced ground failures and seismic-slope failures.

   b) Devise a basis for estimating the amount of displacement resulting from liquefaction-induced ground failures and from seismic slope ground failures.

   c) Assess the implications of the unique characteristics of the thinly bedded local soils for liquefaction potential and for ground failure.

   d) Assess the hazard from tectonic subsidence (ground tilting) and from flooding at lake margins.

   e) Assess the hazard from earthquake-induced snow avalanches.

   f) Assist in developing realistic damage estimates based on studies of ground failure, especially for lifeline systems.

4. Geodetic and subsurface studies (see Appendix I-A).

5. Investigations to aid damage modeling (see Appendix I-B).

OTHER RECOMMENDATIONS TO CONSIDER

The following investigations were suggested by participants of the discussion group. They are stated in terms of a technical question:

1) Can the spatial and temporal distributions of small earthquakes be used as a guide for forecasting the occurrence of large earthquakes, as has usually been assumed? An answer to this question will involve, but not be restricted to, an evaluation of the hypothesis of characteristic earthquakes that still needs resolution:

2) How much attention should be paid to faults (other than the Wasatch fault) that are capable of producing moderate, but still damaging earthquakes?

3) Can ground shaking, its spatial variability, and attenuation be characterized more precisely along the Wasatch front urban corridor? Design and construction of engineered structures requires better definition of the ground-shaking hazard.

APPENDIX I-A:

Geodetic and Subsurface Studies

Phillip Wright, University of Utah Research Institute, prepared this appendix to the report of Discussion Group I.

Geodetic Studies

Even with the enthusiasm shown at the meetings for precise surveying, the potential contribution of such work may be understated. With the work of Arabasz, that shows strike-slip components of motion on certain faults in central Utah that were previously believed to be normal faults, and with the confirmation of this seismological evidence through field geological studies by Anderson, the need for precise horizontal surveys to supplement the leveling surveys is evident. Documentation of the extent of east-west extension along with vertical motions could help us choose among various models of deformation in the Basin and Range province. Knowledge of north-south relative strains would be valuable in visualizing possible strike slip on the north-south faults that predominate in the area.

Precise surveying has the potential for measuring current strain rates in a relatively short time, and additional information might even be available before 1986. Certainly with vertical rates of 4 mm/yr, surveys could be repeated in 5 to 10 years with expectation of valuable information. The same would be true of horizontal surveys.

The surveying should not be restricted to merely releveling the Spanish Fork profile which was implied at the meeting. We should consider spending on the order of $250,000 to establish precise horizontal and vertical networks for at least 5 carefully selected locations along the Wasatch Front. Networks should extend far enough east of the Wasatch fault to detect movement on the more seismically active faults. These networks would provide very valuable data in future years as they are resurveyed. There is no other way to obtain this kind of information.

Subsurface Studies

An interdisciplinary group should be identified to help determine subsurface configuration and conditions, not only of faults, but of the rocks between major faults. Integrated interpretation of interdisciplinary data would be the strategy for this group. The following studies can contribute to such an effort:

1) Structural studies--Geologic mapping and structural studies should be part of the funded effort. We actually know little about the subsurface structure of the area of interest. For example, the Wasatch fault itself is a complex structure not all of whose many strands have been identified either in the alluvial areas or in bedrock.

2) Microseismic studies--Detailed microseismic studies have the potential of mapping active faults at depth in selected areas.

3) Seismic Reflection studies--Such studies can give good detail of the subsurface.

4) Gravity studies--The effort made by M. L. Zoback should be encouraged. We should upgrade the gravity data base.

5) Magnetic studies--Detailed aeromagnetic surveys can reveal pertinent details such as fault boundaries of magnetic bodies and subsurface configurations. Publically available data may not be of the quality needed. Flying detailed surveys over selected portions of the Wasatch front is comparatively inexpensive.

6) Electrical studies--The magneto-telluric (MT) method has great potential to contribute to knowledge of subsurface structure using modern modeling techniques. Dipole-dipole resistivity surveys are also needed to constrain interpretations of the MT data at shallow depths.

Consideration should be given convening a workshop on subsurface studies to help define the state-of-knowledge and availability of data and to recommend research studies. This workshop should include representatives from industry, the USGS, the UGMS, and universities. Oil companies would have motivation to participate in and contribute to such a workshop, and perhaps to provide some funding support. The first day of such a workshop could concentrate on invited, half hour reviews of specific topics. A following half day could concentrate on defining potential contributions, in discipline-based discussion groups, and on a concluding plenary session to integrate results.

APPENDIX I-B:

Investigations to Aid Damage Modeling

Craig Taylor of National Technical Systems prepared this appendix to the report of Discussion Group I.

Studies to Resolve Seismic Risk Problems in Utah

Some of the preliminary findings of our study are summarized below to provide a more complete perspective.

First, we do not currently know how important the seismic-induced ground failure issues are in the Utah environment. They may turn out to be a major contributor to the risk. In the near future, we shall be examining expected pipeline failures in various Wasatch front environments, but the full significance of the ground failure problem is unlikely to be known unless efforts are also made to assess the ground failure potential in canyon corridors. Based on studies of other lifeline networks, however, I suspect that the liquefaction problem is far more severe for most Wasatch front networks than the fault rupture problem.

Second, additional trenching studies and/or scientific knowledge of normal faulting behavior could be useful in resolving the issue of how to distribute larger magnitude earthquakes within the energy release zone. The standard Der Kuireghian and Ang model implies that fault rupture is more likely to occur in the middle of a segment than at its ends. Other rupture models can be devised if this standard model is physically or historically inaccurate. Any model selected will have significant implications for understanding site response studies, as well as interpreting the results of trenching at a given site in terms of magnitude and recurrence times.

Third, modeling of expected damage to lifelines and buildings relies on parameters whose values may be uncertain, and on strategies whose effects may vary. Reduction of uncertainty in the values of some parameters and scientific exploration of hypotheses whose validation could greatly transform the total picture such outcomes would appear to be worthwhile goals of the program.

SUMMARY AND RECOMMENDATIONS OF DISCUSSION GROUP 2
GROUND MOTION MODELING AND LOSS ESTIMATION IN UTAH

Moderator: Maurice Power, Woodward Clyde Consultants
Recorder: Martin McCann, J.R. Benjamin and Associates

FOREWARD

These draft plans and recommendations were developed by the participants of the workshop on "Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah." They are intended to serve as a guide for scientists, engineers, social scientists, public officials, and emergency managers. Representatives of these disciplines can use the plans and recommendations in several ways: 1) to evaluate the present state-of-knowledge of earthquake hazards in Utah including scientific, engineering, and societal preparedness components, 2) to determine if additional scientific, engineering and societal-response information is needed to implement an effective earthquake-loss reduction program in Utah, and 3) to create action plans to implement such a program as soon as possible.

Albert Rogers served as a stimulator for the discussion group, presenting results of a recent study of ground response along the Wasatch front.

The membership of the discussion group included:

Marco Beteta	Federal Emergency Management Agency
Kenneth Campbell	U.S. Geological Survey
Stanley Crawley	University of Utah
Darrel Crawford	Mountain Fuel
William Filan	Utah Geological and Mineral Survey
Steven French	California Polytechnic State University
Garry Guymon	City of Orem
Walter Hays	U.S. Geological Survey
Kenneth King	U.S. Geological Survey
Allen McCandless	Sandy City Planning
Martin McCann, Jr. (Recorder)	Jack R. Benjamin & Assoc., Inc.
Clark Meek	Idaho Bureau of Disaster
Mark Palesh	Centerville City Corporation
David Perkins	U.S. Geological Survey
Maurice Power (Moderator)	Woodward Clyde Consultants
Albert Rogers	U.S. Geological Survey
Donald Steeples	Kansas Geological Survey
Bruce Vandr	U.S. Department of Agriculture--Forest Service
Delbert Ward	Structural Facilities, Inc.
Luci Wilcox	Utah State Office of Education

INTRODUCTION

The objective of this discussion group was to review components 3 and 4, Ground Motion Modeling and Loss Estimation Models, respectively, of the draft work plan for the Regional Earthquake Hazards Assessments program, Wasatch front, Utah, and to identify priorities, program options, and program plans and strategies. A major part of the discussion dealt with ground motion modeling. In the course of the discussion, the participants recognized the need to pursue a number of parallel approaches which meet the immediate needs of the three-year hazards reduction program in which the Wasatch front is receiving first priority, and also advance the state-of-knowledge about ground motion hazards and loss estimation.

RECOMMENDATIONS

In order to serve the needs and objectives of the focused effort of the National Earthquake Hazards Reduction Program (NEHRP) in the Wasatch front area, it was recommended that a group of activities be undertaken in parallel. These recommendations are summarized below:

1) Utilize available data and methods to develop earthquake hazard intensity maps and loss estimation models - With respect to ground motion estimation, a synthesis report should be prepared that documents the data that are available and pertinent for estimating ground response in the Wasatch front area. Probabilistic ground motion hazard analyses of the region should be conducted using currently available data for characterization of seismic sources and ground motion attenuation. Similar studies of loss estimation may also be conducted.

2) Utilize available methods and data to develop loss estimation models for use in the Wasatch front area - This work should be integrated with programs supported by other groups such as the Federal Emergency Management Agency. In parallel, an effort should be undertaken to acquire comprehensive inventory of structures, critical facilities, lifelines, and emergency services.

3) Maintain a sustained interaction between parties interested in earthquake hazards reduction in the Wasatch front - This effort includes technical meetings oriented toward the discussion of important engineering and scientific issues in detail, and workshops involving engineers, physical scientists, planners, and officials involved in defining public policy. Agencies such as the Federal Emergency Management Agency, U.S. Geological Survey, Bureau of Reclamation, Utah Geological and Mineral Survey, Division of Comprehensive Emergency Management, consultants, utilities, and professional organizations are encouraged to support and participate in this activity.

4) Implement programs to advance the state-of-information on the characteristics of the earthquake ground motion hazard in the Wasatch front area. This includes postearthquake investigations.

Members of the discussion group provided a list of specific recommendations to advance the level of information and the capability to predict strong ground motion in the Wasatch front. These include:

a) Data Acquisition - A program should be implemented to gather detailed information on physical properties required for predicting local ground response. A wide range of data types including geologic data, local stratigraphy, shear wave velocities, etc. should be collected. The primary focus of this effort should be to acquire data that are needed to perform microzonation studies.

b) Data Analysis - A data analysis program should be planned and implemented to develop microzonation maps for the Wasatch front area. The analysis should include detailed site response studies. It is important that these results are incorporated into building codes and other areas involved in earthquake hazard mitigation.

c) Instrumentation - A number of instrumentation needs exist to capture a variety of information types. These include strong motion instruments to record site response during strong shaking, and broad-band recorders to provide data from small (M < 4), but relatively frequent earthquakes. Data from these events will be useful in estimating regional attenuation, and local site response and in determining earthquake magnitudes.

d) Earthquake Response - A program plan should be developed that establishes an effective organization to collect data subsequent to future earthquakes. The plan should include provisions to disseminate strong motion instruments in order to record the motion produced by aftershocks, and to survey the damage to structures, life lines and critical facilities. A review of emergency actions and procedures in the post event period should also be conducted.

e) Regional Attenuation - From currently available data and from additonal data acquired from a network of broad-band instruments, attenuation studies should be conducted to estimate region-specific attenuation properties. Topics of study should include estimating crustal Q-values and the effect of earthquake mechanisms and source geometry on ground motion levels.

Ground Motion -- Loss Estimation
Summary

1) 2 Parallel Approaches

   a) Use best data/make ground motion and loss estimation
   b) Collect advanced models, data
   c) Interaction - small technical MTOS
      - EPNI, FEMA, State Agencies, contractors, Federal Agencies

2) Ground Response

   a) Data Acquisition
   - instr. data, for site response
   - geologic data,
   - stratigraphy physical properties
   - s-wave velocities
   - continued purchase of equipment

   b) Data Analysis
   - use data for microzoning, based on site response
   - need to include this information in codes, planning process
   - ultimately need to produce maps

   c) K.K. Instr. needs
   - 4 more site-response strong motion
   - 3-4 broad-band to investigate small earthquakes (M<4)
   - strong motion instr. - free-field, reevaluate needs

   d) Want to recommend that data be collected from new quakes ground motion, loss estimation prepare a plan
   - investigate plan
   - Advisory Council Plan - Del Ward's committee
     - recommendation for adding strong motion instr.

   e) Regional Attenuation
   - use data from broad-band to get crustal Q-values
   - review available studies McGuire's intensity approach
   - has implicaitons as magnitude estimates
   - look at the effect of mechanisms.
   - source modeling to see relative effects of geometry

   Loss Estimates

   - Intensity maps
   - Inventory
   - Want to have some relationship with FEMA work.

SUMMARY AND RECOMMENDATIONS OF DISCUSSION GROUP 3: INFORMATIONS SYSTEMS SESSION

Moderator: Robert Alexander, U.S. Geological Survey
Recorder: Terry Feldman, Federal Emergency Management Agency

FOREWARD

These draft plans and recommendations were developed by the participants of the workshop on "Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah." They are intended to serve as a guide for scientists, engineers, social scientists, public officials, and emergency managers. Representatives of these disciplines can use the plans and recommendations in several ways: 1) to evaluate the present state-of-knowledge of earthquake hazards in Utah including scientific, engineering, and societal preparedness components, 2) to determine if additional scientific, engineering and societal-response information is needed to implement an effective earthquake-loss reduction program in Utah, and 3) to create action plans to implement such a program as soon as possible.

The membership of the discussion group included:

Robert Alexander (Moderator)	U.S. Geological Survey
Walter Cox	Utah Geological and Mineral Survey
Deborah Epps	Wyoming Disaster and Civil Defense
Terry Feldman (Recorder)	Federal Emergency Management Agency
Wendy Hassibe	U.S. Geological Survey
Don Mabey	Utah Geological and Mineral Survey
Harvey Merrell	Consulting Geologist
Sonja Perez	Salt Lake County Emergency Services
Art Tarr	U.S. Geological Survey
Susan Tubbesing	University of Colorado
John Spitzley	Utah State University
Stan Steadman	Utah Department of Health

INTRODUCTION

Information systems that are "user friendly" are the goal of the U.S. Geological Survey's "Regional Earthquake Hazards Assessments" program element. Such information systems are needed to facilitate communication between researchers and to enhance the creation and implementation of loss reduction measures by public officials in Utah.

To create an efficient information system, one must be aware of the total process of information transfer. This process is complex, but it can be generalized as follows:

> The community (people and programs) require geologic hazards information (data, maps, reports, etc.). The process of transferring the information to users in the community (scientists, engineers, architects, social scientists, emergency managers, public officials) is controlled by constraints (political-legal, safety, physical, economic, social technological) which must be eliminated or minimized by creative activities (partnerships, incentives, reduction of costs, development of

technology for solving discrete components of the problem, optimization of decisions, etc.). The activities designed to transfer information require demonstration of their value (demonstration projects, publications, workshops, etc.) for evaluation and promotion of acceptance (changes in the state-of-practice, ordinances, legislation, etc.).

The process is dynamic and changes with time, especially after a damaging earthquake occurs. The information system must serve the needs of a variety of users including local, regional, State, and Federal agencies. The potential data files, in the broadest sense might include: 1) scientific data (seismicity, recurrence intervals of specific seismic source zones and faults, intensity data, strong ground motion records and spectra, etc.), 2) engineering data (physical properties of soil and rock columns, ground water levels, damage distribution inventories of buildings, lifelines, and other facilities, vulnerability/loss algorithms, etc.), 3) land use data (location of commercial buildings, assessor files, zoning data, etc.), 4) socioeconomic data (census/housing data, income files), 5) lifeline networks (transportation, communication, water, sewer, electrical, and gas networks), and 6) response facilities (casualty collection points, fire/police facilities, medical care facilities, broadcast facilities, etc.).

RECOMMENDATIONS

The members of the discussion group made the following recommendations:

1) The most efficient use of resources would be to:

   a) Foster communication among participants of the Wasatch front study; reaching out to the broad user group in Utah.

   b) Work with existing computer facilities, taking advantage of experience and strengths, and working incrementally to correct dificiencies, and c) taking an active role in determining the perceived and actural needs of the user community in Utah for earthquake hazards information.

2) An extraordinary effort should be made to communicate. Possible actions include:

   a) Creation of a network for interdisciplinary communication through a newsletter (like the Wasatch Forum). The newsletter should be published at frequent intervals, be distributed widely, and have a broad scope of subjects.

   b) Devising outreach activities to involve a wide range of user groups. These activities could use strategies such as workshops, small group meetings, exchange of technical information, demonstration of products and results of research, neighborhood meetings, and generation of special information packets and audiovisual materials to give them a stake in the process.

3) A bibliographic data base on hazards should be produced as soon as possible and communicated widely.

4) Steps should be taken to protect the information systems and computer facilities from loss in a major earthquake

5) A priority effort should be given to devising demonstration projects in an area like Davis County (or another area). Each demonstration project should have the following attributes: a) be expanded incrementally as a function of experience and need, b) have feedback and evaluation at each incremental step, c) stress the translation of scientific and technical information into products that meet the needs of user groups, d) take advantage of experience from California (e.g., Southern California Earthquake Preparedness Project) and other areas, e) agree on map scales and other standards, and f) determine the needs of user groups for hazards information and evaluate each group's use of the information.

SUMMARY AND RECOMMENDATIONS OF DISCUSSION GROUP 4: IMPLEMENTATION OPTIONS AVAILABLE IN UTAH

Moderator: Jerry Olson, Federal Emergency Management Agency, Region VIII
Recorder: Wesley Dewsnup, Utah Division of Emergency Management Agency

FOREWARD

These draft plans and recommendations were developed by the participants of the workshop on "Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah." They are intended to serve as a guide for scientists, engineers, social scientists, public officials, and emergency managers. Representatives of these disciplines can use the plans and recommendations in several ways: 1) to evaluate the present state-of-knowledge of earthquake hazards in Utah including scientific, engineering, and societal preparedness components, 2) to determine if additional scientific, engineering and societal-response information is needed to implement an effective earthquake-loss reduction program in Utah, and 3) to create action plans to implement such a program as soon as possible.

The membership of the discussion group included:

Christoher Arnold	Building Systems Development, Inc.
Jon Bischoff	Utah State University
Patricia Bolton	Battelle Seattle Research Center
William Brown	U.S. Geological Survey
Gary Christenson	Utah Geological and Mineral Survey
Stan Crawley	University of Utah
Joseph Delpha	Carbon County Emergency Management Agency
Wesly Dewsnup (Recorder)	Utah Division of Comprehensive Emergency Management
Allen Fawcett	Carbon County Planning Office
Harold Gill	Utah Geological and Mineral Survey
Paula Gori	U.S. Geological Survey
William Lund	Utah Geological and Mineral Survey
Jerry Olson (Moderator)	Federal Emergency Management Agency
Richard Olson	Arizona State University
Jeanne Perkins	Association of Bay Area Governments
Marion Picard	Utah Division of Comprehensive Emergency Management
Valerie Schulthies	Deseret News
George Shaw	Sandy City Planning Department
Stan Steadman	Utah Department of Health
Brent Taylor	Bureau of Reclamation
Charles Thiel	Telesis Inc.
Delbert Ward	Structural Facilities, Inc.

INTRODUCTION

During the last decade, it has become clear that implementation of loss reduction measures is as difficult to accomplish as the research required to produce the technical basis for creating the measures. The factors constraining implementation of loss-reduction measures include:

1) Political-legal--customs and traditional practices, codes, taxation policies, and legislation.

2) Economic--increase in construction costs, willingness to accept risk, profitability, insurability, and social costs.

3) Social--Lack of technical knowledge, lack of appreciation for technical knowledge, personal preference, and higher priorities of the populace.

4) Technological--Lack of scientific technical data, lack of a credible or acceptable methodology, and lack of professional and skilled manpower.

Every earthquake produces a series of scientific/technical lessons--most of which were learned earlier, but nothing was done to implement the new knowledge in terms of loss reduction measures. The most important past lessons applicable to Utah include:

1) The ground shaking will find and test every weakness in a building, damaging both primary and redundant systems. Losses to contents of buildings can be a large percentage of the total loss.

2) Unreinforced masonry buildings will not resist strong earthquake ground shaking without failure.

3) Buildings founded on materials susceptible to liquefaction, differential settlement, and landslides will fail in a large earthquake.

4) Poor quality of construction (e.g., low grade concrete, poorly prepared construction joints in concrete, careless welding, improper placement of reinforcing steel, etc.) will increase vulnerability of a building in an earthquake.

5) A building constructed in accordance with the seismic design provision of a modern building code (a minimum standard) is not as likely to fail in an earthquake as one that was not constructed in this manner. However, even buildings constructed according to code can fail.

6) Proper pre-earthquake planning prevents post-earthquake problems.

Considering these facts, it is clear that implementation of loss reduction measures is a team effort. Each member of the team (scientists, engineers, architects, social scientists, planners, emergency managers, and public officials) have a job to do that, if done effectively, requires the integration and coordination of their activities and programs with others. Otherwise, implementation of loss reduction measures will not be effective. When loss reduction measures are effectively implemented, experience suggests a benefit to cost ratio of at least 5:1.

RECOMMENDATIONS

Members of the discussion group discussed a broad range of subjects in the context of the theme. Their recommendations focused on options that are available in Utah, provided that strong local-State-Federal partnerships are formed and exercised. They include:

1) Communication--A newsletter (e.g., the Wasatch Forum) needs to be created and implemented to reach a wide variety of people.

   Data, maps (e.g., inundation maps in the vicinity of Deer Creek), and research reports [e.g., University of Utah publication on seismicity; UGMS publication on "Earthquake Fault Investigation and Evaluation;" USGS publications (e.g., the Algermissen et al ground shaking hazard maps]; and FEMA publications (e.g., the Southern California Earthquake Preparedness Project reports) should be widely distributed, translating as necessary for the nonscientists users.

   Stronger links should be made with the media to take advantage of opportunities to communicate data and important information to the public.

2) Education and training--Seminars, workshops, and short courses are needed on a regular schedule to keep a core group of individuals abreast of a dynamically changing field. Video tapes and films should be considered to increase efficiency of utilization of experts.

3) County geologists--Local governments need to attain the capability to take the products (data, maps, reports, etc.) produced in the "Regional Earthquake Hazards Assessments" program and apply them to solve problems in their jurisdictions. This application is the only way that the ultimate goal of reducing the loss of life and property from earthquakes will be attained. The Wasatch front counties (Weber, Davis, Salt Lake, Utah, Juab, Cache, Box Elder, Morgan, Wasatch, and Summit) are the places to start. The county geologists are the key resource. Such a process is needed now.

4) County planners--An analogous situation to that of 3 should be tested to determine its feasibility.

5) State Building Code--An effort should be made to require, as a minimum, that all new public buildings in Utah be constructed in accordance with the seismic design provisions of a modern building code (e.g., "The NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buidlings"). Trial use and design of these provisions by the Building Seismic Safety Council have shown that it does not always cost more to design and construct an earthquake-resistant building in terms of a modern code.

6) Emergency response plan--The State should exercise its response plan in terms of a realistic earthquake scenario. Deficiencies, if any, should be eliminated. Additional scenarios should be devised and exercised to test and improve the plan.

SEISMICITY AND EARTHQUAKE HAZARDS OF UTAH AND THE WASATCH FRONT: PARADIGM AND PARADOX

by

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I. INTRODUCTION

Crustal uplift during the past 15 million years has produced more than 4500 m of total displacement along the Wasatch fault, no doubt much of it accompanied by large prehistoric earthquakes. Based upon its overal youthfulness; evidence of significant Holocene slip, it is considered tectonically active today. Thus, residents of the Wasatch Front should recognize that they live in an active tectonic environment where contemporary mountain-building produces a continuing state of readjustment and concomitant earthquakes. The geologic symbiosis between the fertile valleys to the west separated by the Wasatch fault and the spectacular Wasatch Mountains to the east results in an ideal location for a major urban center, but it also necessitates a thorough evaluation of its attendant earthquake hazards.

Much of our new information on earthquakes in Utah has been gathered by the University of Utah Seismograph Stations, a modern computer-recorded 76-station telemetered network that monitors the active fault zones of the southern Intermountain Seismic Belt in Utah and surrounding areas and focuses on the Wasatch Front urban corridor. Utilizing seismological, geodetic, and geologic data we will review the tectonic framework, structural style and temporal-spatial variations of seismogenic faults in the Intermountain area. Fault-zone characteristics inferred from mapping and analyses of active faults, combined with geophysical and geological information, provide a hypothetical model for future large earthquakes. New studies of seismicity, fault segmentation, inversion of seismic moment tensors for strain rates, and statistical evaluation of recurrence intervals provide estimates of earthquake potential. Ultimately, these data taken together with engineering requirements and plans for urban development can provide the fundamental information for delineation and evaluation of earthquake hazards in the Wasatch Front urban region. Our principal focus will be on the Provo-Salt Lake City-Ogden urban corridor, but we will include information regarding the surrounding areas in Utah and in neighboring states where earthquake hazards are similar.

In the past decade, seismologists and students at the University of Utah have investigated many aspects of seismicity in Utah. Many of our discussions here rely upon our combined research efforts for which we appreciate the collaborative contributions of our colleagues. This paper also relies heavily upon seismic reflection interpretations of normal faults, studies of the geometry of fault zones, and general conclusions regarding potential earthquake nucleation on normal faults that were discussed by Smith and Bruhn (1984).

Earthquake hazards of the Wasatch Front were first recognized by G. K.

Gilbert, a pioneering geologist of the 19th century, who in a letter to the Salt Lake Tribune on September 16th, 1883 (Gilbert, 1883) described the location of fault scarps along the Wasatch Front and warned of impending large earthquakes;

> "It is useless to ask when this disaster will occur. Our occupation of the country has been too brief for us to learn how fast the Wasatch grows; and, indeed, it is only by such disasters that we can learn. By the time experience has taught us this, Salt Lake City will have been shaken down."

Gilbert further recognized the location and, hence, the importance of the Wasatch fault;

> "When the earthquake comes, the severest shock is likely to occur along the line of the great fault at the foot of the mountains."

Gilbert's astute observations on the geometry and structural style of the Wasatch fault were summarized in a U.S. Geological Survey Professional Paper titled "Studies of Basin-Range Structure" (Gilbert, 1928).

Following the work by Gilbert, many scientists of University, U.S. Geological Survey, and private consultant affiliations have studied earthquake hazards and active faulting throughout the Wasatch Front and Utah. Their results will not be repeated here, but the interested reader is referred to a summary of "Earthquake Studies of Utah, 1850-1978," edited by Arabasz, Smith, and Richins (1979) for a synthesis of earthquake information for the state of Utah current to 1978. Subsequent earthquake catalogs are available for the Utah region in Richins et al. (1981) and Richins et al. (1984b). Estimates of possible earthquake losses in the Salt Lake City area were investigated by the U.S. Geological Survey (1976). Further assessment of earthquake hazards of the Wasatch Front is contained in the

USGS Open-File Report 80-801 (1980), that includes discussions by Bucknam et al. (1980) and Hayes et al. (1980) regarding probability of exceedance of ground acceleration and empirical scaling of strong ground motion. Results from trenching and mapping of individual segments of the Wasatch fault were summarized by Swan et al. (1980) and Schwartz and Coppersmith (1984).

Current interest in understanding and mitigating earthquake hazards of the Wasatch Front by the U. S. Geological Survey, Earthquake Hazards Reduction Program, is focused on the Salt Lake City-Ogden-Provo urban corridor. This national program places high priority on delineation of earthquake hazards and risk assessment. Discussions in this paper will focus primarily on the tectonic framework, source zone characterization, and mechanism of normal fault earthquake nucleation on the Wasatch Front--properties required to assess earthquake hazard and risk.

II. PARADIGM AND PARADOX

The occurrence of the M7.3 Borah Peak, Idaho, earthquake, October 28, 1983 emphasized the potential for large magnitude earthquakes in the eastern Basin-Range environment and provided important incentives and lessons for evaluating the potential for a similar earthquake on the Wasatch fault (Richins et al., 1984a; Doser, 1984a,b; Smith et al., 1984). This important geological event not only stirred our scientific curiosity, but reminded us of the potential crustal deformation and ground shaking that could accompany a large earthquake on the Wasatch Front. It also provided new scientific models of earthquake nucleation that may be applied to the Wasatch fault.

The past half decade has been a period of renewed interest in earthquakes in the Intermountain region accentuated by new regional network data (Arabasz et al., 1979), by techniques for determining strain rates from the seismic moment tensor (Doser and Smith, 1982) and from geodetic methods (Snay et al., 1984). Detailed evaluations of the M7.5, 1959 Hebgen Lake earthquake, Montana, (Doser, 1984a,b) and the M7.3, 1983 Borah Peak earthquake (Richins et al., 1984a, Smith et. al., 1984) provided important insights into the nucleation process of normal fault events. Detailed microearthquake studies in central Utah by McKee and Arabasz (1982), investigation of the seismogenic potential of normal faulting aided by reflection data by Smith and Bruhn (1984), age dating and mapping of the Wasatch fault (Schwartz and Coppersmith, 1984) and detailed studies of faults using the gravity method (Zoback, 1983) provided important insights into the earthquake generation process of the Intermountain region.

These investigations provide a new framework for evaluating normal faulting earthquakes. They not only provide answers to important issues, but raise several new questions. We suggest several of the important paradigms and paradoxs below:

1. In the past 30 years, the three largest earthquakes in the western United States (Figure 1) were associated with normal faulting that occurred in the Basin-Range environment (1954, Fairview Peak, Nevada, M7.1; 1959 Hebgen Lake, Montana, M7.5; 1983 Borah Peak, Idaho, M7.3). These large events nucleated at depths of ~15 km near the bottom of the seismogenic layer. Their epicenters were displaced laterally 10-15 km from the surface rupture on planar 40°-65° dipping faults. Will large normal fault earthquakes on the Wasatch Front be of the same form, i.e. will large earthquakes nucleate beneath the populated central and western areas of Wasatch Front valleys several kilometers west of the surface expression of the Wasatch fault?

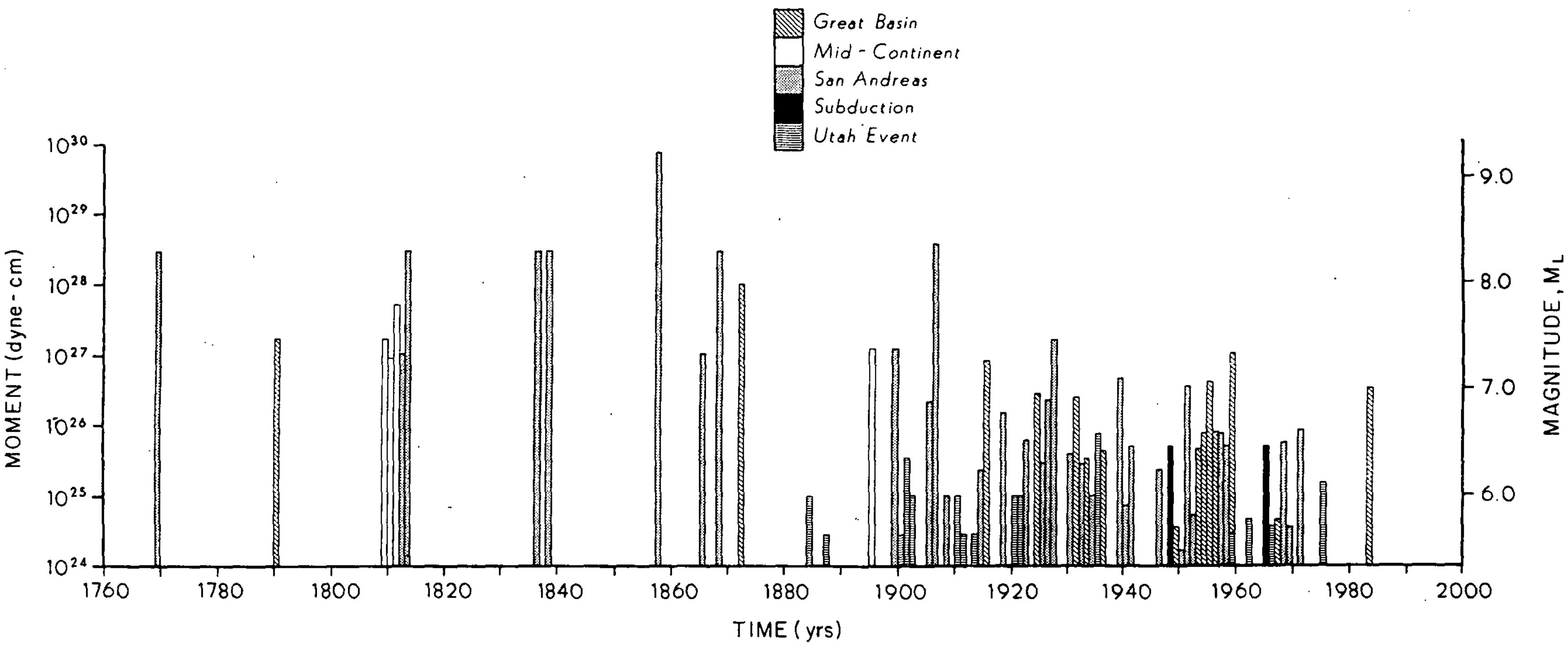

Figure 1. Histogram of large earthquakes, M∿6, in the conterminous United States in historic time.

2. New seismic reflection data, regional tectonics, and rheologic modeling suggest that normal faults in the eastern Basin-Range have a variety of fault plane styles from planar to listric geometries with steep dips near-surface in unconsolidated sediments but low to moderate dips of $\sim 40^{\circ}$ to $\sim 60^{\circ}$ at depths of 4 to 10 km. <u>What is the implication for large earthquake nucleation on these structures?</u>

3. The temporal behavior of individual fault segments along the Wasatch Front may not be necessarily random and independent of adjacent zones. <u>Do individual segments remain active for hundreds to tens of thousands of years while adjacent segments remain quiescent? Will future large earthquakes of M7+ occur along segments of known Quaternary-Holocene displacement on the Wasatch Front? Are the "likely" locations of future large earthquakes associated with mappable segments of faults with Quaternary-Holocene displacement?</u>

4. Contemporary strain rates from cumulative seismic moment tensors and geodetic measurements show general E-W extension at maximum rates of order 1 mm/yr in the Hansel Valley region of northwest Utah, but 1 to 2 orders of magnitude less on the Wasatch Front. Strain rates associated with prehistoric faulting on the northern Wasatch Front are significantly greater. <u>Will areas of seismic and strain quiescence be interrupted by large earthquakes equilibrating the long-term strain accumulation?</u>

5. Empirical measurements of peak ground accelerations from normal faulting earthquakes may be 2 to 3 times smaller than accelerations from equivalent magnitude thrust-type earthquakes (McGarr, 1984). <u>Does this conclusion apply to earthquake hazards assessment on the Wasatch Front?</u>

6. Asymmetric back-tilt from hypothetical M7+ normal-fault earthquakes along the Wasatch Front can produce a heretofore uninvestigated hazard; inundation from adjacent bodies of water, i.e. the Great Salt Lake, Utah Lake, etc. Flooding could encroach eastward several kilometers into developed urban, commercial and agriculture lands. <u>How important is this hazard?</u>

III. WESTERN UNITED STATES PERSPECTIVE

The Intermountain Seismic Belt (ISB) is the general zone of seismicity that extends from southwestern Utah, through eastern Idaho, western Wyoming, and Montana and marks an intraplate boundary of the North American plate (Smith and Sbar, 1974). It is clearly less seismically active than the San Andreas fault, a major transform boundary, and relatively less active than the Walker Lane, central Nevada seismic zone (Figure 2). The map of instrumentally recorded earthquakes (Figure 2) for the western United States demonstrates intense activity along the San Andreas fault in California where one magnitude 8+ and several magnitude 7+ earthquakes have occurred in historic time. In comparison, four magnitude 7+ earthquakes have occurred in the Nevada seismic zone and two magnitude 7+ earthquakes have occurred in the Intermountain region; the M7.5, 1959 Hebgen Lake, Montana, and the M7.3 1983 Borah Peak, Idaho, earthquakes.

The largest historic earthquakes in Utah were the $M_L \sim 6.6$, 1934 Hansel Valley and the M_L 6.5, 1901 Richfield earthquake, (Figure 3). Only the Hansel Valley earthquake produced surface faulting with a 50 cm maximum vertical displacement along a north-south fault at the north end of Great Salt Lake. Six $6>M>6.5$ earthquakes have occurred in historic time throughout the Utah region but apparently none produced surface rupture.

In general, the seismicity of the Intermountain Seismic Belt is characterized by recurrence rates of magnitude 7+ earthquakes on the order of hundreds to thousands of years compared to tens to hundreds of years for the San Andreas fault. Maximum magnitudes are not expected to exceed M7-3/4 for the Utah region, but may exceed magnitude 8 for the San Andreas fault.

An interesting observation from historical seismicity is that more magnitude 7+ earthquakes have occurred in the past 30 years in the Basin-Range environment of normal faulting (M7.1, Dixie Valley earthquake, 1954; M7.5 Hebgen Lake, Montana, earthquake, 1959; and M7.3 Borah Peak, Idaho, earthquake, 1983) than have occurred during the same time period along the San Andreas fault.

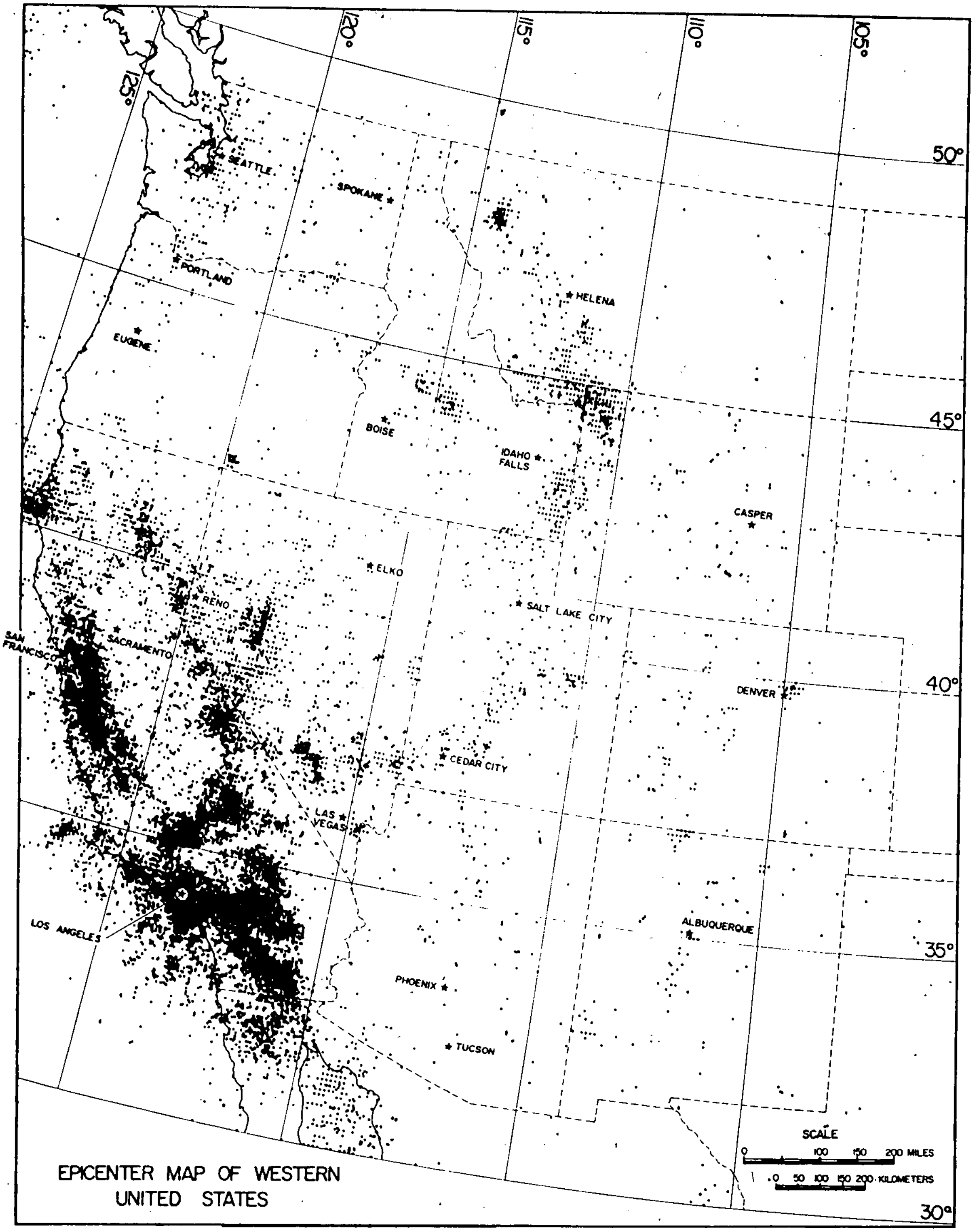

Figure 2. Epicenter map of western United States with data principally from 1950 through 1976. Taken from Smith (1978).

In the Intermountain region, Figure 3 shows that at least 17 historic earthquakes of M$\sim$6 have occurred notably at locations were general changes in direction of regional seismicity pattern occur. Arabasz and Smith (1981) noted that the Intermountain Seismic Belt extends 1300 km, but is divided into several sectors with divergent trends. The larger M6+ earthquakes were generally located near the sector boundaries.

The ISB is difficult to define as a linear zone of earthquakes such as along the San Andreas fault. Rather diffuse seismicity extends across 100-200 km-wide zones and focal depths are generally shallower than 15 km (Smith, 1978). A rather important conclusion cited by Smith and Sbar (1974) and since by several investigators is the poor spatial correlation of epicenters with the scarps of major active faults. Epicenter accuracy is sufficiently good to conclude that the diffuse seismicity pattern is real implying that much of the seismicity is associated with buried or "blind" structures that are seismically active.

The paucity of large M7+ surface-faulting earthquakes in historic time, despite abundant late Quaternary and Holocene fault scarps, further complicates the problem of earthquake evaluation and makes it difficult to assess earthquake hazards on the basis of epicenter locations or by the presence of active fault zones alone. As will be described later, hazard evaluation requires the integration of information on the fault geometry with depth, its relationship to laterally displaced seismicity, and the relationship to timing and distribution of surface faulting.

An important observation from Figure 3 is the location of the 1983, Borah Peak M7.3 earthquake that broke along a 34-km segment of the

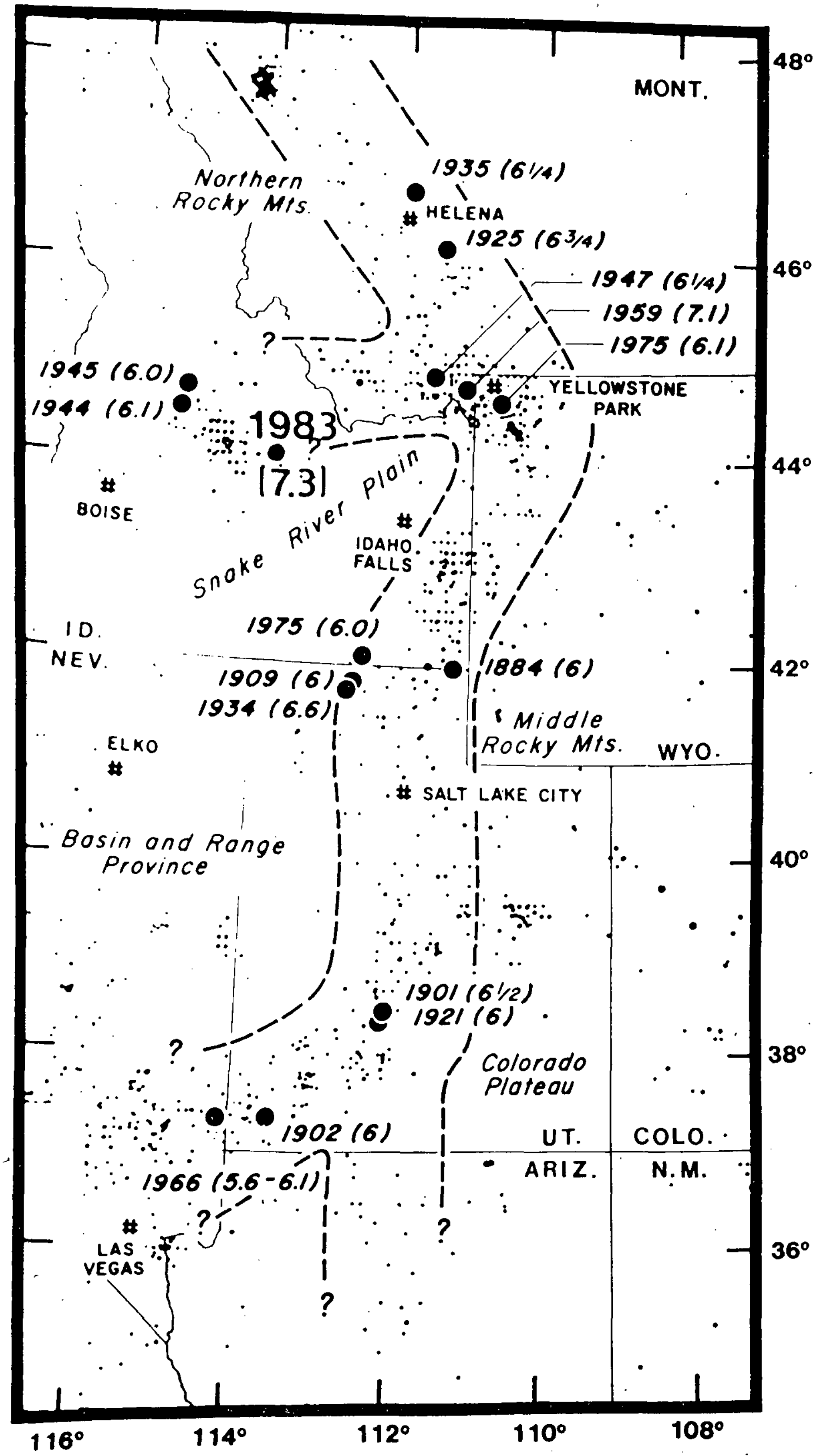

Figure 3. Epicenter map of the Intermountain Seismic Belt with largest historic earthquakes highlighted by large dots (modified from Smith, 1978 and Arabasz and Smith, 1979).

northwest trending Lost River fault (Crone and Machette, 1984). This fault, although considered seismically active, with at least one Holocene displacement event (Hait, 1978), has had no significant earthquakes in historic time. The Borah Peak earthquake occurred on one of at least three segments of the Lost River fault zone, with the southeastern segments having displacements 30,000 years and older (Hait, 1978). This observation suggests a temporal model for Basin-Range normal faults where individual segments are active for thousands of years with several scarp-forming events, while adjacent segments remain quiescent for tens of thousands of years. If this property is valid, it has important ramifications for evaluating earthquake hazards along the defined segments of the Wasatch fault.

IV. EARTHQUAKES IN UTAH

The pattern of early historic earthquakes and Late Cenozoic faulting in Figure 4 (taken from Arabasz and Smith, 1979) shows the generally broad N-S trending zone of seismicity in Utah. Note that Cenozoic faults capable of generating earthquakes occur throughout most of the central and western portion of Utah, not only along the Wasatch fault. In this figure the largest earthquakes for the period 1850-1978 of approximately magnitude 4 or greater are shown. Epicenters for the early historic data are based upon personal felt reports and were not recorded instrumentally, thus the error in epicenters could be as large as $\pm$10-20 km. Nonetheless, the epicenter patterns delineate the active belt of diffuse seismicity characteristic of the southern Intermountain Seismic Belt.

A depiction of the past 22 years (July 1962 to September 1984) of

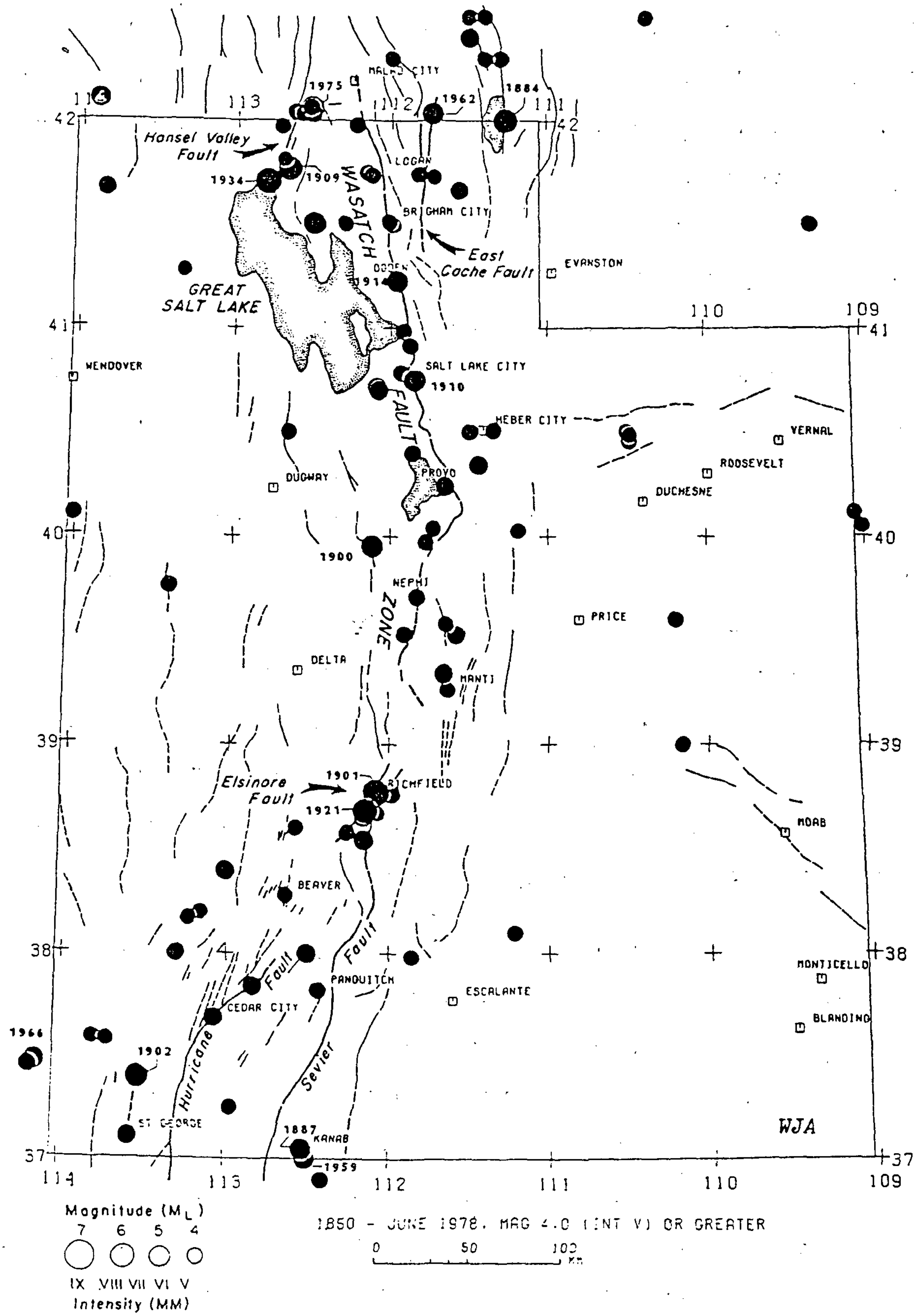

Figure 4. Epicenter map of largest historical earthquakes in Utah, 1850-1978 (from Arabasz and Smith, 1979).

instrumentally-recorded and computer located earthquakes in Utah is shown in Figure 5. In this diagram earthquakes of magnitude 2.5 or greater were plotted from the University of Utah data file. Also, superimposed on the map is an outline of the Wasatch Front study area. Three general zones of seismicity are apparent from the detailed epicenter map (Figure 5): (1) a southwest-northeast trending, 100-200 wide zone that extends from St. George to the vicinity of Richfield, (2) a central to northern Utah diffuse zone of earthquakes that trends generally north-south along either side of the Wasatch fault but with limited earthquake activity except at its northern and southern boundaries, and (3) a change to a northeast trend at the Utah-Idaho border including two areas of significant activity; (a) the 1975, Pocatello Valley M6.0 earthquake at the Utah-Idaho border, and (b) several earthquake swarms near Soda Springs in southeastern Idaho. Induced seismicity related to extraction of coal in eastern Utah is clearly visible as three clusters of activity 100 km southeast of Provo. An important observation from the seismicity map is that much of Utah has experienced earthquakes of magnitude 2.5 and greater in historic times, demonstrating the on-going tectonics over much of the state.

A rather important property of seismicity is the space-time variation of earthquake occurrence. For example, the seismic behavior of the Wasatch fault north and south of Salt Lake City since at least 1962, shows zones of relative seismic quiescence or gaps in seismicity. We know very little about the timing of large earthquakes in Utah because none have occurred during historic time. Hence the cyclic nature of normal faulting earthquakes in Utah in terms of mainshock and aftershock distributions and their relationship to surface faulting can not be used to evaluate the long-term

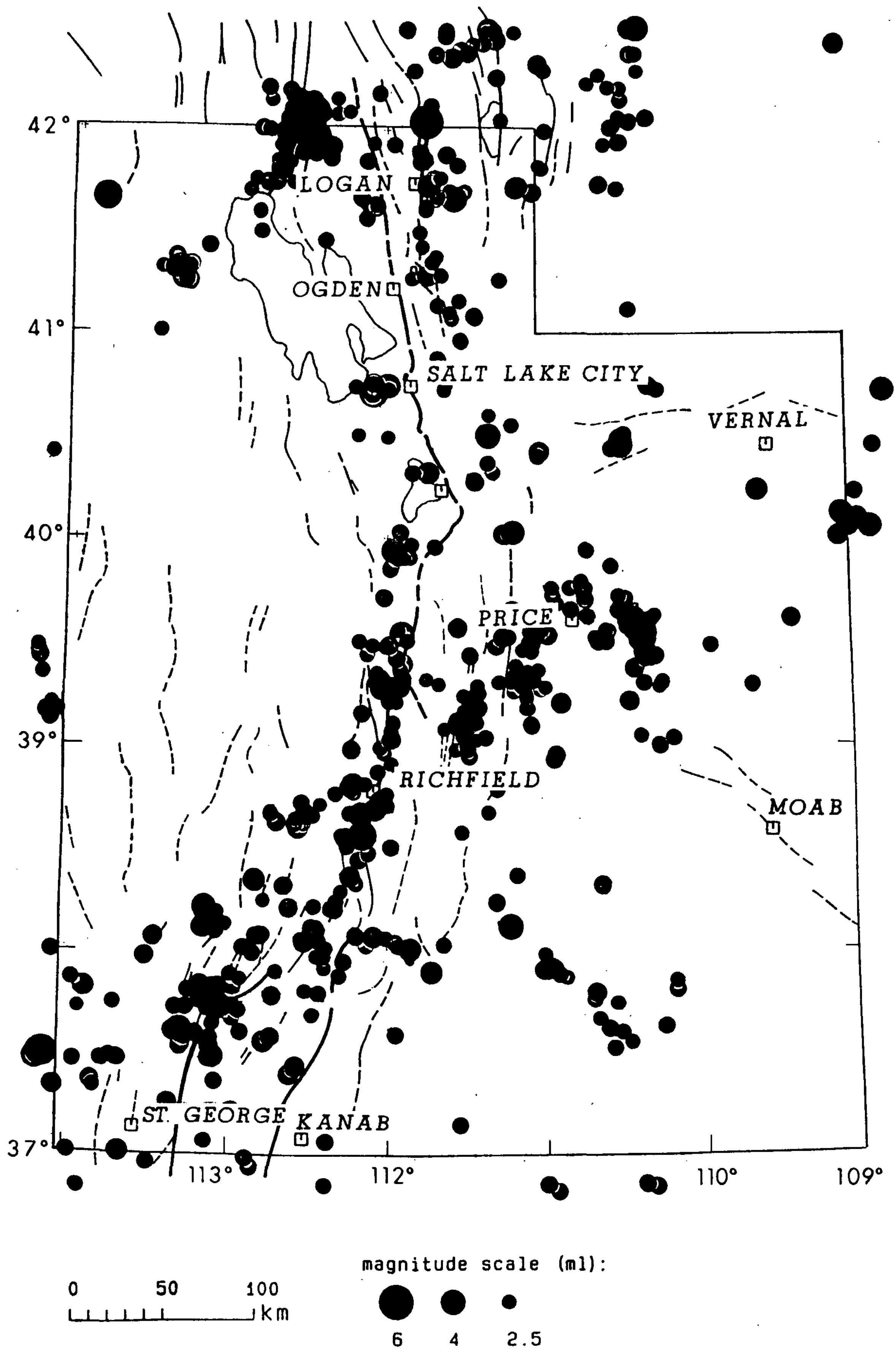

Figure 5. Epicenter map of Utah: July, 1962-September 1984. Lines show locations of the Late Cenozoic faults.

behavior of the zones of low seismicity.

To view the space-time patterns of earthquakes in Utah, a computer-generated movie has been produced with the assistance of Einar Kjartansson. In this production done at the Stanford University Exploration Research Laboratory, earthquakes were plotted on a color-graphics CRT where earthquake epicenters are located on a background map and magnitudes are scaled in color from the cool, blue-green colors for low magnitude to warm, orange-red colors for larger magnitudes. Two periods are presented: (1) the early historic record from December, 1853 through June, 1962; and (2) a modern record from July, 1962 through December, 1983. Discussions of the space-time variations from aftershock distributions and possible precursory manifestations were discussed during the movie shown during the Workshop on "Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah," August, 1984, meeting in Salt Lake City.

V. WASATCH FRONT: SEISMICITY AND FAULTING

A detailed epicenter and fault map of the general Wasatch Front region is shown in Figure 6. Here earthquakes from 1974 through 1982 are plotted on a generalized tectonic map with bedrock geology, Laramide-Sevier thrust faults, and Late Cenozoic normal faults to examine the relationship between earthquakes and tectonic features. The most notable earthquake activity during the 1974-1982 period occurred in the Pocatello Valley-Hansel Valley area of northern Utah-southeastern Idaho where a magnitude 6.0 event occurred in March 1975 (Arabasz et al., 1979).

A persistent zone of earthquake activity extends southward beneath the

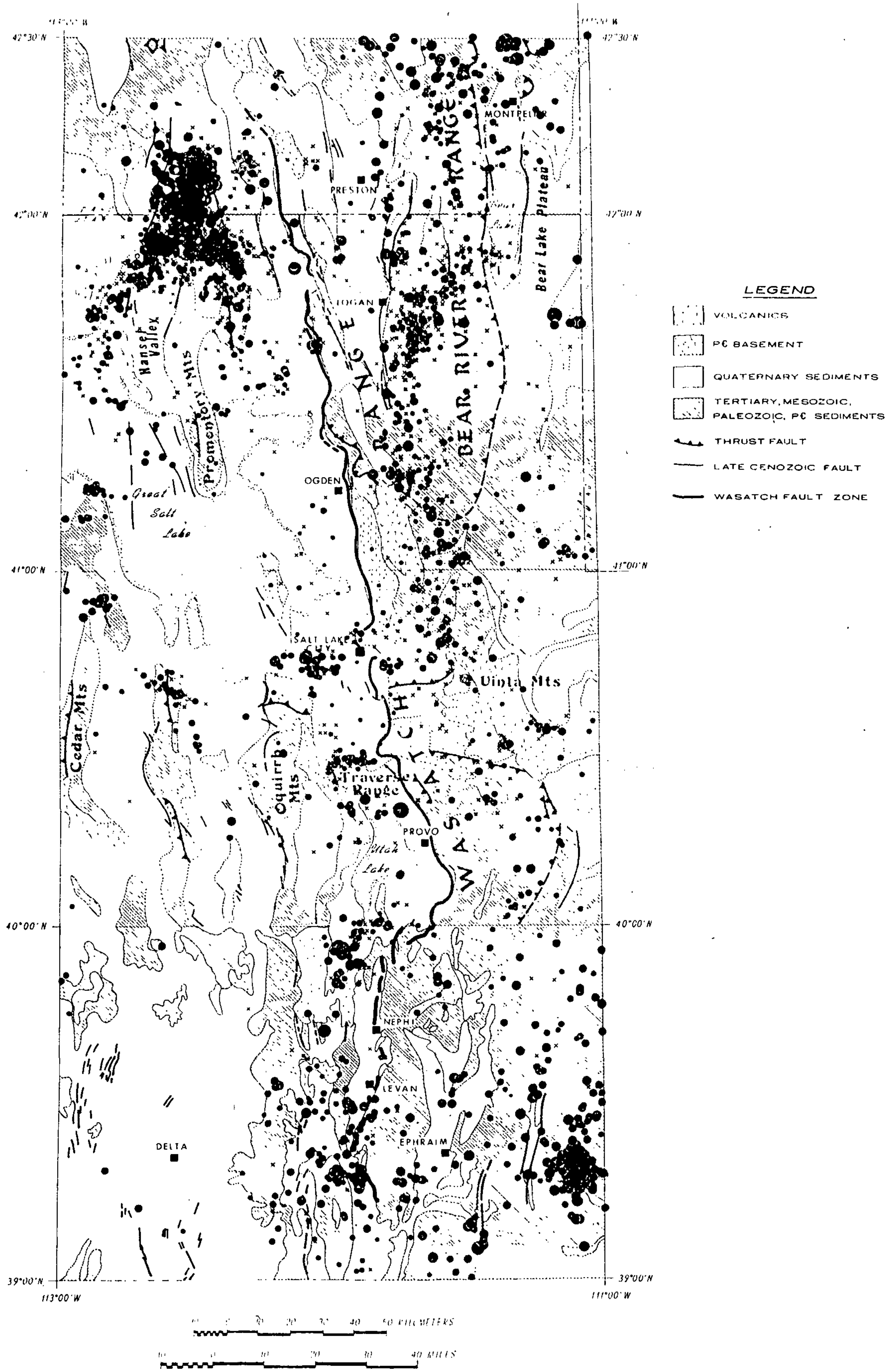

Figure 6. Epicenter and regional tectonic map of the Wasatch Front (taken from Smith and Bruhn, 1984). Epicenters from University of Utah files for period: 1974-1982.

Bear River Range, on the east side of Cache Valley terminating 20 km east of Salt Lake City. Earthquakes extend along an east-west zone across the Salt Lake City-Magna area, in the vicinity of the M5.2, 1962 Magna earthquake. This area also has had several occurrences of earthquake swarms. Concentrated zones of activity extend across the Traverse Range south of the Salt Lake Valley and at the southern end of Utah Lake including a magnitude 3.9 event in 1982 near Orem. Activity continues south as a notable trend along the Juab Valley displaced west of the Wasatch fault. Activity east of Ephraim is primarily mining related activity.

The Wasatch fault, shown by a heavy line, extends from near Malad, Idaho, southward 370 km on the west side of the Wasatch Range (Figure 6). The notable quiescence of earthquakes along the Wasatch fault north of Salt Lake City, on the east side of the Salt Lake Valley, and south of Provo have been earlier recognized as seismic gaps by Smith and Sbar (1974) and Arabasz and Smith (1981), i.e. areas of seismic quiescence that otherwise would be expected to have earthquake activity along an active fault segment. One interpretation of the zones of low seismicity is taken from an analogy with plate tectonics where averaged over centuries or more, movement may be expected at all points along the intraplate boundary. Thus, gaps in the seismic activity could be developed along a boundary such as the Wasatch fault as a result of the past occurrence of large earthquakes. Eventually these gaps may be filled in by future earthquakes. If this interpretation is valid, then areas of unusually low seismicity and areas of previous faulting may be regarded as having a higher probability for future large earthquakes.

Other possible explanations for the apparent low seismicity along the quiet zones of the Wasatch fault are: (1) release of strain energy by aseismic creep and/or by crustal rebound of Lake Bonneville, and (2) the return rate for large earthquakes is sufficiently large that the time window of the past ~100 years of recording was too small to sample the long-term seismicity. Another important hypothesis to be tested, suggests that earthquakes occurring along the west side of the Wasatch fault, for example at Salt Lake City near Magna and along the Santaquin-Nephi-Levan area may reflect earthquakes associated with the westward extension of the Wasatch fault zone at depth.

In examining the role of pre-existing geologic structures on the origin of the Wasatch fault, Smith and Bruhn (1984) hypothesized that the influence of pre-existing Laramide thrust sheets correlate in a general way with the surface delineation of fault zone segmentation as proposed by Schwartz and Coppersmith (1984). In Figure 7 a map of thrust sheets and the Wasatch fault shows an interesting correlation between the segment boundaries and lateral terminations of the thrust sheets.

To examine the hypothesized westward extension of the Wasatch fault geometry, Smith and Bruhn (1984) interpreted seismic reflection profiles across the East Cache fault, the Wasatch fault, and adjacent fault zones in the Great Salt Lake. Figure 8 shows two seismic reflection profiles, one across the East Cache Fault near Logan where seismic reflections dipping westward beneath the Cache Valley may be interpreted as a moderate- to low-angle fault that flattens at depths of approximately 4 km beneath the valley fill. Eastward stratal tilt of Quaternary and Tertiary sediments

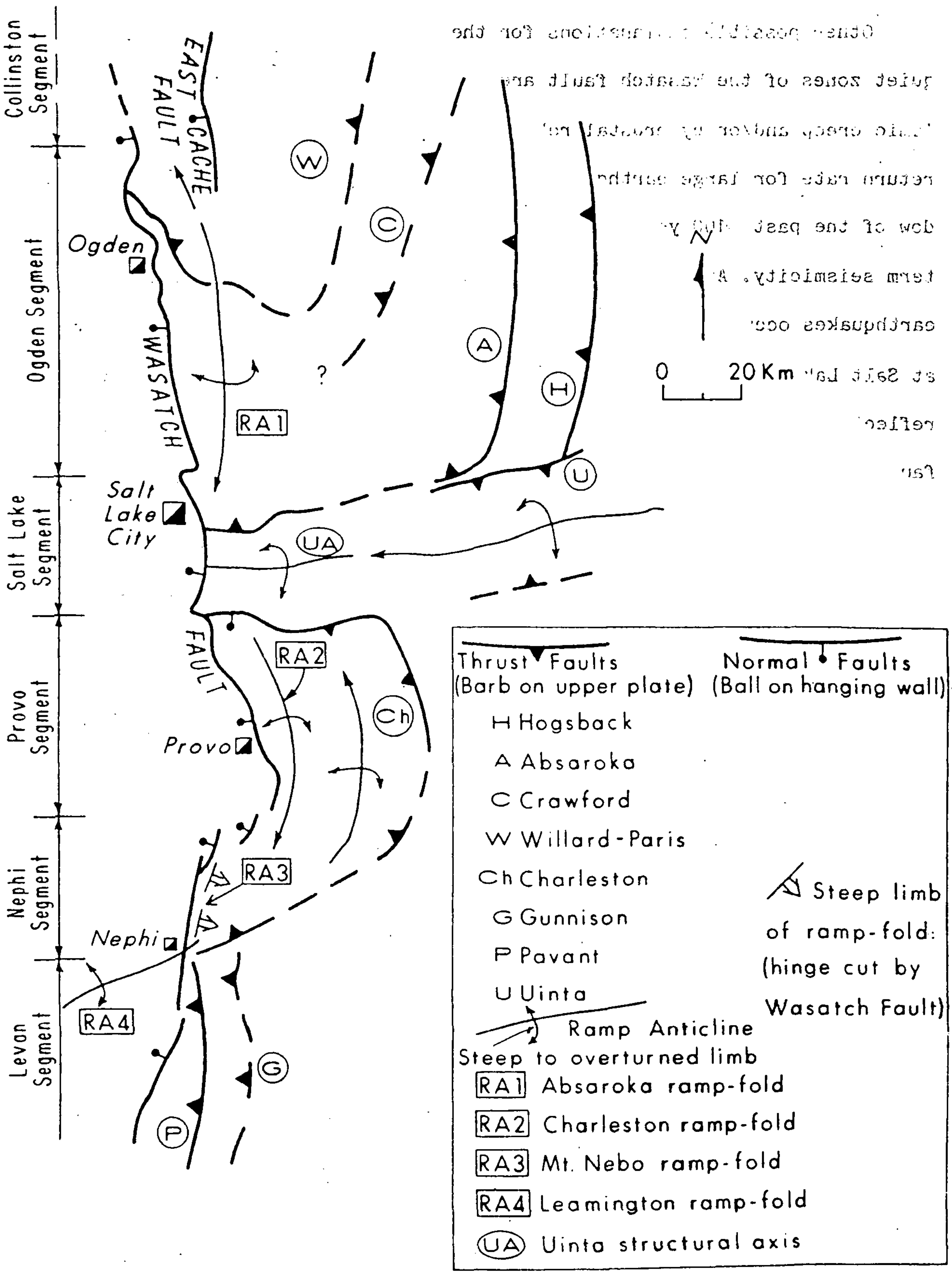

Figure 7. Tectonic map of Wasatch Front and adjacent mountain ranges illustrating the Quaternary normal fault segments proposed by Schwartz and Coppersmith (1984). Figure taken from Smith and Bruhn (1984).

suggests the valley fill may have rotated along a listric fault.

A seismic reflection profile across the mouth of the Weber Canyon, south of Ogden (Figure 8), shows a lack of reflection truncations beneath or west of the projected location of a steeply dipping Wasatch fault. Rather a very low-angle zone of reflection truncations begins near the fault and flattens to zero dip at ~2 km beneath the valley. Whether this reflection represents a fault can not be equivocally interpreted, the Wasatch fault is not imaged here as a steeply dipping major through-going structure.

Additional seismic reflection profiles discussed by Smith and Bruhn (1984) and unpublished reflection data for the Brigham City area, the Great Salt Lake, the north Salt Lake City area, and near Levan show that the Wasatch fault zone varies in dip from values as steep as $\sim 60^{\circ}$ to as shallow as $\sim 40^{\circ}$--all suggestive of westward projection of the seismogenic zone beneath the populated Wasatch Front. Thus, while the seismic reflection data do not provide a unique interpretation of the attitude and extent of faulting, it is clear that we must recognize that this structural style of normal-faulting may characterize M7+ earthquakes in an extensional environment.

VI. LESSONS FROM THE M 7.3 BORAH PEAK, IDAHO, EARTHQUAKE

On October 28, 1983 an M7.3 earthquake occurred along a segment of the Lost River fault zone, central Idaho (Richins et al., 1984a; Doser, 1984b,c; Smith et. al., 1984). This major earthquake produced a 34-km long fault scarp with up to 2.5 m of near-vertical displacement along a known

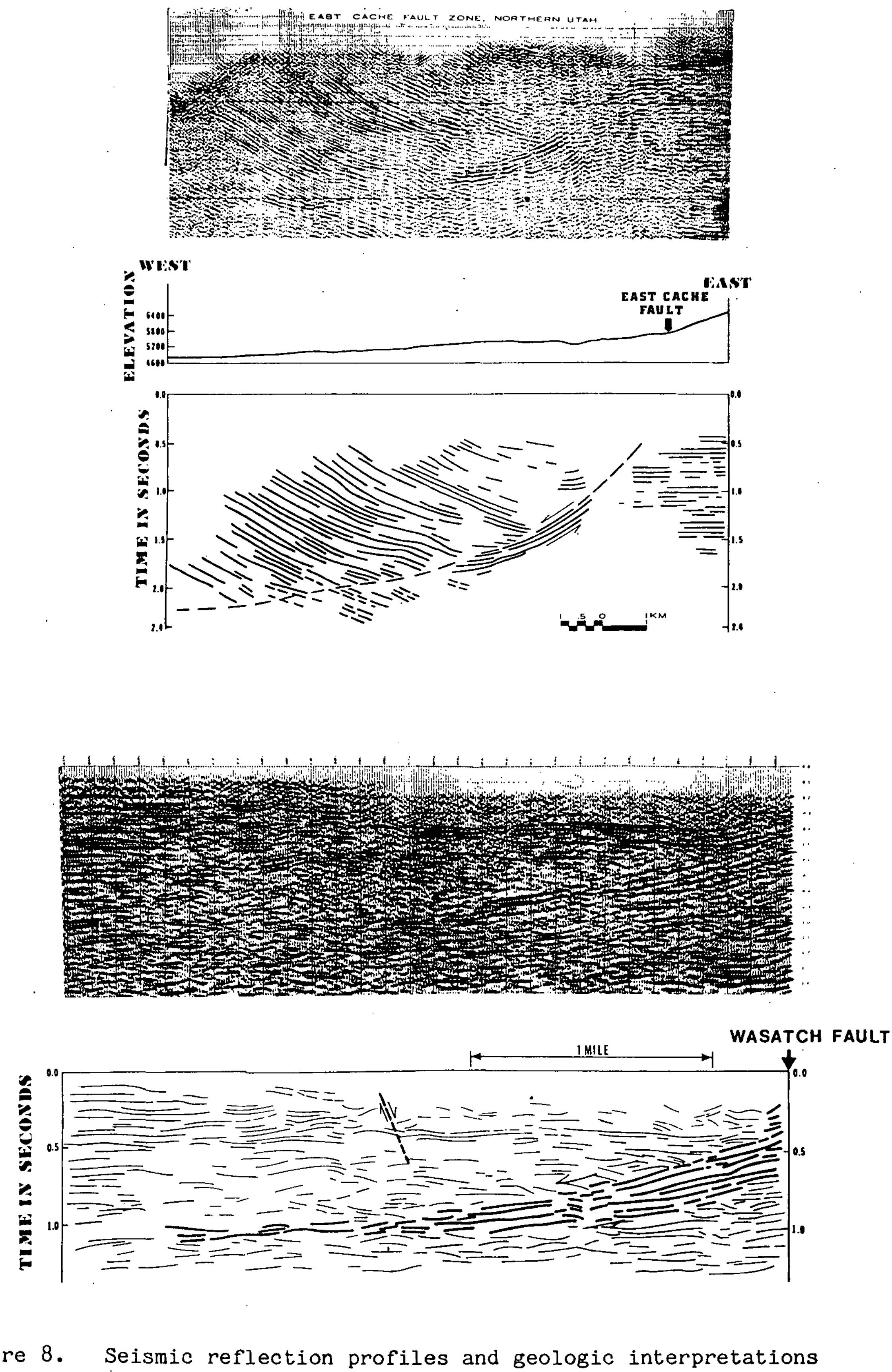

Figure 8. Seismic reflection profiles and geologic interpretations across: a) East Cache fault, south of Logan, Utah; and b) Wasatch fault, south of Ogden, Utah.

Quaternary fault (Crone and Machette, 1984). The Borah Peak earthquake aftershock zone was extensively monitored by the University of Utah, the U.S. Geological Survey, and other collaborative investigators with up to 50-portable stations (Richins et al., 1984a; Doser, 1984b; Smith et al., 1984). The importance of the Borah Peak earthquake to the Wasatch Front is that the age and structural style of faulting are similar to that of the Wasatch Front.

Primary results of the Borah Peak earthquake analyses show that the main shock nucleated at a depth of $\sim$16 km, but was located 10-15 km laterally SW from the end of the surface rupture (Doser, 1984b,c). Aftershocks extend along a zone parallel to the surface rupture, but were also displaced 10-20 km SW of the surface fault. Cross-sections of accurately determined foci of aftershocks show that they define a finite width zone that dips southwesterly at $\sim 45^{\circ}$ (Richins et al., 1984a). A plane passing through the aftershock cluster intersects the hypocenter of the main shock whose fault plane solution (Doser, 1984b,c) indicates a 49° southwest dip. It appears that the Borah Peak earthquake occurred on a moderately dipping planar fault zone where the main shock nucleated at the base of the seismogenic zone and near the hypothetical brittle-ductile transition (Smith et al., 1984).

An interesting observation from the central portion of the Borah Peak scarp near its point of maximum displacement is the attitude of the hanging-wall bedrock surface that dips at $\sim 45^{\circ}$ and projects southwest along the subsurface extension of the fault plane mapped by the aftershock hypocenters. On the east side of the Salt Lake Valley, Gilbert (1928) noted that the adjacent hanging-wall blocks of the Wasatch fault had $45^{o}W$ dips that he suggested project westward on the main Wasatch fault surface. Although Gilbert's (1928) interpretation of the shallow dip of the Wasatch fault has been controversial, the similarities of structural geometries between the Borah Peak earthquake and the Wasatch Front are striking.

VII. GEOMETRY OF FAULTING AND 'LIKELY' LOCATIONS OF FUTURE LARGE WASATCH FRONT EARTHQUAKES

During the past decade accelerated research on the Wasatch fault principally by trenching and detailed mapping (Schwartz and Coppersmith, 1984) have noted several important features: (1) the Wasatch fault can be divided into segments that appear to break as independent zones, and (2) individual segments have statistically different repeat times and displacement histories. Smith and Bruhn (1984) noted (also see Figure 7) that the Wasatch fault segmentation also correlates with the lateral termination of major Laramide thrust structures that disrupt fault plane continuity. We regard the current delineation of fault segmentation as preliminary with need for additional statistical and geological conformation but it can provide a basis for a working model of Wasatch Front earthquakes.

By definition a segment is a sector of a major fault zone that may break independent of adjacent segments with each segment having its own displacement rate properties and history. Thus, one segment may become active while adjacent segments remain quiescent. The Borah Peak earthquake apparently occurred on one of approximately three segments that Hait (1978) showed has had one displacement event in Holocene time, while the adjacent segments have been quiescent for the past 30,000 years. If these arguments are valid for the Wasatch fault then the segments themselves may be a starting point for estimating the location of likely future large earthquakes.

To compare the structural geology of large normal faulting events in the Basin-Range, Figure 9 shows cross-sections through the fault zones of three large, M7+ earthquakes, their inferred fault planes, orientations and fault plane dip: (1) the 1954 Dixie Valley, Nevada, M7.1; (2) the 1959 Hebgen Lake, Montana, M7.5, and (3) the 1983 Borah Peak, Idaho, M7.3. These large earthquakes have occurred in a similar intraplate extensional stress regime as the Wasatch Front, on planar faults with from 40°-65° dip and at nucleation depths of ~15 km.

We propose a hypothetical working model for large Wasatch Front earthquakes in which a westward-dipping fault zone could nucleate an earthquake at a depths of ~15 km beneath the adjacent valley (Figure 9). This model has important implications because it suggests that the hypocenters of major earthquakes would occur beneath the populated centers of the Wasatch Front, several kilometers west of the Wasatch fault. The influence of a deep, ~15 km, overburden, fault plane directivity, etc. on strong ground motions in the overlying populated areas is not known but may have important effects on strong ground acceleration. Note that the histograms of aftershocks and on-going seismicity for the three major earthquakes in the Great Basin, including aftershocks as large as M6+, occur in the shallower seismogenic layer from the near-surface to the maximum depth of the large event (Figure 9).

Smith and Bruhn (1984) hypothesized that large M7+ shocks may nucleate

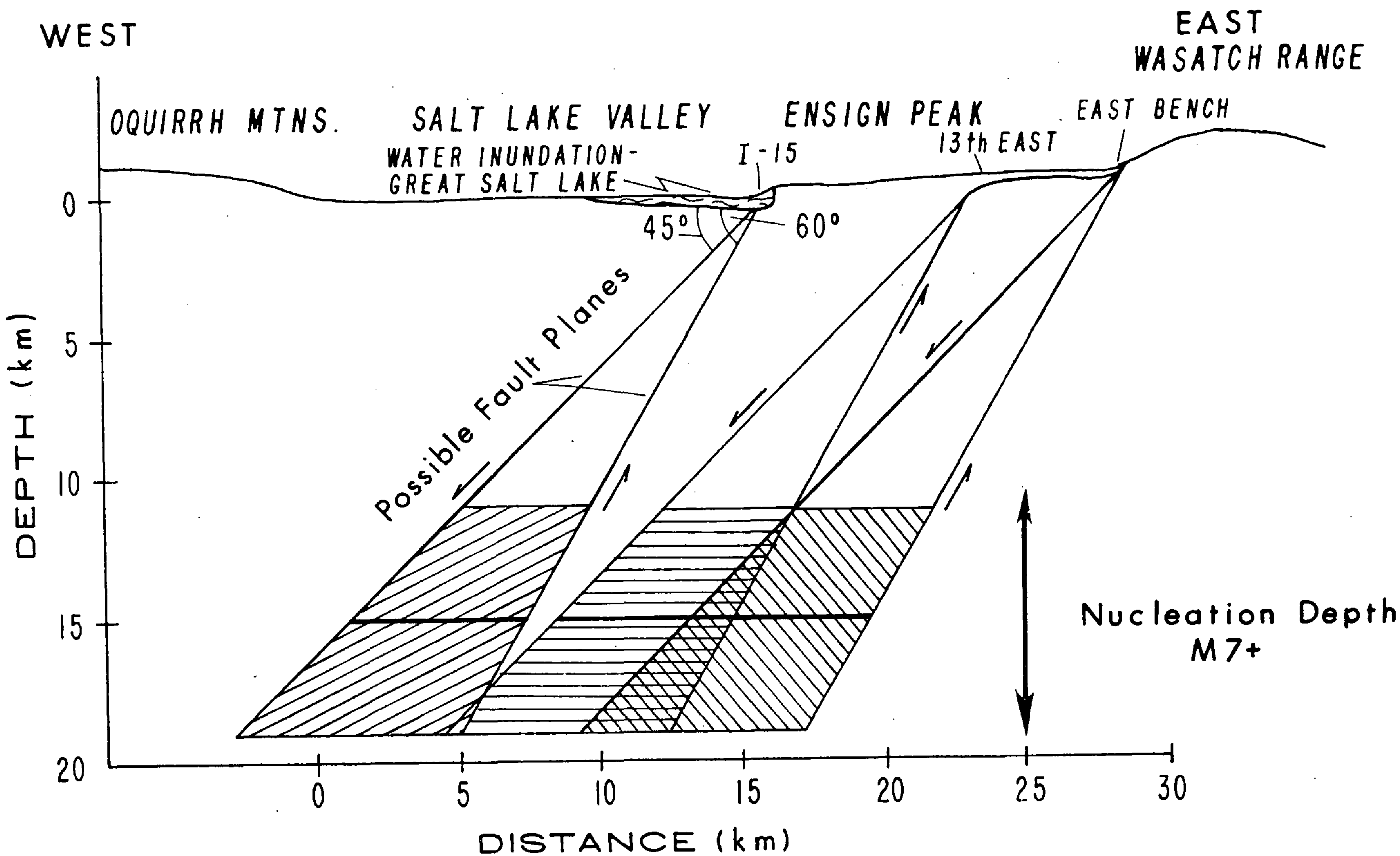

Figure 9. Cross-sections across fault zones of the three largest historic Basin-Range type earthquakes with hypothetical model for a large earthquake on the Wasatch Front, Salt Lake City area. M7.5, 1959, Hebgen Lake, Montana earthquake (data from Doser, 1984a; M7.3, 1983, Borah Peak, Idaho earthquake (data from Richins, et al., 1984a), and M7.1, 1954, Dixie Valley, Nevada earthquake (data from Okaya and Thompson, 1984).

at the base of a brittle layer perhaps in the upper part of a ductile layer where shear stresses are at a maximum. Thus, the intraplate extensional deformation of the Basin-Range could drive the energy system to maximum values of a few hundred bars. The energy is then released by a major earthquake at the base of the seismogenic layer that propagates to the surface as a major surface faulting event. Aftershocks and inter-event seismicity in the upper-crust may reflect interblock adjustments and antithetic normal faulting.

A plot of space-time seismicity from 1962 through 1984 (Figure 10) along the Wasatch Front demonstrates the development of zones of seismic quiescence or seismic gaps that are bounded by segment terminations (Schwartz and Coppersmith, 1984). The notable increase in seismicity, at about 1975, is an artifact of the observational level of earthquakes produced by the installation of the detailed Wasatch Front network at that time. Nonetheless, the sector from Brigham City southward through the Ogden area appears relatively aseismic at the M3+ level. A distinct increase in seismicity occurs north of Salt Lake City along the east-west zone of the Ensign Peak salient and in the Magna area where persistent earthquake swarms and a 1962, magnitude 5.2 earthquake have occurred. This zone seems to mark the northern edge of the Salt Lake segment where much of the earthquake activity occurs 10 to 20 km west of the Wasatch fault. The south end of the Salt Lake segment is marked by activity along the Traverse Range, but seismic quiescence is apparent from Orem southward to approximately Santaquin at the north end of the Nephi segment. Notable activity occurs near the Wasatch fault and westward beneath the Levan segment beneath the Juab Valley (McKee and Arabasz, 1982).

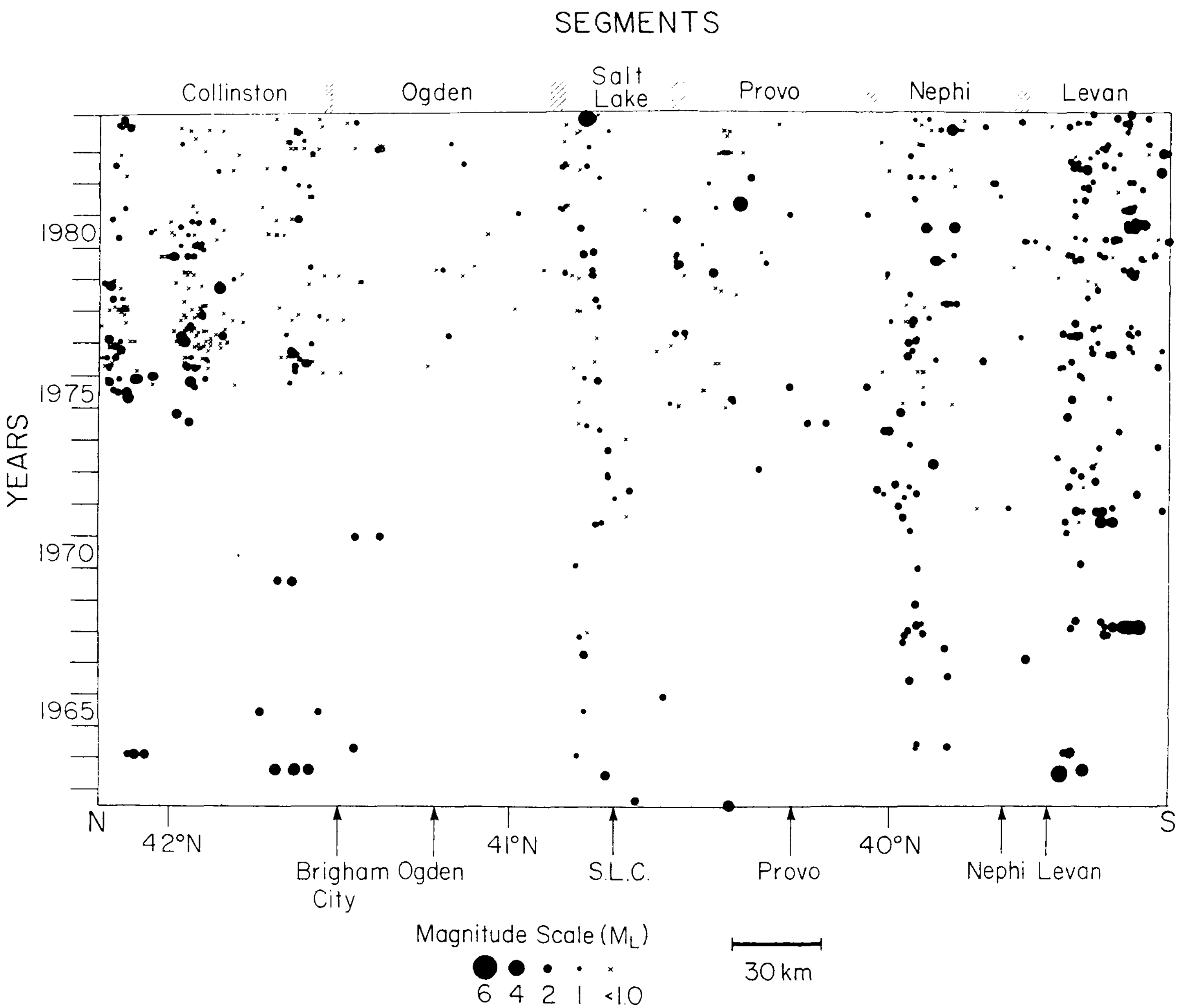

Figure 10. Space-time distribution of earthquakes within 10 km of the Wasatch fault, 1962-1984.

The question then arises, are the zones of seismic quiescence truly seismic gaps and at what magnitude level are they significant? If one applies the westward-dipping hypothetical Wasatch fault model (Figure 11), earthquakes occurring west of the Wasatch fault such as near Magna, the Traverse Range, and the extensive zone south of Santaquin may represent down-dip activity associated with past large Wasatch Front events they could represent E-W transverse shear zones or stress concentration at the ends of the segments (or asperities). While the hypotheses cannot be tested without detailed seismic reflection profiling and accurate earthquake monitoring the nevertheless provide testable explanations.

VIII. EARTHQUAKE PRODUCED FLOODING

An important effect of faulting associated with large normal-fault earthquakes is the asymmetric back-tilt of the footwall block. This property was well developed in the M7.5 Hebgen Lake earthquake where a maximum of 6.1 m displacement occurred at the surface, with back-tilt extending $\sim$18 km in width and 30 km in length at the top of the footwall block (Figure 12). Recognizing that large bodies of water occur in close proximity to the Wasatch fault, eastward tilt in response to a large earthquake on the Wasatch fault could introduce an unrecognized hazard. For the purposes of comparison we have superposed the observed subsidence from the M7.5 Hebgen Lake earthquake at arbitrary locations on the Wasatch fault and calculated the ground deformation by subtracting the deformation from the ground elevation. The Hebgen Lake event was considered a maximum credible hypothetical event (Doser, 1984b). Three locations were arbitrarily chosen along the Wasatch fault, at: (1) Bountiful (Figure 13a), (2) Salt Lake City

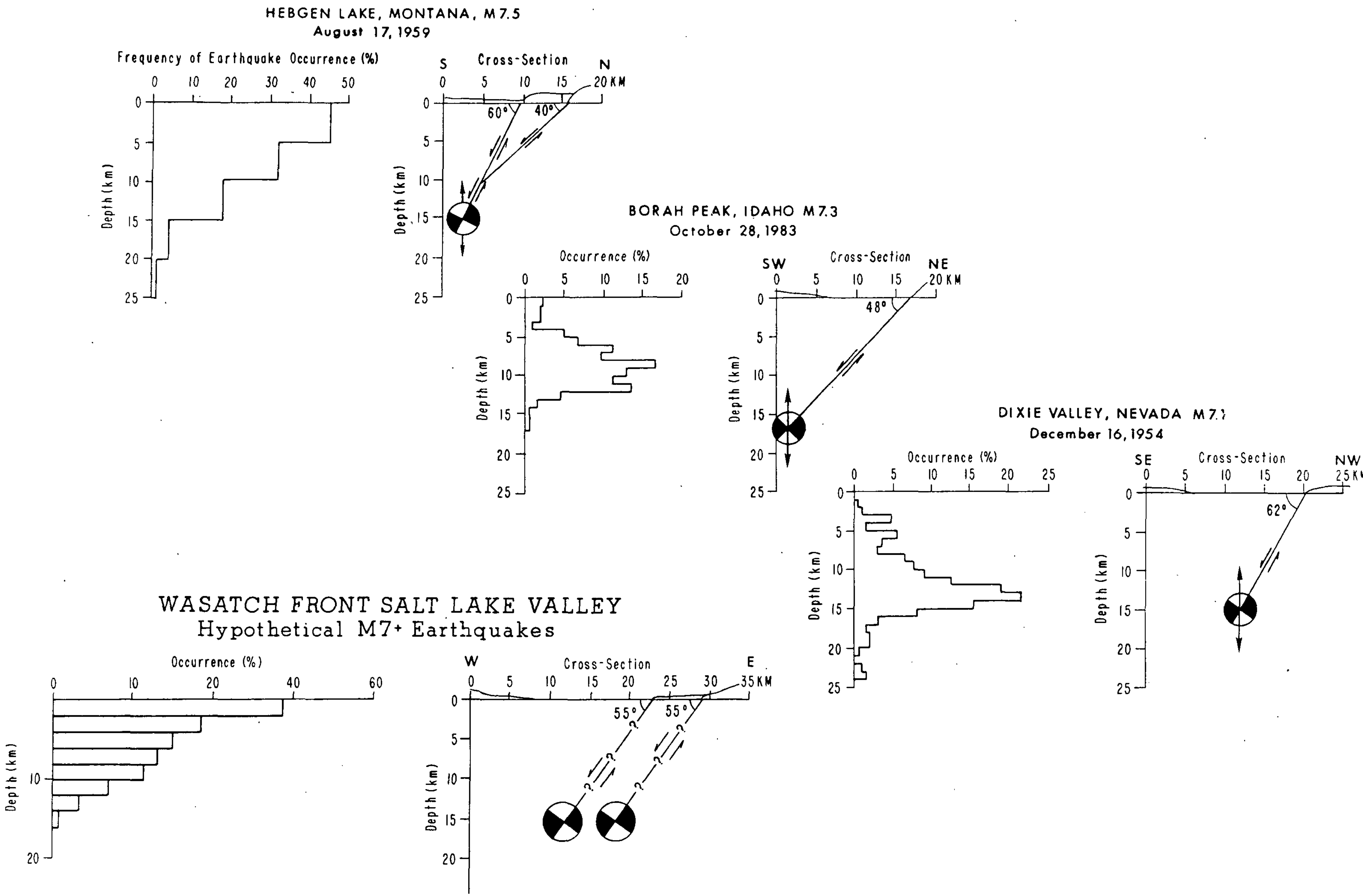

Figure 11. Hypothetical model for large earthquakes that could plausibly nucleate at ~15 km depth on the main westward dipping Wasatch fault. Fault plane geometries inferred from comparison with other large Basin-Range earthquakes and interpretations of reflection data.

Observed Surface Deformation

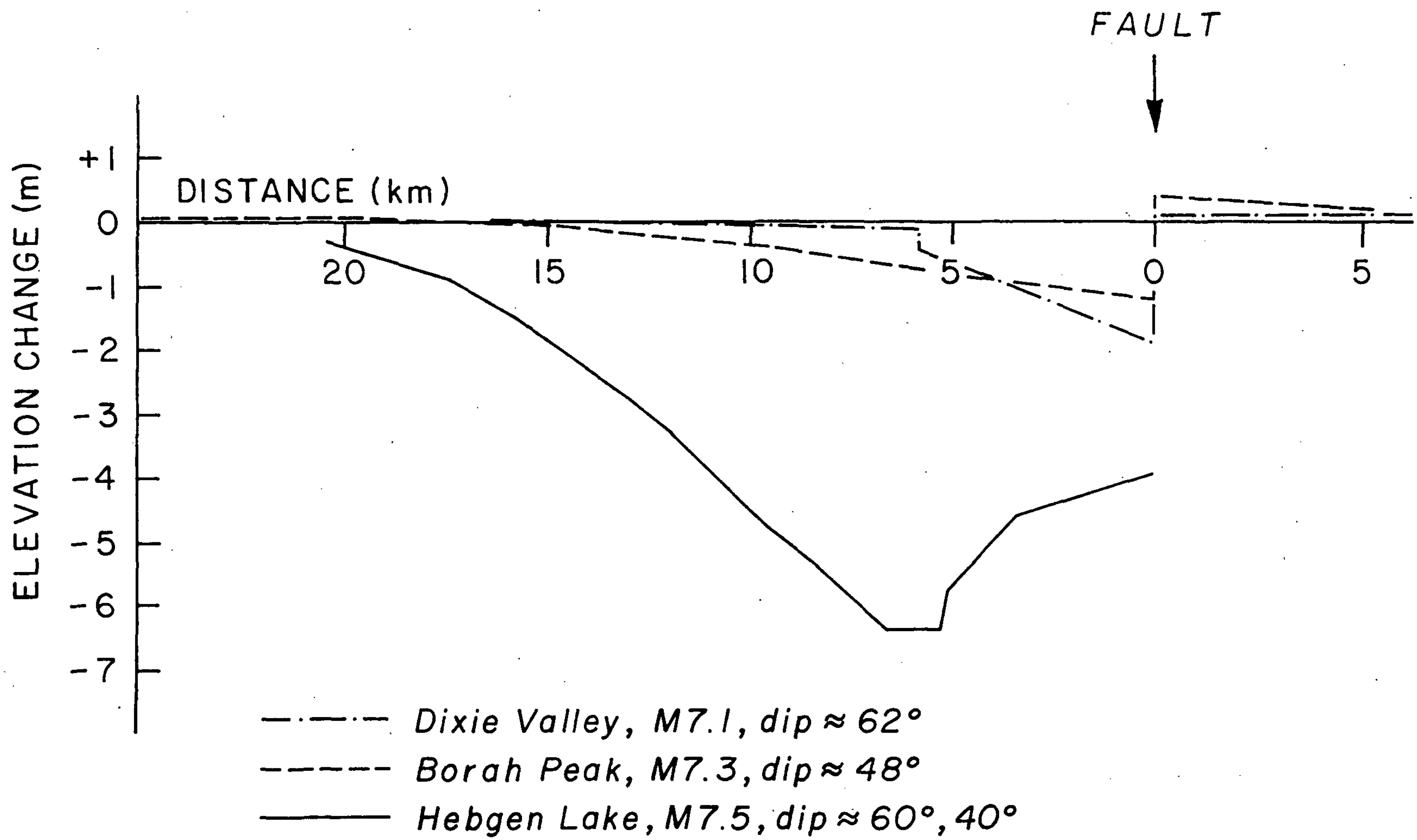

Figure 12. Vertical deformation of the three Basin-Range M7+ earthquakes; M7.1, 1954 Dixie Valley, Nevada; M7.3, 1983 Borah Peak, Idaho (Stein and Barrientos. 1984); and M7.5, 1959 Hebgen Lake, Montana (Savage and Hastie, 1966).

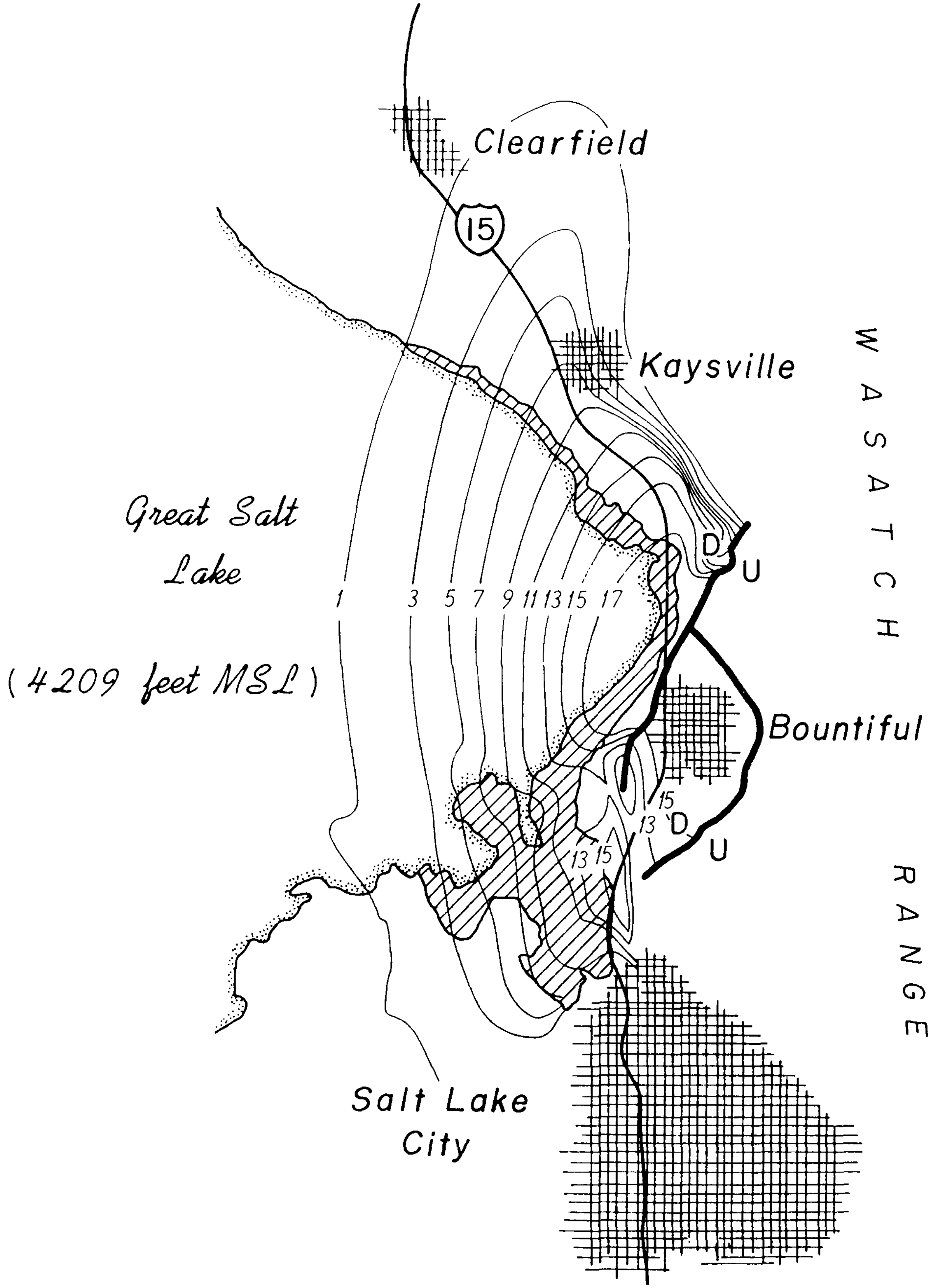

Figure 13. Deformation induced flooding at three Wasatch Front locations for a hypothetical M7.5 Hebgen Lake size earthquake; a) Bountiful, b) Salt Lake City, c) Provo. Heavy lines correspond to surface faults and contours correspond to subsidence (in feet) from Hebgen Lake earthquake deformation. Diagonal pattern corresponds to area that could be effected by earthquake induced flooding for this scenario.

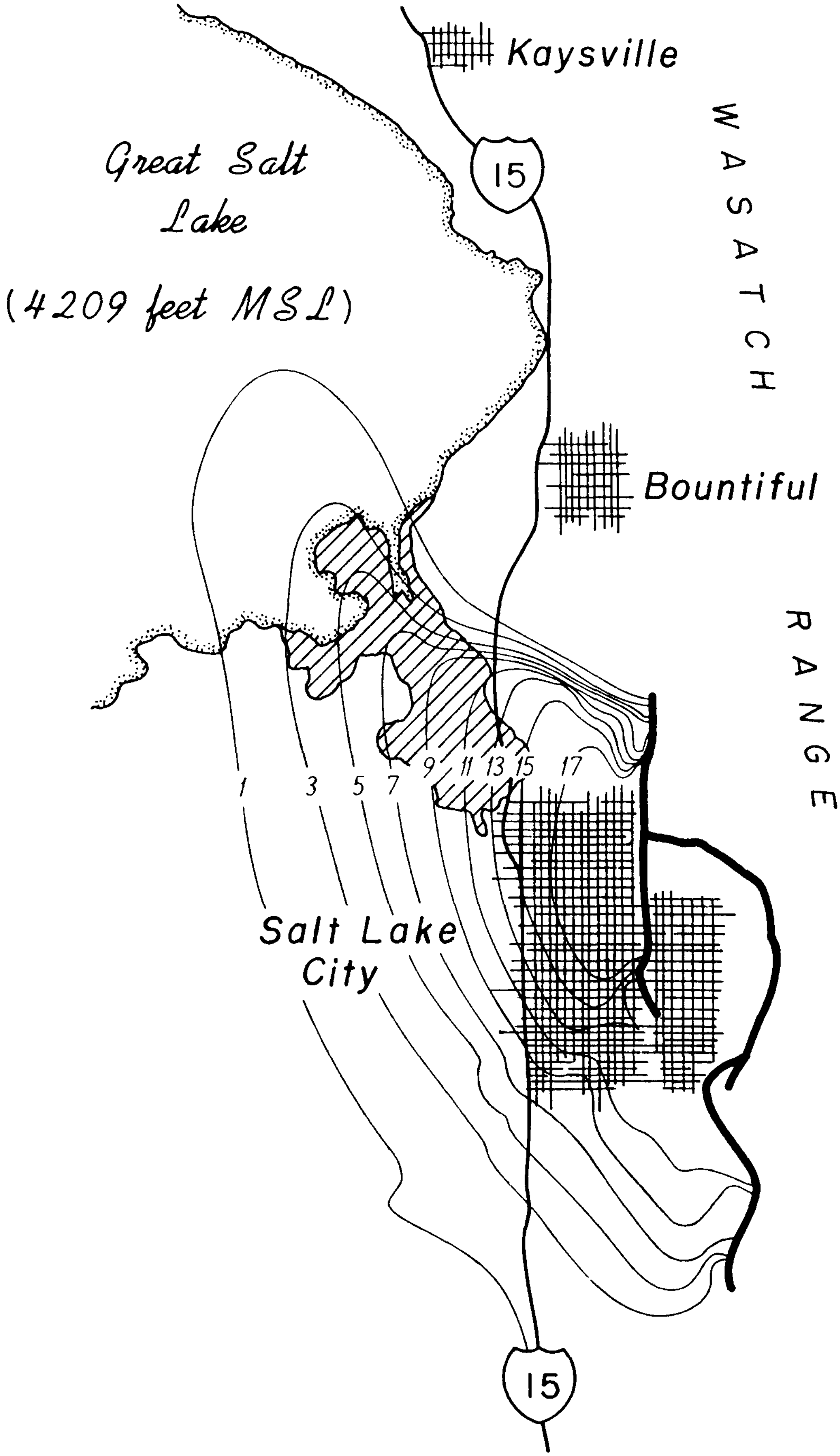
Kaysville
Great Salt Lake
(4209 feet MSL)
15
WASATCH
Bountiful
RANGE
1
3
5
7
9
11
13
15
17
Salt Lake City
15

Figure 13b.

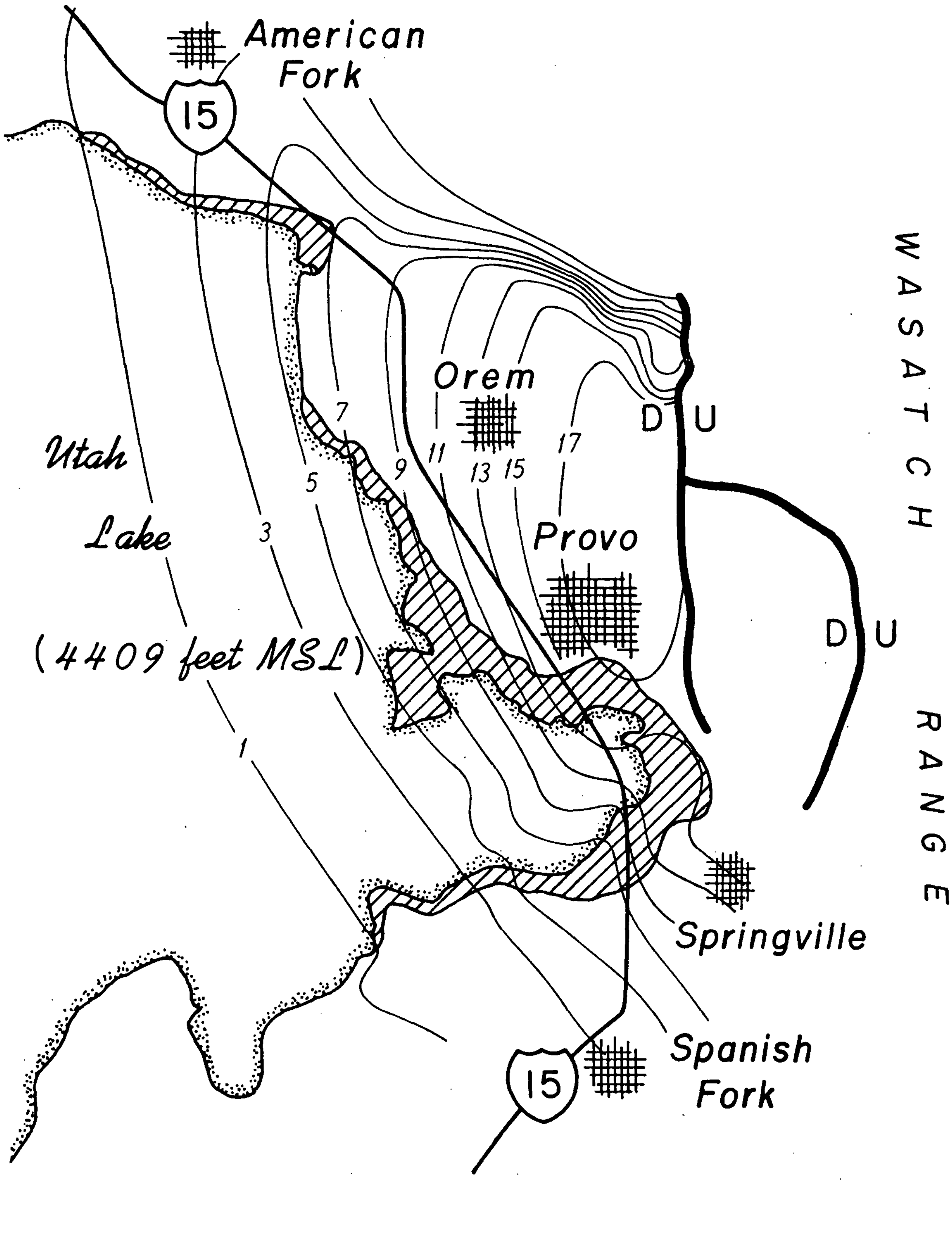
American Fork
15
Utah
Lake
(4409 feet MSL)
1
3
5
7
9
11
13
15
17
Orem
Provo
D
U
D
U
WASATCH
RANGE
Springville
Spanish Fork
15

Figure 13c.

(Figure 13b), (3) Provo-Springville (Figure 13c). The effect of the backward tilt into bodies of water is flooding into the zones of subsidence (Figure 12). Selecting the 1984 high water mark of 4209 feet for the Great Salt Lake allowed inundation eastward into the western Bountiful area with flooding extending eastward to about the location of Interstate I-15. In the Salt Lake City example, flooding extended southeast across the northwest parts of the City. In central Utah, Utah Lake at a maximum 1984 level of 4494 feet could inundate areas east of the Interstate I-15, between Provo and Springville. Note that these hypothetical models are simply a hazard scenario that, heretofore, has been unrecognized. These scenarios cannot be applied to the Wasatch fault without much more information and justification of assumptions. For example, the extent of inundation depends upon location of faulting, dip, and total displacement, parameters that are not yet known accurately for the Wasatch Front. Note that flooding of this nature also depends upon water levels that fluctuate rapidly over tens of years, but the hazard is accentuated by high water associated with the recent increases in precipitation.

IX. RECOMMENDATIONS

The above discussions highlight data and new concepts of seismicity of the Wasatch Front principally focusing on recent seismicity, fault zone geometry, explanations of Wasatch Front epicenter patterns and possible locations of future large earthquakes--all ingredients of an accurate assessment of earthquake hazards. Based on our investigations we would like to recommend to the U.S. Geological Survey and the National Science Foundation for incorporation into the National Earthquake Hazards Reduction

Program and to the State of Utah-USGS cooperative program the following technical considerations:

1. Accelerated investigations of major Quaternary-Holocene normal fault zones emphasizing information from adjacent bedrock exposures, mechanical and chemistry properties of fault zones, geometric and geomorphic information on inferred fault zones, and most importantly incorporating geophysical information such as seismic reflection, refraction, and gravity techniques to map the fault with <u>depth</u> beneath adjacent valleys.

2. Deep penetration seismic reflection profiles designed to image dipping structures should be recorded across all major segments of the Wasatch fault and adjacent fault zones to provide high-resolution information on fault zone geometry, structure, style, depth, etc. This research effort will compliment borehole and fault zone evaluation.

3. Detailed evaluations of fault zone segmentation is required to examine with statistical uncertainties: segment lengths, end-points, fault geometries. etc.

4. Deep boreholes should be drilled into selected segments of the Wasatch fault to penetrate the fault zone for purposes of determining Quaternary-Holocene stratigraphy, borehole properties, geochemical/geopressure information, in situ stress, etc.

5. Expanded efforts in trenching of at least two to three sites per fault segment are necessary to establish statistical certainties, accurate recurrence rates, slip rates, displacement histories, and maximum magnitudes.

6. Increased research is necessary to evaluate the probabilistic and deterministic models of temporal and spatial occurrence of normal faulting earthquakes and to incorporate and synthesize all of the existing information on dating, fault area, recurrence intervals, fault geometry, stress, etc.

7. Accelerated research should be focused on the dynamics of normal faulting. Emphasis on normal fault mechanisms including precursory phenomena, modeling of ground motion, modeling space-time histories, etc. are needed.

8. Long-term stable funding is required for effective operation of the southern Intermountain Seismic Belt regional seismograph network for baseline data acquisition. Three-component broad-band seismographs at selected digital stations should be installed and ancillary seismological studies of the dynamics and kinematics of normal faulting should be emphasized.

9. Expanded geodetic (horizontal and vertical) networks across major fault zones should be established with frequent reobservations to assess pre-seismic, co-seismic and post-seismic deformation.

10. Theoretical modeling and implementation of an expanded strong motion network to predict and evaluate peak ground accelerations associated with active segments of the Wasatch fault will be an important contribution to engineering assessments of risk.

ACKNOWLEDGMENTS

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FAULT BEHAVIOR AND EARTHQUAKE RECURRENCE ALONG THE WASATCH FAULT ZONE

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INTRODUCTION

The Wasatch fault zone is an active intraplate normal fault that extends for approximately 370 km along the western front of the Wasatch range. The majority of Utah's population lives along the Wasatch Front and all of the principal urban areas and most of the larger towns are located adjacent to the Wasatch fault zone and associated faults such as the East Cache fault. Paleoseismological studies of these faults show they have been the sources of repeated past large magnitude earthquakes in the range of M 6-3/4 - 7-1/2 (Swan and others, 1980, 1982), although no surface faulting earthquakes have occurred on these faults since settlement of the area in 1847. Because of this, an understanding of the future behavior of these faults, especially the size of future earthquakes, the amount of surface displacement and style of ground deformation associated with the events, the probable location and timing of the events, and the ground motions produced during the earthquakes is critical to the mitigation of seismic hazards along the Wasatch Front.

In 1977, the first trenches were excavated across the Wasatch fault zone at the Kaysville site (Figure 1) for the specific purpose of quantifying

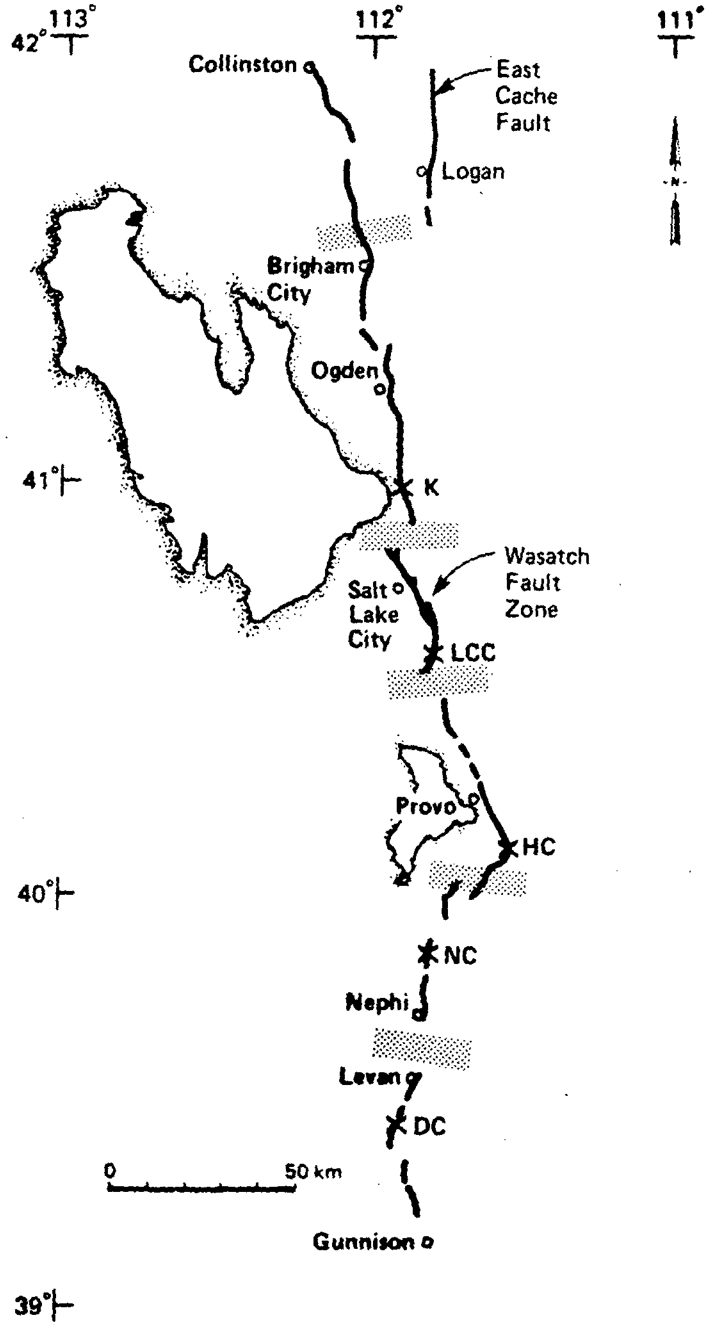

Figure 1 Locality Map for Wasatch and East Cache Fault Zones. Sites Described in the Text Are K = Kaysville, LCC = Little Cottonwood Canyon, HC = Hobble Creek, NC = North Creek, DC = Deep Creek. Stippled Bands Define Proposed Boundaries of Major Fault Segments.

earthquake recurrence. Since then, investigations have been conducted at the Hobble Creek, Little Cottonwood Canyon, and North Creek sites along the Wasatch fault zone and at Logan along the East Cache fault (Figure 1). These investigations have yielded information on slip rate, recurrence intervals for past surface faulting earthquakes, displacement per event for past earthquakes, and fault segmentation, and they provide a basis for evaluating the late Plesitocene-Holocene behavior the Wasatch fault zone. Results from these investigations have been presented by Swan and others (1980), Schwartz and others (1983), and Schwartz and Coppersmith (1984). The present paper summarizes the data collected at all sites and discusses the implications of these data to fault behavior and earthquake recurrence.

SLIP RATE

Slip rates provide a means for comparing relative behavior of different parts of a fault zone. In addition, slip rates can be used to model earthquake recurrence. Slip rate data for the Wasatch fault zone are summarized in Table 1. Late Pleistocene-Holocene rates for the Wasatch fault zone range from essentially $\geq$ 0 along the segment of the fault north of Brigham City to 1.36 mm/yr along the Nephi segment. The rate for the East Cache fault is 0.1-0.2 mm/yr. These slip rates were developed from topographic profiling of displaced geomorphic features, including surfaces that grade to the Provo shoreline, glacial moraines, alluvial fans, and stream terraces. However, rates based on different-aged datums may not be exactly comparable. Also, care must be exercised in extrapolating rates calculated at a point for long distances along the trace of the fault. Considering these factors, we view the slip rates as representing a generally constant rate of strain

TABLE 1

FAULT BEHAVIOR DATA
WASATCH FAULT ZONE

Segment	Site	Slip Rate ($mm\ a^{-1}$)[a]	Displacement per Event (m): Measured	Displacement per Event (m): Average[b]	Recurrence: Interval	Recurrence: Average (yr)	Elapsed Time (yr)[c]	Reference
Collinston	-	≥ 0 (13,500)	-	-	-	-	≥ 13,500	Schwartz and others (1983)
Ogden	Kaysville	1.3 (+0.5, -0.2)[e] (8,000; +1000, -2000)	1.6 1.7	- -	2 (after 1580)[d]	2000	≤ 500	Swan and others (1980)
Salt Lake City	Little Cottonwood Canyon	0.76 (+0.6, -0.2) (19,000 ± 2000)	-	2 (2)	-	2400-3000	-	Swan and others (1981); Schwartz and Coppersmith (1984)
Provo	Hobble Creek	0.85 - 1.0[e] (13,500)	2.7	1.6-2.3 (6-7)	6-7 (after 13,500)	1700-2600	> 1000	Swan and others (1980)
Nephi	North Creek	1.27-1.36 (± 0.1) (4580)[d]	2.0-2.2 2.0-2.5 2.6	2.3 (3) -	2 (between 4580 and 3640)[d] 1 (after 1100)[d]	1700-2700	300-500	Schwartz and Coppersmith (1984)
Levan	Deep Creek	≤ 0.35 ± 0.05 (7300)[d]	2.5	-	1 (after 7300)[d]	-	<1750[d]	Schwartz and Coppersmith (1984)
East Cache	Logan	0.1-0.2 (14,000-15,000)	1.35 1.4	- -	1 (between 15,000 and 13,500) 1 (after 13,500)	-	6000-10,000	Swan and others (1982)

a Age of displaced datum (years B.P.) on which slip rate is based is shown in parentheses.
b Number of events on which average is based is shown in parentheses.
c Time in years since the most recent surface faulting earthquake.
d Age in ^{14}C yr B.P.
e Modified from Swan et al. (1980).

accumulation of about 1 mm/yr along the Wasatch fault zone between Nephi and Brigham City during Holocene time. This rate of strain accumulation is one to two orders of magnitude greater than the rate for faults in other parts of the Basin and Range province.

DISPLACEMENT PER EVENT

Information on the amount of displacement per event for past surface faulting earthquakes is important for assessing the magnitude of past earthquakes, for developing models of earthquake recurrence, and for developing estimates of the amount of displacement that might occur where lifelines such as water and gas pipelines cross fault traces. The thickness of colluvial deposits (colluvial wedges) adjacent to the fault observed in trenches, profiling of fault scarps, and measuring the heights of tectonic terraces inset into the upthrown block of the fault are the methods generally used for evaluating the size of paleodisplacements.

Displacement per event data are summarized in Table 1. Investigations of historical surface ruptures on normal faults in the Basin and Range, such as the 1915 Pleasant Valley and the 1983 Borah Peak earthquakes, show systematic variation in displacement along the surface trace of the fault. For the Wasatch fault zone, we do not know where individual trench sites are located with respect to past surface ruptures, and there is some uncertainty as to whether an individual measurement represents a minimum, an average, or a maximum displacement for that surface faulting event. Despite this, the data clearly show that displacement per event has been consistently large. The measured values range from 1.6 to 2.6 m, and the average displacement per event is about 2 m. The data also indicate that displacements at the same location along the fault have been essentially the same during successive events.

EARTHQUAKE RECURRENCE INTERVALS

Factors that affect the evaluation of earthquake recurrence at a specific location along a fault include the completeness of the stratigraphic record, the local erosional and depositional environment, and the threshold earthquake magnitude that produces recognizable surface-fault rupture. Recurrence estimates at individual sites along the Wasatch fault zone have been based on a combination of trenching and mapping. Trenching of normal fault scarps has shown the usefulness of scarp-derived colluvial deposits in quantifying the number of past surface faulting events. In trenches, these are commonly seen as stacked units or wedges grading away from the main fault scarp. Mapping is especially important because it helps establish many stratigraphic and structural relationships that clarify observations made in trenches and it aids in identifying secondary features such as tectonic terraces and segmented alluvial fans that also provide evidence of recurrence.

Data on the recurrence of surface faulting earthquakes at individual sites along the Wasatch fault zone are shown in Table 1. Recurrence intervals clearly vary along the length of the zone. Average intervals are shortest along the four central segments of the zone between Brigham City and Nephi, where they range from 1700 to 3000 years. In contrast, the ends are less active. A minimum interval of 5000 years occurred along the southern segment of the zone prior to its most recent event, and the northern segment does not appear to have had a recognizable scarp-forming event during the past 13,500 years. Where radiocarbon dates constrain the actual interval between events, it is evident that the actual recurrence is not uniform and may vary from the average by at least a factor of two. At the North Creek site, for example, there have been three surface faulting earthquakes during the past 4,580 ^{14}C yr B.P.; two of these occurred between 4,580 and 3,640 ^{14}C yr B.P. and the most recent event is estimated to have occurred within the past 300 to 500 years. At this location, the interval between successive events was not uniform and varied from somewhat less than 1,000 years between the oldest and middle events to longer than 3,000 years between the middle and most recent events. This non-uniformity of earthquake recurrence is typical of faults in intraplate environments.

Swan and others (1980) suggested an average recurrence interval along the entire Wasatch fault zone of 50 to 430 years. This was calculated by using minimum (500 yr) and maximum (2600 yr) intervals estimated at the Kaysville and Hobble Creek sites, respectively, and assuming that these were representative of 6 to 10 independent fault segments. Additional investigations have shown that the fault zone is most likely composed of six segments, the recurrence interval can differ significantly between segments, and the recurrence along a given segment can also be highly variable. Based on these additional data, and the behavioral variability they indicate, Schwartz and Coppersmith (1984) have revised the estimate of the average recurrence for the zone by using the number of events observed or estimated in the geological record along each segment of the fault over a particular interval, which in this case was selected as the past 8000 years on the basis of available radiocarbon dates and the ages of displaced datums. Using this approach, they calculated a range of 400 to 666 and a preferred value of 444 years for the average recurrence interval for a surface faulting earthquake along the entire Wasatch fault zone. This is similar to the longer interval suggested by Swan and others (1980), and we feel it is presently the best estimate of the average recurrence for the zone.

The occurrence of successive large and similiar displacement events along the Wasatch fault zone coupled with the variability in timing between these events and the lack of evidence of small-displacement events, has led to the development of the characteristic earthquake recurrence model (Schwartz and Coppersmith, 1984). This recurrence model suggests that: a) linear frequency-magnitude distributions over a full range of eathquake magnitudes may not be appropriate for individual faults or fault segments and moderate magnitude events smaller than the characteristic earthquake may be relatively less likely to occur than the larger event, b) the magnitude of the characteristic earthquake may approximate the maximum earthquake (M 7 - 7$^1/_2$ for the Wasatch fault zone) and, c) stress application appears to be non-uniform and faults may fail in response to localized, rapid increase in stress. Similar behavior appears to characterize other Basin and Range normal faults.

SEGMENTATION

A normal fault as long as the Wasatch fault zone (370 km) will only rupture along part of its total length during a surface faulting earthquake. A major question is does rupture occur randomly along the fault or are there distinct rupture segments, perhaps controlled by the geometry of the fault and by older structural trends, that behave consistently through time? Quantifying the number of potential rupture segments is a key factor in evaluating recurrence for the entire fault zone and in estimating where the next rupture is most likely to occur.

Swan and others (1980), on the basis of rupture lengths of historical Basin and Range surface faulting earthquakes with $M > 6\frac{1}{2} < 7\frac{1}{2}$ suggested that the Wasatch fault zone consists of 6 to 10 segments, although the individual segments were not specifically identified. Based on additional data, we now believe there are six major segments. Selection of each segment is based to varying degrees on fault geometry, scarp morphology, slip rate, and timing the most recent event, gravity data, and geodetic data. The proposed fault segments are shown on Figure 1. From north to south, the segments and their length and orientation are: 1) Collinston, $\geq$30 km, N20W; 2) Ogden, 70 km, N10W; 3) Salt Lake City, 35 km, convex east N20E to N30W; 4) Provo, 55 km, N25W; 5) Nephi, 35 km, N11E; and 6) Levan, 40 km, convex west. The Collinston segment has had no identifiable surface faulting during the past 13,500 years. The Ogden segment has experienced multiple displacements, including two within the past 1580 ^{14}C yr B.P. and with the most recent of these within the past 500 years. The Salt Lake City and Provo segments have each had repeated Holocene events; the timing of the most recent event along the Salt Lake City segment is not known, and the youngest event on the Provo segment appears to have occurred more than 1000 years ago. Along the Nephi segment one event has occurred within the past 1100 ^{14}C yr B.P. and possibly as recently as 300 years ago; two earlier events occurred on this segment between 4580 and 3640 ^{14}C yr B.P. The Levan segment has experienced only one event during the past 7300 ^{14}C yr B.P. and this event occurred less than 1750 ^{14}C yr B.P. ago.

Proposed segment boundaries are not sharply defined. The boundaries may represent structurally complex transition zones a few to more than ten kilometers wide. To varying degrees, boundaries selected on the basis of paleoseismic and geomorphic observations are coincident with changes in the trend of segments; major salients in the range front; intersecting east-west or northeast structural trends observed in the bedrock geology of the range (Smith and Bruhn, 1984); saddles, cross faults, and transverse structural trends interpreted from gravity data (Zoback, 1983); and geodetic changes (Snay and others, 1984).

WHERE DO WE GO FROM HERE?

Two aspects of the investigations undertaken to date deserve especially close attention in future studies for evaluating seismic hazards. These are refinement of fault zone segmentation and development of tighter constraints on earthquake recurrence with emphasis on the timing of the most recent surface faulting earthquake along each segment.

The delineation of segments and evaluation of their past behavior through several seismic cycles has a major impact on the evaluation of seismic hazards along the Wastach Front. The segments may provide a basis for constraining the location and length of rupture during single events. The potential rupture length is an important parameter for estimating maximum earthquake magnitude and it can be combined with displacement per event and fault width data to estimate the most realistic maximum earthquake for that segment.

The elapsed time since the most recent event, the average recurrence interval, and the standard deviation of recurrence from the mean can be used to calculate real-time probabilities of occurrence of the next event on a segment during a selected interval (e.g., the next 50, 100, and 200 years). With better constrained, systematic data on elapsed time and average recurrence along the zone, it is possible to identify the segment of the fault that has the greatest likelihood of producing the next large earthquake. For example, the elapsed time since the most recent event along the proposed Salt Lake City and Provo segments, which lie astride the largest population centers, are not constrained by radiocarbon dating, although geomorphic observations suggest that the elapsed time since the most recent event on at least the Provo segment is significantly longer than on the adjacent Nephi segment to the south or on the Ogden segment north of Salt Lake City (Table 1). Therefore, elapsed time data are extremely important, and these two segments deserve close attention in this regard.

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LIQUEFACTION POTENTIAL AND SLOPE STABILITY WASATCH FRONT AREA

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Introduction

The effects of earthquakes can cause loss of life and costly property damage; therefore, in areas of high seismic activity, earthquake hazard reduction must be an important consideration for intelligent land use planning. Damage during earthquakes can result from surface faulting, ground shaking, ground failure, generation of large waves (tsunamies and seiches) in bodies of water, and regional subsidence or downwarping. All of these causes of damage need to be considered in reducing earthquake hazards.

Ground failure associated with earthquake-induced soil liquefaction has caused major damage in various parts of the world during past earthquakes. The seismic history of the Wasatch front area in north-central Utah clearly indicates that ground motion of sufficient intensity and duration to induce liquefaction of susceptible soils is very likely to occur in the relatively near future.

Deposits of loose fine sand, highly susceptible to liquefaction, exist along the Wasatch front. Areas of shallow ground water are also widespread. In addition, evidence of liquefaction was observed following the 1934 Hansel Valley earthquake in Box Elder County, Utah and again following the Cache Valley earthquake of 1962.

The seismic history, subsurface soil and ground water conditions, and evidence of liquefaction in Utah indicate that liquefaction is a significant hazard which must be assessed as an important element in seismic hazard reduction planning.

In addition to earthquake hazards a number of other geologic hazards exist along the Wasatch Front and should also be considered in land use planning. During approximately three months in the spring of 1983, the state of Utah, with a population of about 2 million people, sustained direct damages from landslides, debris flows, mud floods, and flooding in excess of $250 million. These disastrous events were so widespread and extensive that 22 of the 29 counties in the state were declared national disaster areas.

Considering all of these geologic hazards in a rational manner will require using a risk analysis framework. It is important that this framework be defined as soon as possible so that the format for individual hazard mapping programs can be adjusted to accomodate combining the results of several different studies.

Liquefaction Potential Mapping

As part of the U.S. Geological Survey's Earthquake Hazard Reduction program "Liquefaction Potential Maps" have been prepared for Davis, Salt Lake and Utah Counties and a study for the Northern Wasatch Front is pending. Liquefaction potential was evaluated from existing subsurface data and from supplementary subsurface investigations performed during the studies.

For this regional assessment, liquefaction implies liquefaction-induced ground failure. The liquefaction potential is classified as high, moderate, low and very low depending on the probability that a critical acceleration will be exceeded in 100 years. The critical acceleration for a given location is defined as the lowest value of the maximum ground surface acceleration required to induce liquefaction. The catagories of high, moderate, low and very low correspond to probabilities of exceeding the critical acceleration in the ranges of greater than 50 percent, 10 to 50 percent, 5 to 10 percent and less than 5 percent, respectively.

The Liquefaction Potential Maps that were developed show that for a significant portion of the Wasatch Front the probability of exceeding the critical acceleration in 100 years is greater than 50 percent. Hence, liquefaction induced ground failure is a significant seismic hazard.

Ground slope information, as well as the subsurface conditions documented on Soils and Ground Water Data Maps, can be used in combination with the Liquefaction Potential Maps as a means of assessing the type of ground failure likely to occur. Three slope zones have been identified from the characteristic failure modes induced by liquefaction during historic earthquakes (Youd, 1981, personal communication).

At slope gradients less than about 0.5 percent, loss of bearing capacity is the type of ground failure most likely to be induced by soil liquefaction. Stratified soil conditions, which exist in the study areas, provide vertical confinement for liquefiable layers and may tend to reduce the probability of bearing capacity failures. Buildings imposing light loads on the subsurface soils may not be affected by loss of bearing capacity during an earthquake. Heavy buildings, on the other hand, might be severely affected. Additionally, during earthquakes, heavy buildings subjected to movement from deformation of the subsurface soils might cause damage to adjacent lightly-loaded structures.

Buried tanks, even those full of water or gasoline, could "float" to the surface if the soils surrounding them were to liquefy. For this to happen, however, the tanks would have to be buried in very thick deposits of sand. The statified nature of the soils in the study areas generally tend to reduce the likelihood of this type of failure.

Slope gradients ranging from about 0.5 percent to about 5.0 percent tend to fail by lateral spread processes as a result of soil liquefaction. Evidence exists in Davis County for five large lateral spread landslides. Consequently, it appears that these kinds of failures have occured in response to earthquakes within the past few thousand years.

Lateral spread landslides present the greatest concern because of the potential consequences. A small amount of movement can do a great deal of damage. Lifelines (buried utilities) are particularly vulnerable. A large area along the Wasatch Front area falls within the slope range characterized by lateral spread landslides induced by soil liquefaction.

Slopes steeper than about 5 percent tend to fail as flow slides if the mass of soil comprising the slope liquefies. In the study area, the stratified nature of the geologic materials suggests that flow-type failures are likely to be relatively rare. Instead, translational landslides or lateral spreads are likely to result from liquefaction on slopes steeper than about 5 percent.

The results of our research on the liquefaction potential along the Wasatch Front leads us to conclude that lateral spread landsliding is the type of ground failure most likely to accompany soil liquefaction. The probability of extensive damage due to this type of ground failure is very high. All types of structures could be damaged by liquefaction-induced ground failure; lifelines are especially susceptible to damage.

Landslide Potential Research

During the unusally heavy spring snowmelt period of 1983, over ninety landslides occurred along the Wasatch Front between Bountiful and Kaysville, Utah. Many of these landslides, commonly referred to as "depris slides" or "soil slips", came to rest only a short distance downslope from the zone of initiation. However, some of them mobilized into debris flows which transported large boulders up to five miles. One debris flow inundated nine square blocks of the town of Farmington with over 90,000 cubic yards of debris and caused extensive damage.

Readings on open stand-pipe piezometers which were installed near five of the landslides shortly after slope failure show complex groundwater behavior with sharp fluctuations in piezometric pressure. Artesian pore water pressures were observed on a slope with a gradient in excess of 30 degrees indicating a strong influence of confining layers within the soil strata. Visual observations by landslide hazard warning teams during the height of landslide activity and photographic documentation shown that a time delay exists between initial ground cracking and subsequent ground failure and debris flow mobilization.

In response to the landslide activity during 1983 a number of research projects were initiated that will lead to a better understanding of the landslide hazard along the Wasatch Front. These projects are listed below.

Project	Research Group	Sponsored by
Seismic Slope Stability Map of the Urban Corridor of Davis and Salt Lake Counties	Dames & Moore Utah State University	USGS
Debris Slide Initiation	Utah State University	NSF
Probabilistic Landslide Potential Delineation	Utah State Universtiy	USFS, USU, NSF
Potential for Debris Flow Along the Wasatch Front	U.S. Geological Survey	USGS
Landslide Surveillance	University of Utah	UGMS, Utah CEM
Numerous Landslide Reconnaissance Investigations	Utah Geological and Mineral Survey	UGMS
Numerical Modeling of Debris Flows	Utah State University	USU
Monitoring Debris Flows	U.S. Geological Survey	USGS

Photographic documentation and eyewitness accounts during the spring of 1983 indicated that landslides which triggered debris flows were often preceded by ground cracking on steep mountain slopes. When the cracks were identified, the time lag between initial slope cracking and subsequent complete slope failure sometimes provided a reaction period during which threatened residents could be either evacuated or put on alert.

Anticipating further landslide activity in the spring of 1984, a reconnaissance aerial photography program was initiated with the support of the Boise Air National Guard to systematically identify incipient landslides which could mobilize debris flows. The program emphasized a quick turn-around time of 3 to 4 days from the date of photography to the interpretation of the photographs. When signs of instability were identified, the potential hazards were reported to the Utah Geological and Mineral Survey and the USDA Forest Service for follow-up investigation and appropriate action. The program successfully identified several areas on the basis of ground cracking which subsequently failed and mobilized into debris flows.

In addition to the aerial photography coverage that was obtained from the Boise Air National Guard other coverage of the Wasatch Front has been obtained and is available for landslide studies.

Conclusion

There are numerous geologic hazards along the Wasatch Front that must be considered as part of intelligent land use planning activities. Three studies sponsored by the U.S.G.S. Earthquake Hazard reduction program indicate that there are significant areas in Davis, Salt Lake and Utah Counties with high liquefaction potential. Furthermore, the events of 1983 indicate that landslides, debris flows and floods are of significant concern. An important step must be taken soon to coordinate hazard mapping studies so that they can be integrated in a Risk Analysis Framework.

THE GROUND-SHAKING HAZARD ALONG THE WASATCH FAULT ZONE, UTAH

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SUMMARY

This paper combines probabilisitic estimates of bedrock ground motion and empirical soil-transfer functions for sites in the Salt Lake City, Ogden, and Provo area to evaluate the earthquake ground-shaking hazard along the Wasatch fault zone, Utah. The Wasatch fault zone, which has the potential for generating moderate to large earthquakes, could cause peak bedrock accelerations of and velocities of as much as 0.28 g and 16 cm/s, respectively. The ground-shaking hazard in the Salt Lake City, Ogden, and Provo area is greatest for sites underlain by thick, fine-grained silts and clay because they amplify ground motion in some period bands by as much as a factor of ten.

INTRODUCTION

Salt Lake City, Ogden, and Provo are located adjacent to the Wasatch fault zone, Utah (Fig. 1). The Wasatch fault zone has the potential for generating moderate to large earthquakes which could cause serious social and economic disruption to approximately 900,000 people (about 80 percent of the population of Utah). Moderate and large earthquakes would cause damage from ground-shaking, surface fault rupture, earthquake-induced landslides, and liquefaction.

Evaluation of the earthquake hazards of ground shaking, surface fault rupture, and earthquake-induced ground failure along the Wasatch fault zone is a complex research task, as illustrated in Fig. 2. Evaluation of the ground-shaking hazard in each urban area requires: 1) identification of the seismogenic zones, 2) definition of an earthquake-occurrence model for each seismogenic zone, 3) formulation of a regional seismic-wave attenuation model, and 4) evaluation of the site-specific effects of soil and rock on ground motion.

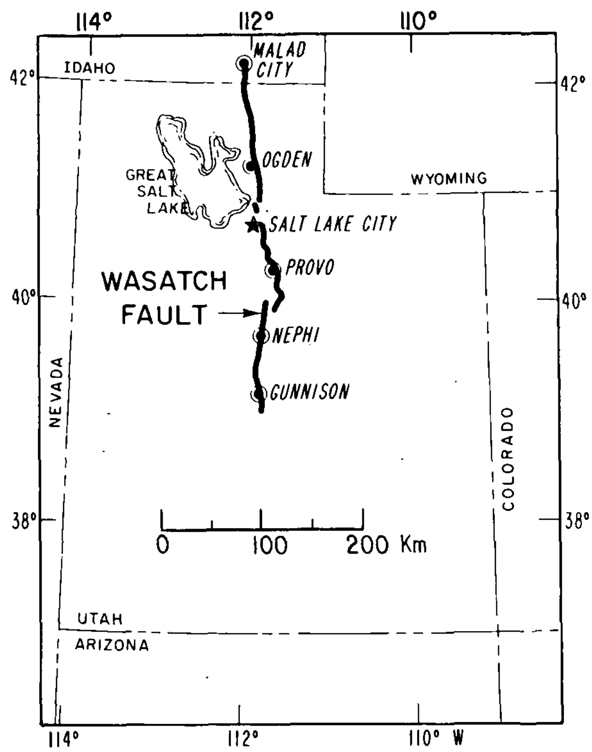

Figure 1.--Map showing Salt Lake City, Ogden, and Provo, and the Wasatch fault zone.

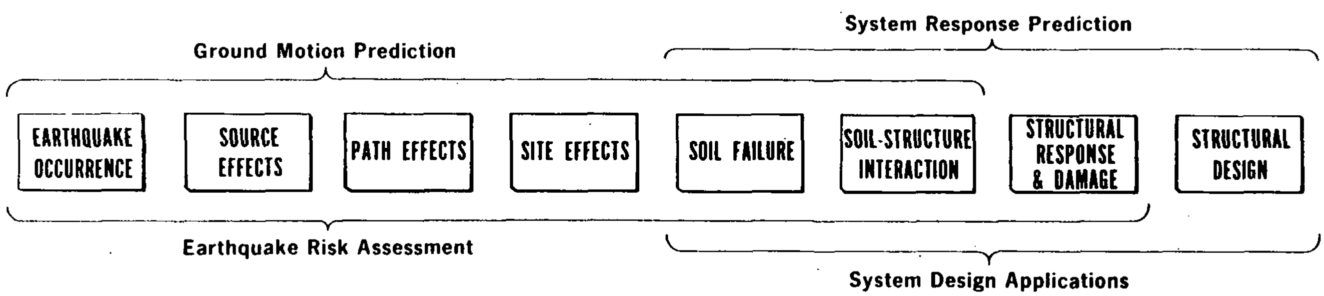

Figure 2.--Schematic illustration of the steps involved in evaluating the earthquake hazards of ground shaking, surface fault rupture, and earthquake-induced ground failure. Evaluation of the ground-shaking hazard requires consideration of the first four steps.

THE RESEARCH PROBLEM

The fundamental problem in the evaluation of the ground-shaking hazard in Salt Lake City, Ogden, and Provo is the lack of scientific and engineering data. Only one strong motion accelerogram, recorded in the 1962 of earthquake of magnitude 5.7 in Cache Valley, exists in Utah. No strong ground-motion data exist to define regional seismic-wave attenuation relations and site response. Because of these significant gaps in data, evaluation of the ground-shaking hazard requires an approach that combines probabilistic estimates of the bedrock ground motion and empirical estimates of the site response. The following sections briefly describe the information used to evaluate the ground-shaking hazard in the Salt Lake City, Odgen, and Provo area, emphasizing the evaluation of site response.

Earthquake Occurrence - Although the Wasatch fault zone, a 370-km-long north-trending zone of young, active, normal faulting has produced many earthquakes, it has not produced an earthquake as large as magnitude 6 since 1850 (Ref. 1). The geologic and geomorphic records clearly show that individual faults in this zone have been active for millions of years (Ref. 2.) and have the potential for generating an earthquake of magnitude 7.5. Exploratory trenching and analysis of scarp morphology and scarp-derived colluvial deposits at two locations along the fault zone suggest that the recurrence interval of moderate to large earthquakes (i.e., magnitudes of 6.5 to 7.5) for the Wasatch fault zone ranges from about 50 to 430 years (Ref. 3).

Maps of Bedrock Ground Motion - Maps of the ground-shaking hazard for bedrock have been prepared for the United States (Ref. 4). In terms of peak bedrock acceleration, these maps show that the Wasatch front has a significant ground-shaking hazard compared with other areas of the Nation (Fig. 3). For Utah, historical seismicity and geologic information were integrated to define seismogenic zones (Fig. 4). Using these zones, an assumed attenuation function, and a probability of nonexceedance of 90 percent during an exposure time of 50 years, values of 0.28 g and 16 cm/s were calculated as the maximum values of peak horizontal bedrock ground acceleration and ground velocity along the Wasatch front. (Fig 5.).

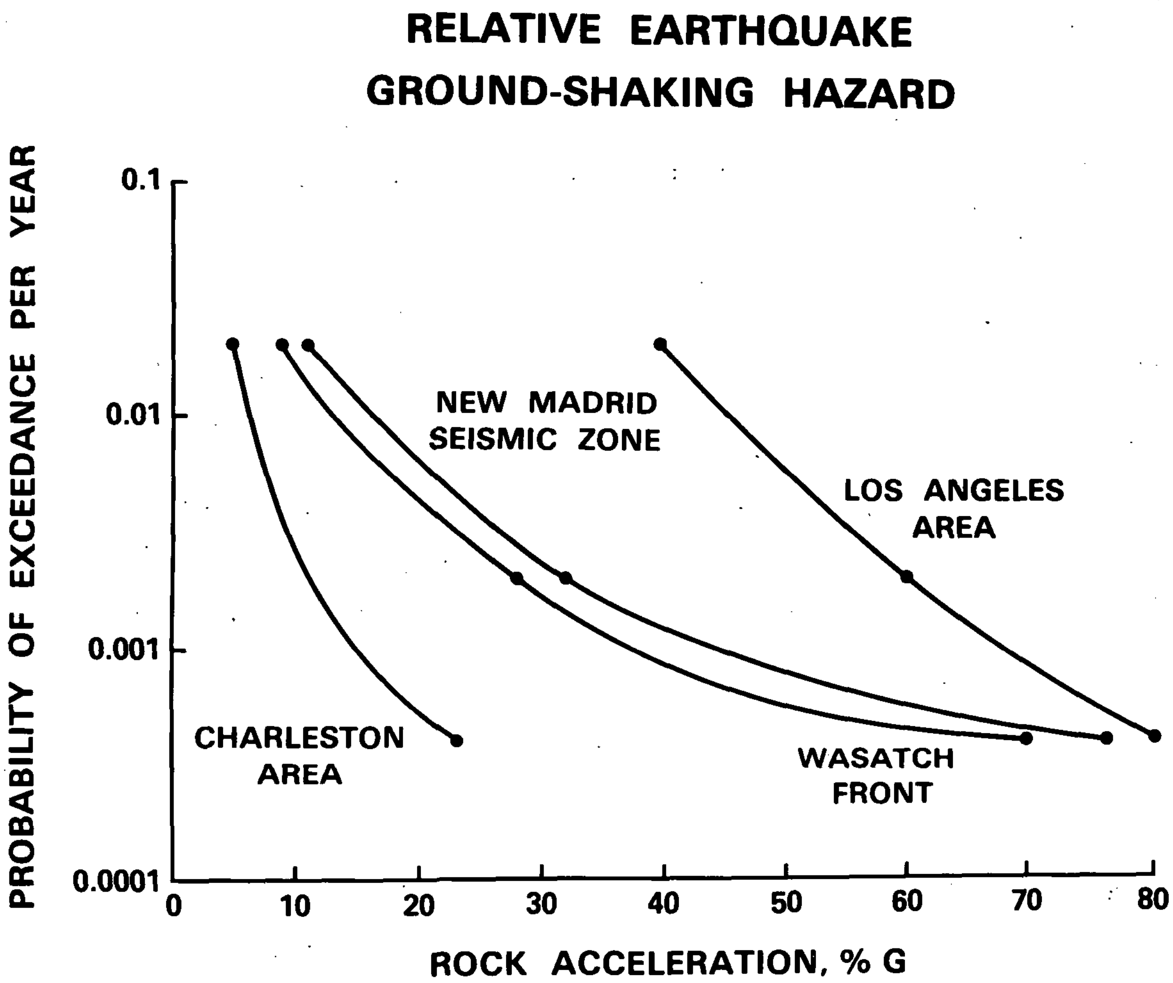

Figure 3.--Curves comparing the bedrock ground-shaking hazard in various geographic areas. Each curve represents a 90 percent probability of nonexceedence (from Ref. 4).

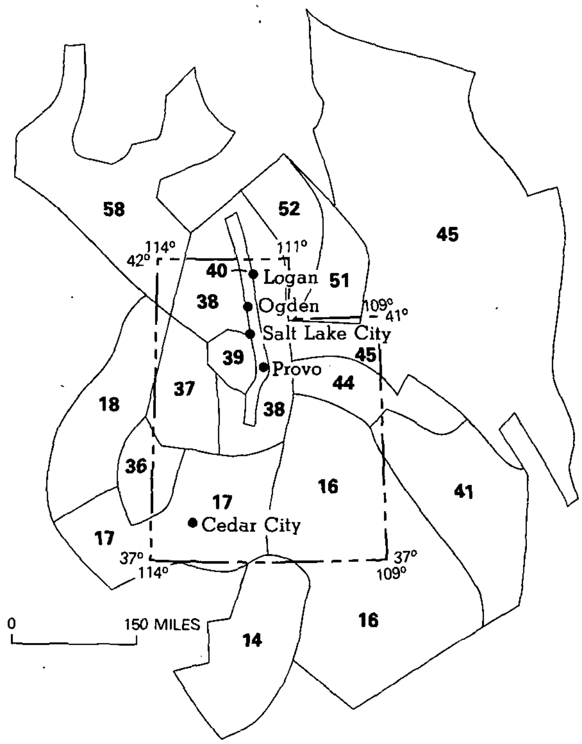

Figure 4.--Map showing seismogenic zones in Utah (from Ref. 4).

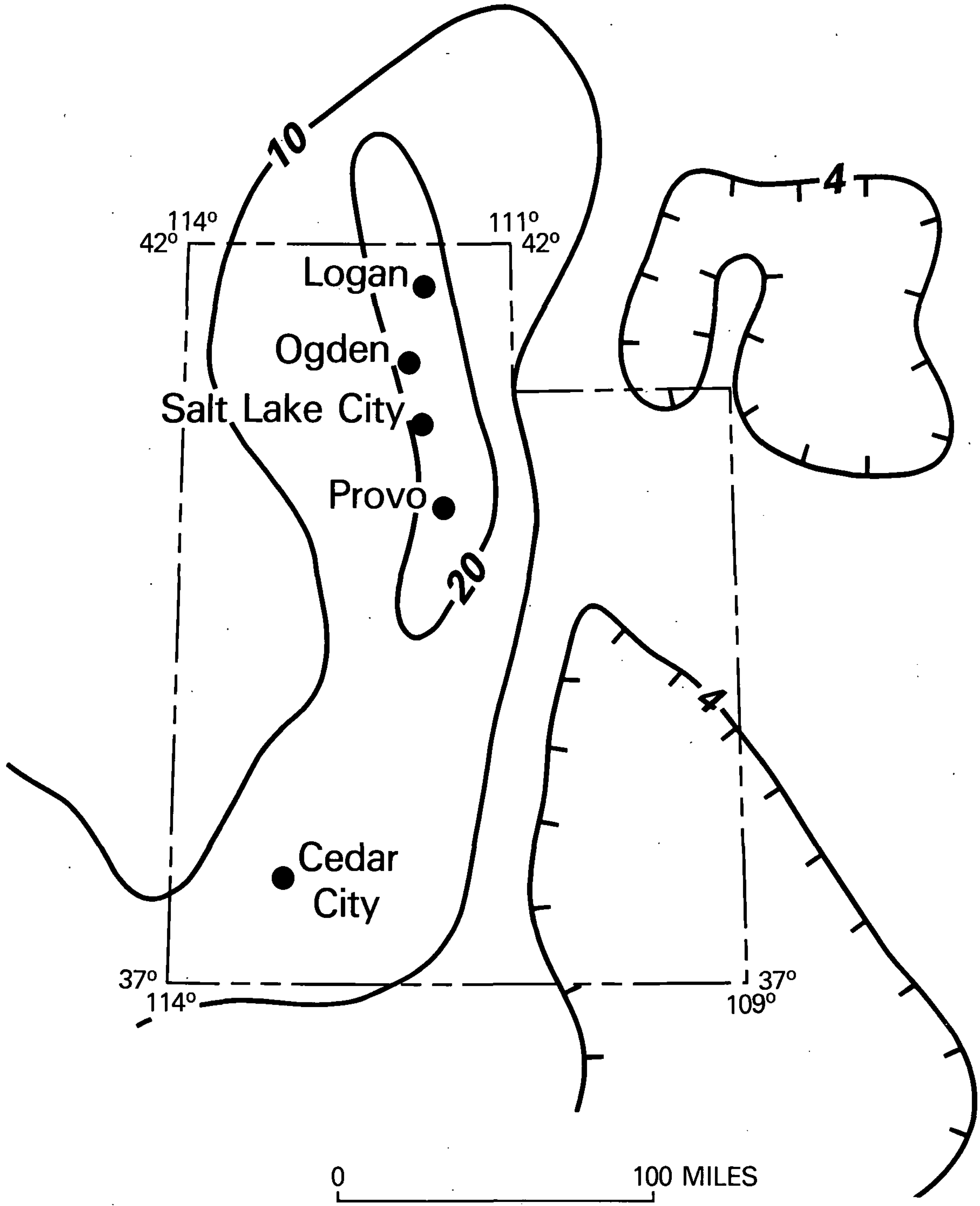

Figure 5A.--Map of the probabilistic bedrock peak horizontal ground acceleration. The map represents a 90 percent probability of nonexceedance in a 50 year exposure time (from Ref. 4).

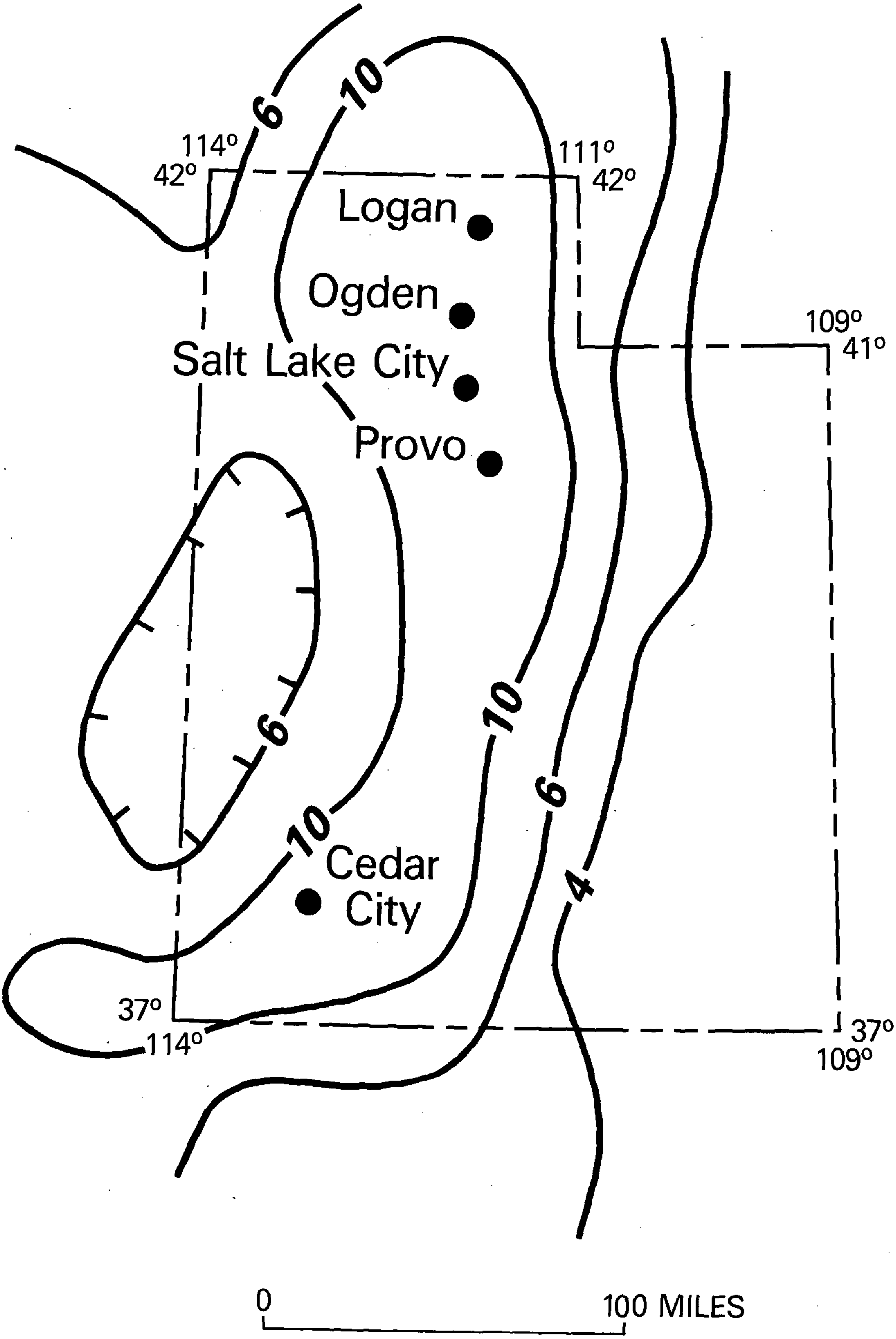

Figure 5B.--Map of the probabilistic bedrock peak horizontal ground velocity. The map represents a 90 percent probability of nonexceedance in a 50 year exposure time (from Ref. 4).

Because empirical data showing the characteristics of ground response under low-to high-strain ground shaking are lacking along the Wasatch fault zone, a special effort, described in the following sections, was made to quantify the physical properties of the unconsolidated materials along the Wasatch front and to define their response to ground shaking. Sites underlain by unconsolidated materials subjected to a peak acceleration of 0.28 g and a peak velocity of 16 cm/s are generally expected to have larger values of ground shaking due to amplification of ground motion (Ref. 5). Some researchers (for example, Ref. 6) disagree with this conclusion when the peak bedrock acceleration is 0.2 g or greater.

Physical Properties of Unconsolidated Materials - The surficial materials underlying Salt Lake City, Ogden, and Provo (Ref. 7) are related to the deposits of several lakes, (the last being Lake Bonneville) that filled the Great Salt Lake Basin during the Pleistocene Epoch. Salt Lake City, Ogden, and Provo are founded on several different types of unconsolidated materials which have been classified in terms of depositional environments: onshore, nearshore, and offshore.

Salt Lake City is founded on several different types of nearshore deposits which have been studied fairly extensively. The deposits range in thickness from about 100 to 900 m, have shear-wave velocities that average about 200 m/s, and have a natural moisture content by weight of about 43 percent.

In Odgen and Provo, less information is available; however, the available data suggest that the physical properties of the unconsolidated materials underlying these cities are similar to those underlying Salt Lake City. A borehole in the Provo area indicates a shear-wave velocity of about 155 m/s. These two values (155 m/s and 200 m/s) compare with values ranging from 55 to 310 m/s for soil types in the San Francisco Bay region (Ref. 8), suggesting that the shear strength (at failure) of the unconsolidated materials in the two geographic areas is roughly the same.

Ground Motion Measurements - Ground motion from nuclear explosions at the Nevada Test Site was measured at 40 locations in Salt Lake City, 13 locations

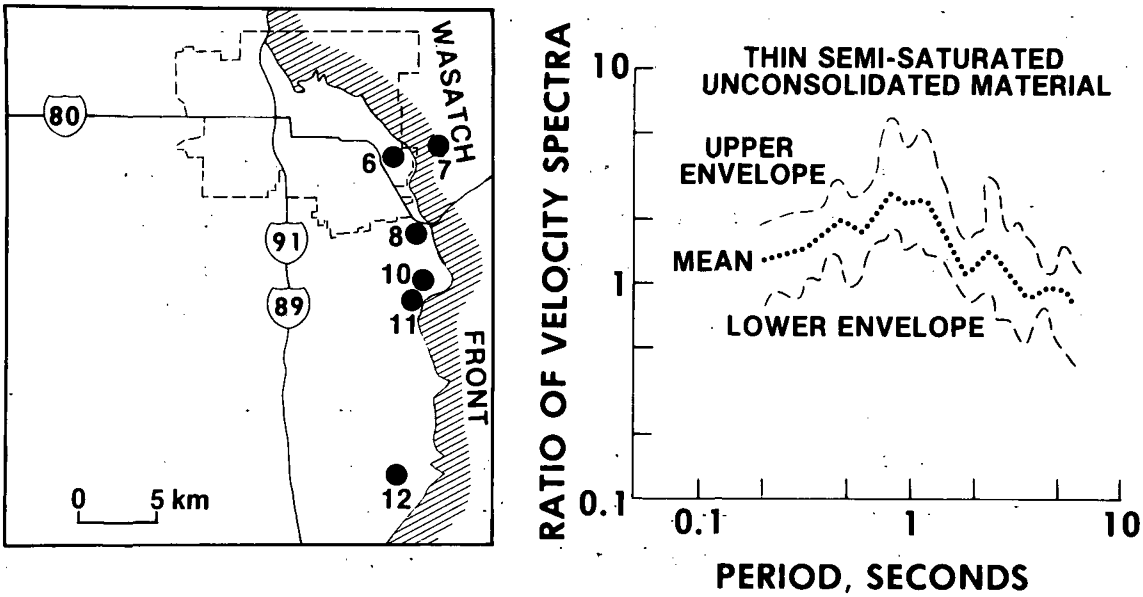

Figure 6.--Range of transfer functions showing horizontal response of sites underlain by thin (150 m or less) unconsolidated onshore deposits (sectons 6, 8, 10, 11, 12) relative to a rock site (station 7) on the Wasatch front, Salt Lake City area.

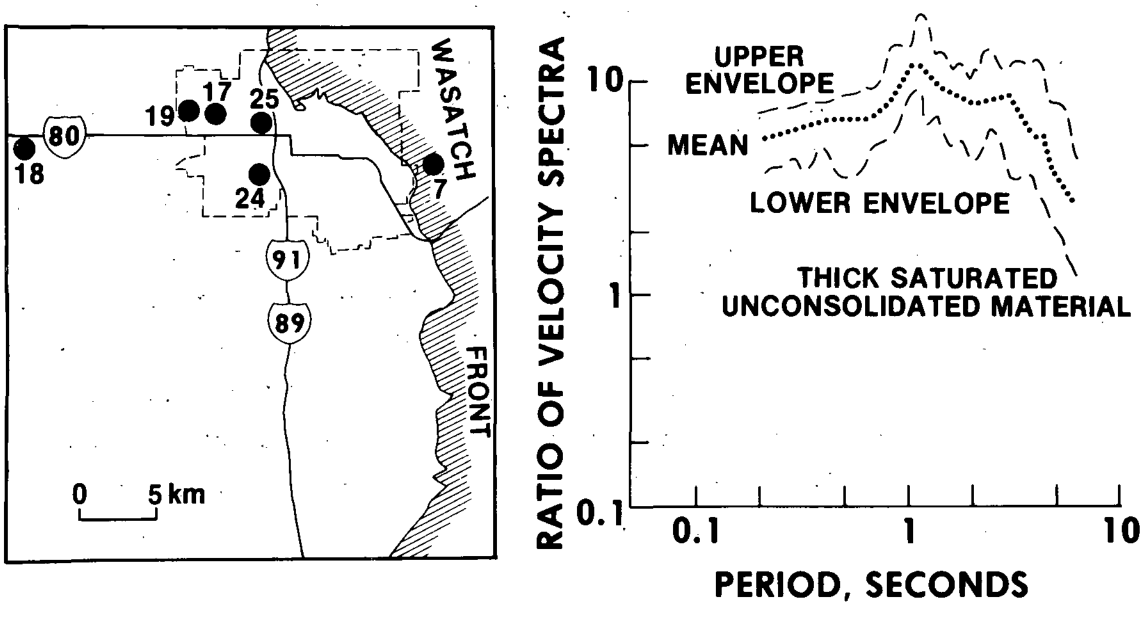

Figure 7.--Range of transfer functions showing horizontal response of sites underlain by thick (450-750 m) unconsolidated nearshore and offshore deposits (stations 17, 18, 19, 24, 25) relative to a rock site (station 7) on the Wasatch front, Salt Lake City area.

in Ogden, and 11 locations in Provo, using portable broadband velocity seismographs. These data were used to derive empirical site-transfer functions. Some of the recording sites in each city were located on the Wasatch front and underlain by rock (for example, limestone, shale, sandstone, and quartz monzonite); the others were underlain by unconsolidated materials. The recording sites satisfied the following criteria: 1) they encompassed all of the depositional environments (onshore, nearshore, and offshore), 2) they exhibited a wide range of physical properties, and 3) they were located within about 30 km of the Wasatch fault zone. Measurements at some sites were duplicated to verify the transfer functions.

Soil Transfer Functions - Soil transfer functions derived from nuclear-explosion ground-motion data recorded in Salt Lake City, Ogden, and Provo, show that the consolidated and unconsolidated materials underlying these three major cities have distinctive characteristics of ground response. A transfer function (which is defined as the average ratio of the 5-percent damped, horizontal, velocity response spectra for a pair of sites underlain by soil and rock) correlates with changes in thickness and type of unconsolidated material (Refs. 9-15). Empirical data suggest that a reliable transfer function can be determined for some soil types from either earthquake or nuclear-explosion ground-motion data in spite of differences in their ranges of peak ground acceleration and dynamic shear strain. The level of dynamic shear-strain is defined as the ratio of the peak particle velocity induced in the soil column to the shear-wave velocity of the soil. Past studies (Ref. 12) indicate that the response of some soil types remains linear under levels of strain of about 0.5 percent (i.e., the ratio of 115 cm/s and 200 m/s corresponding to the peak particle velocity observed in the 1979 Imperial Valley earthquake and the shear-wave velocity of the near-surface soil). The value of 0.5 percent is the greatest level of dynamic shear strain represented by the current strong-motion data sample. The maximum level of shear strain expected along the Wasatch front in a 50 year period would be about 0.08 percent (the ratio of 16 cm/s and 200 m/s). Ground motions corresponding to higher levels of shear strain than 0.5 percent (i.e., produced in laboratory measurements) have not been recorded.

The transfer functions for the Salt Lake City area (Figs. 6, 7) show that the site response varies markedly. The response for sites underlain by thin deposits of gravel and coarse sand is about a factor of 2, relative to a rock site on the Wasatch front, across most of the spectrum. However, the response for sites underlain by thick deposits of silt and clay is as much as a factor of 10 in some period bands.

The transfer functions for the Odgen and Provo areas show features similar to those in the Salt Lake City area. For the Provo area, the response for sites underlain by unconsolidated materials reaches a factor of about 8, in some period bands, relative to a rock site on the Wasatch front. The relative response is about 5 in the Ogden area.

THE GROUND-SHAKING HAZARD

Combining the probabilistic maps of bedrock ground motion and the empirical data on site response indicates that a significant ground-shaking hazard exists along the Wastach front (Figs. 8, 9). The most significant implication is that site amplification of as much as a factor of 10, in the period band that coincides with the natural periods of vibration of 2-7 story buildings, can occur in the Salt Lake City, Odgen, and Provo areas. For Salt Lake City, the map of site response (Fig. 8) shows that the response of sites underlain by unconsolidated materials increases as distance from the Wasatch fault zone increases and is greatest in regions of thick, fine-grained deposits of silts and clay near the center of the Jordan River Valley. The effect of water saturation on site response is not clear. The data suggest that a broad area in each city would be exposed to about the same level of ground shaking and expected to undergo extensive damage. Although the strain dependence of soils along the Wasatch front is unknown, some empirical data (Ref. 10) suggest that even in large earthquakes linear ground response would be expected beyond about 2 km from the Wasatch fault zone.

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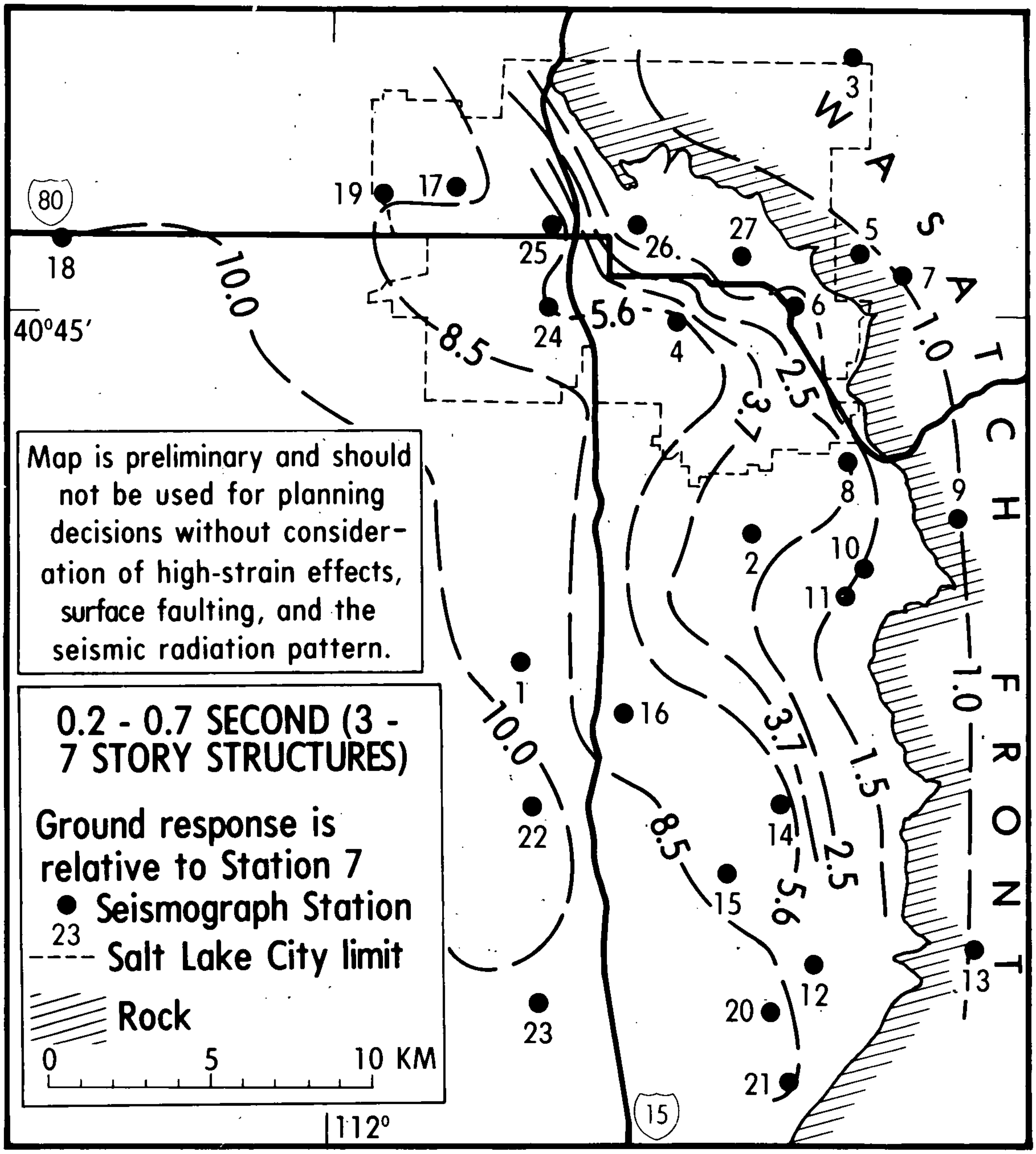

Figure 8.--Map of estimated horizontal site response for the period band 0.2-0.7 sec., Salt Lake City area. Values on contours were taken from the transfer functions. This period band corresponds to the natural period of vibration of 2-7 story buildings. Recording stations are shown by solid circles. Corporate limits of Salt Lake City are dashed.

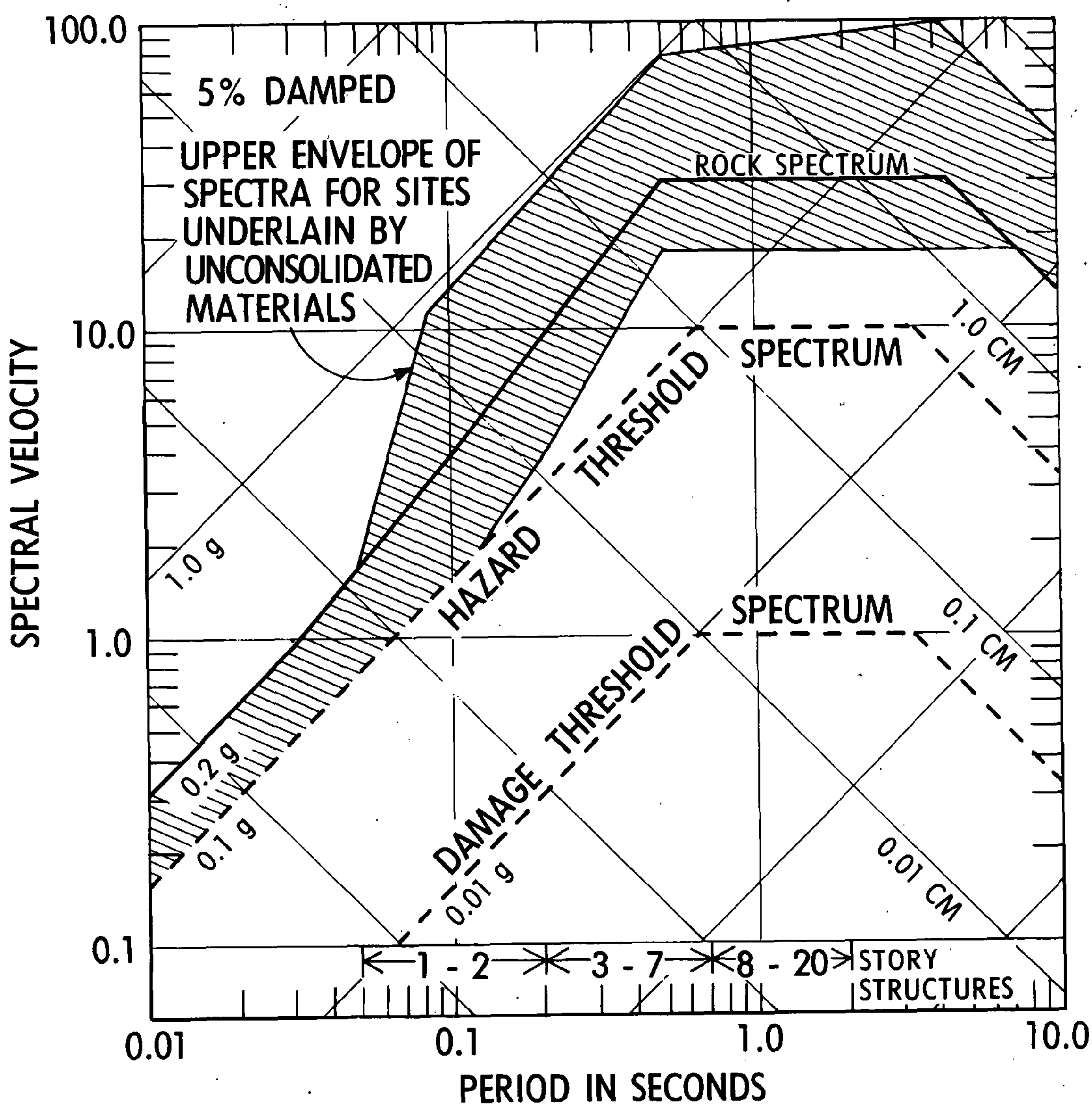

Figure 9.--Graph showing the estimated ground-shaking hazard in Salt Lake City, Ogden, and Provo based on the assumption of a magnitude 7.5 earthquake occurring on the Wasatch fault zone and producing a peak bedrock acceleration of 0.2 g. The variation shown corresponds to differences in the site response indicated by the site-transfer functions.

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WASATCH FRONT HAZARDS INFORMATION SYSTEM

by

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INTRODUCTION

If data are to be widely used by a diverse group of users, the data should be organized in a fashion that permits easy identification and access. The Information Systems component of the "Regional and Urban Earthquake Hazards Evaluation: Wasatch Front, Utah" addresses that requirement. A large but unorganized amount of data relating to the earthquake hazard along the Wasatch Front already exists in published maps, reports, and computerized data sets. As research studies continue and mature, the data base will grow. If these data are properly organized, the resultant data base would be an extremely valuable resource to a wide variety of user groups.

OBJECTIVES

The objectives of this component are: 1) to make quality data readily available to meet the needs of researchers and policymakers, 2) to create an information system that assures that new data will be available in the form most useful to meeting program objectives, 3) to devise a system whereby potential users will have easy access to data in media, scales, and formats that will be most useful to them, and 4) to provide continuing information on objectives and progress of the program element. Accomplishing these objectives will require: 1) inventorying existing data sets, 2) developing data standards for critical data sets, 3) identifying user groups and their needs, 4) developing strategies for data management and data dissemination, and 5) assuring that pertinent hazards data are available to the user community.

IMPLEMENTATION

Accomplishing the above objectives will require the concerted efforts of many individuals and institutions. We realized that establishing a kind of information "clearinghouse" early on would provide a focus for the Information Systems component and further, would expedite accomplishing the more difficult objectives. One initial manifestation of the clearinghouse concept is the Information Directory, an informally-produced and regularly-updated guide to all kinds of resources: personnel, publications, computers and other tools, data bases, and software. The Information Directory is intended, in part, to be the repository of lists of existing data sets, computer programs, base materials, and project personnel. The Information Directory is also intended to provide access to key contacts, people who can answer questions easily and fast, and access to procedures that can provide a needed item (such as a base map) rapidly.

Another manifestation of the clearinghouse concept is the Newsletter that will be prepared and published quarterly by the USGS and UGMS. The Newsletter will contain ephemeral and newsy items of interest to participants and associates in the form of brief progress reports of scientific studies, lists of new publications, an event calendar listing technical meetings and conferences with abstract due dates, short articles written by participants, and descriptions of new projects. The

Newsletter and Information Directory are intended to be complementary in their scope of information dissemination.

The inventory of existing resources has identified two areas of particular interest. For example, the UGMS supports a computerized bibliography of geotechnical literature about Utah that potentially could be extremely valuable for literature searches. The bibliography is, however, not as comprehensive or complete in the geophysical literature as we believe desirable for the Urban Hazards Evaluation. The UGMS has targeted the upgrade of the bibliography as a priority task this year. Another example is the need for a single, accepted earthquake catalog of Utah. The absence of a standard catalog perpetuates confusion and the appearance of disagreement when no substantial disagreement may actually exist. We believe a committee of experts should be convened to resolve the conflicts among the existing Utah earthquake catalogs, and the resultant catalog and an accompanying map published.

Progress has been made in developing data management and dissemination strategies. Procedures for accessing bibliographies of Utah geology and Wasatch Front base materials have been incorporated into the Information Directory. An upgrade of the UGMS computer system to increase its capability for data communications and advanced data processing is underway. Following completion of the upgrade, communications tests and other experiments are planned to expedite exchange of data sets and software between computer centers.

A PROSPECTIVE ASSESSMENT FOR RECOVERY FOLLOWING A MAJOR, DAMAGING UTAH EARTHQUAKE

by

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INTRODUCTION

The rational preparation for and recovery from a future earthquake in Utah will depend upon developing a proper perspective on the nature and extent of its impacts. This paper explores a sequence of events that could happen following a great earthquake. The purpose of this paper is to present a hypothetical future situation, not to represent that which is specifically expected to occur. While the author has attempted to be realistic in forming the estimate of future events, there is no representation that the events portrayed in this paper are expected. Indeed many potential conditions, such as failure of a major dam or occurrence of a extended, urban fire storm, have not been presumed to occur.

The premise of this paper is that a massive earthquake has occurred with an epicenter within Salt Lake City that has caused damage all along the urbanized Wasatch Front--affecting about 85% of the State's population. Shortly after the event the Acting Governor (the Governor was seriously injured and taken to an out-of state hospital for treatment and is not expected to return for some time) appointed an Earthquake Commission to advise him on how to manage the State's emergency policies and programs. It was appointed when the normal emergency management process was widely perceived as having broken down. The 10 Commissioners represent diverse interests within the State. They were appointed with the concurrence of the leaders of each of the political parties in a bipartisan commitment to restore the State's social and economic vitality.

The events given in this paper are presumed to have taken place in preparation for and during a Commission hearing. The participants at the Workshop were split up into three groups and asked to role-play as if they were members of a particular constituency: the Ski Development Council, the Business Round Table, and the State Republican Legislative Leadership. The role-playing exercise proceeded through the following steps:

1. A background briefing on the event by Commission staff followed by questions from the participants;

2. Individual group meetings by the constituency groups to discuss the problems posed to them by the earthquake and the recovery process;

3. Testimony before the Commission presenting the groups needs, views and interests; and,

4. Presentation by the Commission of its initial recommendations.

The Commissioners asked questions during the testimony offered by the interest groups. The highly interactive aspects of these presentations can not be captured in a written paper.

UTAH EARTHQUAKE COMMISSION

The Governor's original charge to the Commission was to:

1. Monitor State and Federal emergency programs;
2. Advise on areas where there are problems or inequities;
3. Recommend priority State actions to improve emergency response; and,
4. Act as the people's ombudsman.

Now that the immediate emergency response problems are somewhat under control, the Governor has discovered that there has been little thinking on how to proceed with the recovery. He also has discovered that the political temperature is heating up as various interests sense their possibility for gain or loss. To protect himself politically, develop a constituency for program recommendations and allow public access to the process of recovery policy making, he has expanded the charge to the Commission and directed it to:

5. Recommend State programs, priorities and actions to assure rapid, economic, and equitable reconstruction and recovery.

The Commission's preliminary report is to be ready within two weeks; their final report and recommendations to be presented within 10 weeks.

Immediately upon receipt of the Governor's additional instructions the Commission started the process of information collection by calling public hearings. Yesterday the Commission received detailed briefings on the physical event and testimony from a number of technical experts, from both Utah and other States, who have examined recovery processes after other earthquakes and related large-scale natural disasters and conducted research on recovery processes. Today they will hear from any organization desiring to present its views. The organizations making presentations this morning are listed below; others are scheduled for the afternoon and the following day (Table 1).

The hearing was called on very short notice, not allowing time for the preparation of written position papers. The rules of the hearing were very simple; each group's representatives were given 10 minutes to express their position. The Commissioners questioned each group on their testimony and on positions taken by other groups that had appeared. To assure that each organization's interests were well presented it was recommended that consideration be given to the following items for inclusion in their presentations:

- The special problems that your constituency faces, particularly those that are distinct from other public groups, and deserve allocation of public resources or those where you are hurt by actions that help someone else;

- Specific policies or programs you advocate to benefit your interests; and/or,

- The criteria the Commission should use to evaluate its overall recommendations to assure proper allocation of scarce resources.

Table 1 - Organizations testifying before the Utah Earthquake Commission on January 17th.

Citizens Coalition of Provo
State Emergency Response Director
Federal Coordinating Officer
Association of County Executives
Parent Teachers Association of Utah
Chairman, Nephi City Council
Publisher, Desert News
Uintah Tribal Council
WXYX-TV News Director
The National Association for the Advancement of Colored People
The Utah Grange
State AFL-CIO, Building Trades Council
Mayor, Salt Lake City
Wasatch Ski and Tourist Development League
Business Round Table of Utah
The Minority Caucus for Equality
Chairman, State Committee of the Governor's political party
Chairman, State Committee of the opposition political party
The Chairman, Peace and Freedom Party
The Chairwoman, Libertarian Party
Sevier County Cattlemen's Association

BACKGROUND BRIEFING ON THE EVENT

On Tuesday, January 3 at 9:15a.m., 14 days ago, a massive earthquake occurred in Utah. It is reported to have had a magnitude (M_s) of approximately 7.5 by the National Earthquake Information Service in Colorado. The earthquake was centered within Salt Lake City. A preliminary analysis of the few strong ground motion recordings taken in the area, coupled with macroseismic observations, indicate that strong shaking lasted over 30 seconds, with a maximum effective acceleration of over 0.7 g observed near the fault. There have been few aftershocks, with none resulting in substantial damage.

Most of the major damage is in Utah. Damage has occurred in Idaho, Wyoming and Nevada, although it is not nearly as extensive or concentrated as observed in Utah. The press characterizes this earthquake as the most severe natural disaster to have occurred in the United States during the life of the Republic. There is considerable consternation in political circles because the great earthquake everyone has expected in California happened here. The public, while generally aware of its risk, had done very little to protect themselves through making most facilities earthquake resistant, not with standing the efforts of the some public emergency response agencies to develop and publicize preparedness plans. Thus for all intents and purposes the community was unprepared.

The nature of the resultant damage can be characterized by four major observations. First, damage to unreinforced brick structures, which have inherently little earthquake resistance, has been extensive. Second, there have been large scale landslides on a scale not seen before in the United States. Third, the damage to lifelines is unprecedented. Lifelines are the electrical, water, sewer, communications and transportation systems that tie a community together and provide the services on which we all depend. Fourth, there has been extensive damage to water supply structures, e.g. distribution systems, and flood control works, e.g. levees, debris basins, agricultural tanks and ponds and dams.

The Earthquake Engineering Research Institute (EERI) reconnaissance team has made an estimate for the Federal Emergency Management Agency (FEMA) of the extent of damage. Figure 1 shows a first, highly preliminary, distribution of damage throughout the region for the January 3rd event. Damage intensities are expressed in the Modified Mercalli intensities (MMI) intensity scale. Roughly speaking the MMI can be characterized as given in Table 2. It has been speculated by some seismologists that there may be aftershocks, or more properly additional earthquakes, on other segments of the Wasatch Fault in the

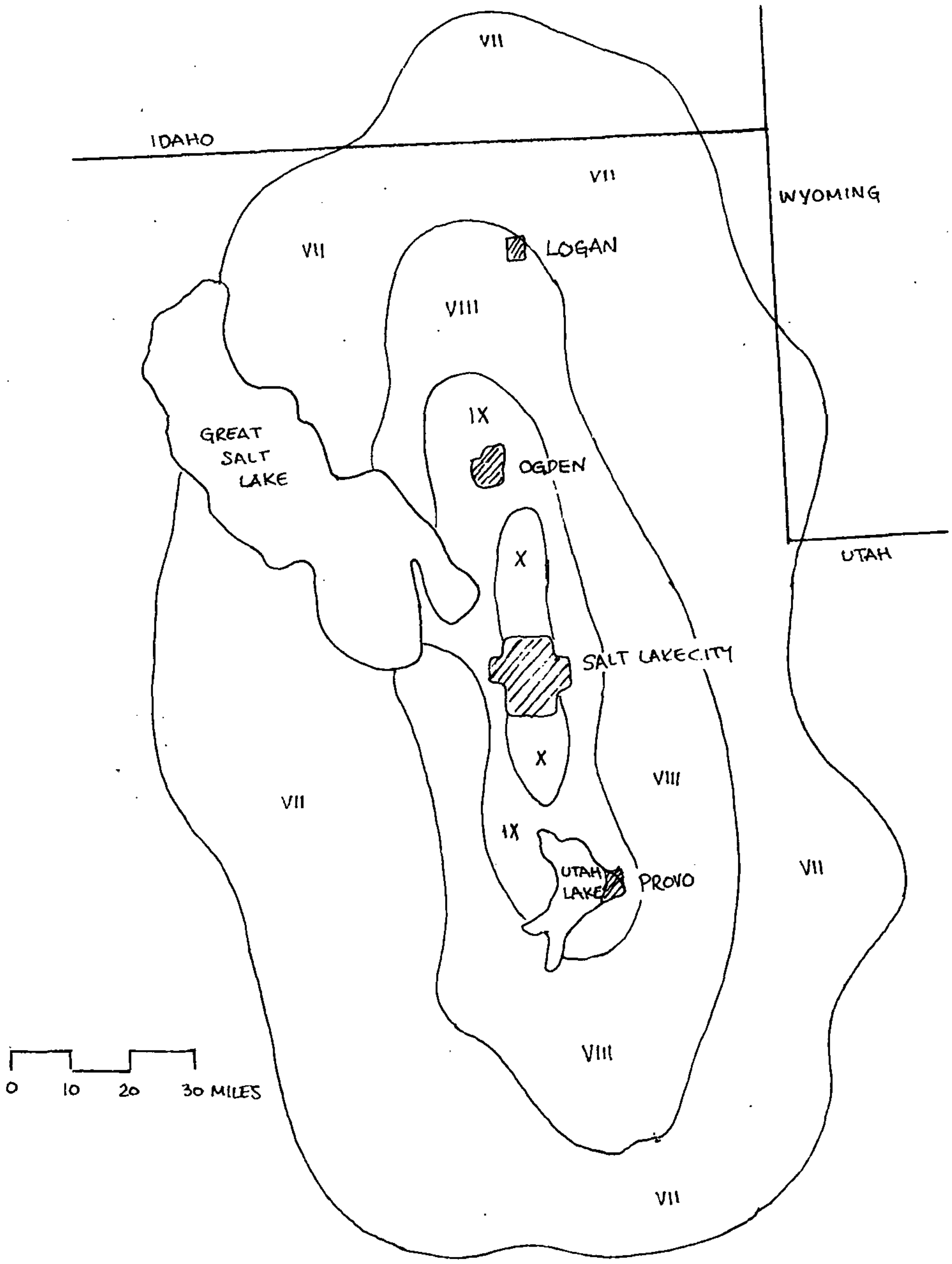

Figure 1 - Preliminary isoseismals for the January 3rd earthquake. See Table 2 for definition of quantities.

near (days to years) future that could be more severe than the recent event since so many structures are already in a damaged state and thus would be even more vulnerable than before.

Preliminary assessments of the extent of life loss, injury damage and the extent of housing loss have been assembled by the Utah Comprehensive Emergency Management Agency:

By each of these measures, this is the largest peace-time emergency natural disaster ever recorded in the United States. Although these figures are huge, they are considerably less than the first widely reported estimates of $30 billion in losses and 25,000 dead that were widely quoted in the first week.

The President has thus far declared Disasters in parts of Utah, Nevada, Idaho and Wyoming. The resources of the Federal Emergency Management Agency (FEMA), the Utah Comprehensive Emergency (CEMA) Management Agency and other State and local emergency response organizations, Church groups, principally the LDS, and supporting public relief organizations while excellent are being severely strained. Without the extensive use of military personnel, it is doubtful that any organized response would have been possible. The acting Governor has not called up the National Guard. Damage is so widespread that calling them up would have caused special hardship to their families. Selected companies from areas where damage has been low have formed and are currently assigned to debris removal and other public services.

Special problems not observed in other major earthquake and natural hazard occurrences have been caused by the earthquakes occurrence at the beginning of what has started out to be a severe winter. Snow cover is extensive and continued inclement weather has severely hampered the recovery effort. Extensive damage to natural gas and electrical supply and distribution systems has made many otherwise safe homes uninhabitable because of lack of heat.

Damage has been particularly heavy to commercial and governmental buildings, transportation and utility systems and flood control works. Approximately

Table 2 - The Modified Mercalli Intensity Scale (abstracted).

MMI	Description
XII	Damage completed
XI	Few if any masonry structures remain standing. Broad fissures in the ground.
X	Some well-built wooden structures damaged; most masonry and frame structures destroyed along with their foundations; ground badly cracked. Considerable landslides along river banks and steep slopes.
IX	Considerable damage in specially designed structures; well-designed frame structures thrown out of plumb. Buildings thrown off of their foundations. Underground pipes broken.
VIII	Damage slight to specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Canel walls thrown out of frame structures. Fallen chimneys, factory stacks, columns, monuments and walls. Heavy furniture overturned.
VII	Everyone runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable to poorly built or badly designed structures.
VI	Felt by all; many frightened and run outdoors. Damage slight.
V	Felt by nearly everyone; many awakened. Unstable objects fall over; some plaster cracking.

- Approximately 3,100 deaths thus far;
- Over 10,000 injuries that required hospitalization, many of whom have been taken to out of State hospitals;
- Direct damage of the order of $10 billion; and,
- Loss of over 35,100 housing units.

two-thirds of the life loss and injury occurred within the MMI IX and X areas, while most of the housing loss is within the MMl VII and higher area. A preliminary assessment of impacts indicates:

- Interstate highways are open to the north and south, but closed to the west and east. Most primary and secondary roads into the mountains from the valley are impassable within the MMI VIII area due to the extensive rock slides in the mountains.

- There were no major dam failures, although both the Dear Creek Reservoir and Pine View Dam were damaged and could pose safety problems in moderate to major aftershocks, should they occur. There has been damage to at least 200 earthen dams, almost exclusively agricultural tanks and minor water supply and flood control works and many miles of levees have been destroyed. Noting the urban flooding problems of 1983 and 1984, this damage could allow a secondary disaster when spring run-off is not controlled and causes extensive flooding.

- Over 200 chemical spills have been reported; most were from storage facilities for agricultural chemicals, but the most serious were from chemical plants and petroleum refineries. The extent of surface and ground water contamination and resultant health hazards is unclear.

- Railroad transportation is open to the north and south, service to the west has been partially restored and partial service to the east is expected within the month.

- Commercial airports within the region are closed to commercial traffic because of extensive runway failures, power outages and control tower damage. The FAA has restricted flights in the region from Logan to Provo and has restricted access to air space in the region.

- There is great confusion and conflicting information on the status of military installations in the area and the extent to which hazardous conditions may exist that could be of public concern. Many of the reports are rumors coming from outside the impacted area, but none the less they have triggered concern in the community. The cloak of national security for selected situations, no matter how well intended and appropriate, seems to be exacerbating the situation.

- Water systems in the region are heavily damaged. Public authorities have recommended against use of municipally supplied water within the MMI IX region due to extensive damage to water storage, treatment and distribution systems. All users of surface water from Logan to Provo have been warned of potential contamination from large agricultural chemical spills. Unfortunately, boiling, the usual suggestion for questionably safe water is not very effective in reducing organic chemical contamination to acceptable risk levels.

- Interstate natural gas and petroleum pipelines have been closed until they can be repaired and inspected. Storage facilities have been seriously damaged and will not be easily repaired. Natural gas pipelines within MMI VII areas were all closed immediately after the earthquake for inspection; numerous breaks have been discovered and are in the process of being repaired. Local natural gas distribution within MMI VIII areas has been curtailed in many areas. Major local service disruption is expected to persist for the next month.

- Telephone service within the MMI IX region is approximately 40% of normal service; many areas are served only by short wave radios. Amateur and CB radio operators have formed a fairly effective communications network. Rural service is variable.

- Electricity production capacity in the region is now at 30% of the pre-earthquake level within the MMI VIII area. It is estimated that 50% capacity will be restored within the year; full restoration is at least a year away. Interstate high voltage lines have been restored. The transformers stepping down the voltage to service areas were damaged and there is no backup equipment. It will be several months before new transformers can be manufactured.

- Electrical service is available to 60% of the residential areas within MMI VIII and to 30% of business areas. Traffic control and street lights are generally not functioning and are a low priority for repair and energy allocation.

- Numerous schools suffered substantial damage with much associated life loss.

- Damage to mobile homes was particular heavy compared to other construction types. They were knocked off of their leveling supports since they were seldom braced for lateral forces.

- Approximately 50% of the pre-earthquake hospital beds available within the State are available.

- The occurrence of large fires was moderated by the unusually heavy snowfall before and after the earthquake.

- Flooding on the eastern margin of the Great Salt Lake is extensive. This is associated with the down throw of the west side of the fault. Commercial and manufacturing areas are the most effected.

- The impacts on the financial community has been unprecedented. Among the most important are:

  o The Salt Lake Federal Reserve Bank Branch computers have been down since the event. Most major banks Data Processing facilities similarly have been damaged and have effected bank records and operations. The loss of data communications among Utah banks has severly constrained agency's ability to perform their commercial and regulatory functions. Standard and Poors Corp. has suspended the ratings of all Utah municipal, special district, utility and selected business bonds.

- These bonds are widely held. Suspension has impaired their value, disrupted the market in tax exempt bonds and thrown into question the viability of several retirement funds.

- The financial condition of insurance companies within the State is uncertain. While there was little earthquake insurance written in the region, expected payments for medical costs, workman's compensation, business interruption, automobile damage, and professional liability coverage are expected to be very large. The theory is already being advanced that earthquake damage should be covered by normal commercial and household insurance since the damage resulted from inadequate design and construction practices, not the earthquake itself. If these negligent actions had not occurred, the theory is that the damage would not have occurred. Thus the source of damage is contended to be negligence and thus covered under an all-risk policy. While this legal theory may sound far-fetched, it has been successfully argued in California and upheld under appeal to the State Supreme Court.

- There are widespread shortages of construction materials, equipment and skilled personnel. Costs for some materials have been bid up out of sight--particularly plywood. A large influx of potential construction workers from other areas is expected; although, there is little use for them now except for debris removal and clean up.

- Cleanup and recovery is well underway at the individual and family level where they do not need externally supplied resources.

Individual and family response in the impacted area has been outstanding. Generally the clean-up and recovery processes at the individual family level are well underway. The outpouring of assistance has been overwhelming. There has been a large inflow of people from unaffected areas offering help. Disrupted roadways have impeded their entry to many areas. Social scientists refer to this as "convergence". Initially, public response organizations were overwhelmed with these offers of aid. The convergence of people at sites of extreme need far exceeded the capacity for utilization in those cases in which they could get there; they initially impeded efficient response. This is now under control, in part, due to the imposition of restricted access by the highway patrol in the most severly affected areas.

NATIONAL POLITICAL SITUATION

The political situation 14 days after the earthquake can be encapsulate in the following observations:

- Many Representatives and Senators are demanding regular, personal briefings on the situation. Three Congressional committees have already scheduled hearings; and more are in the offing. There is a regular military shuttle being run to show Congressmen and high Administration officials the damaged area. The President and Vice-President have visited the area.

- There are widespread reports that spilled toxic materials are just sitting there with no efforts underway to clean them up.

- Over 10,000 people are still housed in temporary shelters, and there is no apparent plan on how or when these people will be placed in more permanent housing. The blockage of many roadways is preventing importation of trailers; they are being set up far from those who have need for them. Unfortunately, most trailers used and stored in the area were not properly supported and were damaged beyond use by the earthquake.

- There is confusion on whether areas down stream of the Pine View Dam and Dear Creek Reservoir should be evacuated. There are reports that damage was so extensive that a moderate earthquake could cause their failure. Actions thus far by emergency response officials range from attempted evacuation to assurances that everything is fine since the water level is being reduced.

- Winter conditions and the shortage of natural gas and electricity for home heating are causing major family and community problems.

- Priorities among Federal agencies are unclear; staff and resources are not consistently assigned. A perfunctory review indicated that even with the consolidation of emergency functions under FEMA several years ago there are still many separate program responses under way, apparently with different policy objectives, both with other agencies and with community aspirations.

- The constitutional prohibition of State debt is expected to bring the State's government to a halt. Tax revenues for the year from corporations and individuals are expected to be minimal since almost every tax payer in the State will have casualty losses exceeding income.

- Liability of public officials for negligent actions is open to question. It has been noted that there were repeated, credible notices of the nature and extent of earthquake hazards and risk, to public structures (schools, libraries and other public buildings), to building code regulated buildings, and to regulated lifelines and commercial activities. Major hazards were identified in State reports and reports by reputable scientists and engineers, but were not acted upon, either by recognition or program initiative.

- A caucus of Senators and Congressmen are publicly calling for the President to exert direct leadership.

- Even though the earthquake occurred only 14 days ago, legislation providing additional funds to the depleted Federal Disaster Response Fund has been enacted and signed into law. In addition, the following bills have been introduced or their sponsor s have indicated that they are likely to be introduced in the next few days:

  o To remove the requirement of 25% cost sharing by the State as a condition for Federal assistance.

  o Reduce the SBA interest rate for reconstruction loans to 1% for a term of 50 years and allow the replacement of current financing of damaged businesses with such loans beyond the limit set by the amount of damage incurred.

- Increase the amount of individual family grants to $10,000 from the current $5,000 limit and relax the conditions for qualification.

- Repeal the Davis-Bacon Act, which establishes prevailing construction wage rates usually tied to union shops, so that artificially high wages need not be paid for clean-up and reconstruction.

- Eliminate minority contracting requirements for Federal procurement of goods and services.

- Increase the minority contracting (including Native Americans) set aside to 20%.

- Waive payment of Medicare premiums for everyone in the impacted areas.

- Provide Federal guarantees, after the fact, for the bonds of severely affected State and local governments and selected public service institutions.

- Provide Federal reinsurance for private firms, ex post facto.

- Provide supplemental unemployment coverage, aid to dependent children, and welfare benefits.

This list is long and growing longer. There appears to be little constituency for restraint, and certainly none yet voiced at the national level.

STATE POLITICAL SITUATION

The initial altruistic reaction of the public is now beginning to crumble. Initially the priorities for action were clear to everyone, but now that the emergency period is essentially over, individuals are beginning to assess how the specific interests can be advanced or hurt by the actions taken by government. The Acting Governor is being assaulted by all types of requests for preferential treatment because of the special public interest served by allocating scarce resources to a specific purpose.

Politically the Governor is in a no-win situation. Intrastate tensions are on the rise as areas with little damage see no end to the sole allocation of resources to the damaged area and the diversion of day to day resources they employ for the foreseeable future outside their communities. There appears to be little constituency for constraint.

As recovery is beginning, there are no models, plans or precedents on which the State can depend for the formulation of policies, the establishment of criteria, or the estimation of needs. Bad examples from international earthquakes abound, but it is not clear how they apply in Utah.

The Acting Governor has extended the charge of the Earthquake Commission to assess recovery needs, to sift through all the competing demands and to recommend the basis for an equitable, efficient and economic recovery program. In this way he hopes to insulate government for a period from intense political pressures and allow for the formulation of a rational recovery program. There is of course the problem of the influence of the Federal government, as it seeks to serve political and social interest of the nation, which in some cases are at odds with the desires of the community. The Utah delegation has been very supportive but it is not clear how effective and lasting their protective actions will be. The President's assistance has been sought, but no assurances have been obtained other than a commitment to discuss program objectives. The request of the Acting Governor to have veto power over specific policy and programmatic actions is still under discussion as is the request that all recovery funds and assistance be under the direction of the Governor and the Legislature, not Federal agency personnel.

The opposition party has identified the opportunity to take control of the State's elective positions in the coming election and is expected to take every opportunity to highlight the errors, omissions, and actions of the Governor and legislators as soon as the emergency period is clearly over.

Some are already actively campaigning and are using the press quite effectively.

COMMUNICATIONS PROBLEMS

There is a public information nightmare. The flow of information and miss-information to the public is staggering and continuous. The electronic media preempted there regularly scheduled programing and presented continuous, live broadcasts for the first few days. Most of these reports have been pictures of the damage and interviews with either eye witnesses or "experts" from undamaged areas. These "experts" have included: some with knowledge or experience directly related to this earthquake; some who have special interests they are trying to advance using this earthquake as a target of opportunity; and, some with no knowledge of the area but vigorous opinions. "Factual" data from the damaged area is incomplete and often contradictory. The range of contradictory reports covers the need for medical transportation, the imminent collapse of dams, the contamination of water supplies, the extent of chemicals spills, fire occurrence, public health threats, building safety, freezing and hungry children, and the imminence of large aftershocks, to name but a few.

The disaster intelligence functions of the FEMA and other emergency response agencies have been overwhelmed with the problem of trying to verify rumors and respond to the immediate demands of the press, who are insisting on their right to access to the damaged area even though they are interfering with emergency functions. Among the key problems leading to this condition are:

- Several key emergency response officials were killed or injured; Several counties have no organized response capability;

- Radio frequencies used by local fire, police and emergency response organizations are different among themselves and among adjacent jurisdictions;

- Unconfirmed reports are receiving wide spread media coverage; and,

- Reports are focused on individual observations.

As the social scientists are quick to point out, the conditions for rumoring are ideal: a) there are conflicting official reports; b) formal information channels are disrupted; c) there are perceived harmful effects; and, d) informal communications are heightened.

Rumoring is rampant.

A major innovation that seems to now be controlling external rumors spread by the electronic media was the establishment of rumor control centers in Denver and San Francisco.

SELECTED PRESENTATIONS AT THE HEARING

Business Round Table

The Business Round Table is made up of the chief executives of large and small firms located within the State. As the recovery process is now beginning, it is clear that there is no overall concept for fostering recovery either by the Federal government or the State. What guidance there is seems to hold that the restoration of business and commerce is of the lowest priority, especially when compared to assistance to householders. While there was no objection by the business community to this during the life saving phase, now that recovery is underway the need is great to provide assistance that allows the economy to be restored. The business community does not want government to assume a direct role of its activities--but it does want the government to allocate some of its effort to the restoration of utilities, transportation and the other intermediary functions that allow the business and commercial sectors to function. The case of one business woman from Salt Lake City may be instructive in understanding the problems faced by business.

Case of a Stationary and Business Supply Store: We have run a small business downtown for three generation. Our building fell down during the earthquake. We were never informed that the building was dangerous by the city or State, although the press now reports that the city was informed of the danger posed by our type of building years ago. My building is totally gone; this means that I have no inventory, but I still owe money for it. I have property, but no means to earn the money to pay taxes currently due. I and many other businesses in the area would like to see a suspension of sales and property taxes for the coming year or longer. When I go back to my property to rebuild I will have to incure major expenses. Many may find that they are unwilling to do so unless they are given some financial help and incentive. I don't want the State to help marginal business to be re-established, but to enhance the likelihood that healthy ones like mine do not use this as an excuse to walk away from the community. The chains, with their superior political position and out of State based economic power could spell the end to me and my employees livelihood. Mortgage foreclosures could start this process. We need relief. My business and many of my colleagues have been here for a long time and are the backbone of the community. Unemployment is another big problem. Of my seven employees, one was killed, one severely injured, and the rest are now unemployed and need assistance while I attempt to restart my business. Nothing seems to be happening downtown; when can I return; where can I set up my business since I'm not allowed to sell out of my home; what am I going to do; when will I be informed of what to expect. I attended several meetings of business people prior to this hearing and we agree that we need representation on the Governor's Commission. Thre are essentially no business interests represented on the Commission. Since recovery is first and foremost a business problem, we believe that we should have the majority of its members--including individuals sensitive to the special problems of small business. We are concerned that while business is at the bottom of the list, small business is at the very bottom of the list. Representation, if limited to a few, is likely to go to big business that have out of State offices, markets, and the like, and we feel that they can take care of themselves. The small business community is large and varied and should have several representatives on the Commission.

The second small businessman to testify noted that several meetings had been held in his area sponsored by various members of the business community. They have not been able to agree at all on what should be done. The business community is diverse with widely different interests. Some can get back into business without any help, while others will need lots of help and yet others will have to change businesses. They were able to agree that establishing some priorities was necessary and recommended that some other organization that is outside the immediate interests put together an inventory of the status of individual businesses in the impacted are and then develop a prioritized list of which businesses are most important to get back on their feet in a hurry, which ones can be put back with relatively little effort or expense, and which ones should be asked to wait for assistance. The only organization that was seriously considered that could perform this function is the LDS Church. They felt that they will give the most neutral assessment and would not be subject to the same types of problems as would an advocacy organization such as the Chamber of Commerce. The fact that these groups have been unable to agree on criteria for allocations of priorities for reconstruction indicates how difficult it is to establish them; they have faith as a group, including members and nonmembers, that the Church can and will do this. Concern that the Church would favor its own business interests in establishing priorities is not wide. Its objectivity and fairness are not questioned and the group is prepared to follow its recommendations. If Utah were in a vacuum, they would prefer that government did nothing and let them solve their own problems. But there is wide spread sentiment that out of State factors and financial interests could close down State businesses unless they receive some protection.

Damage to the banking system has been substantial and is a matter of great importance and urgency to the business community. Most banks are highly dependent upon computer systems for every aspect of their operation. Data processing facilities were particularly hard hit. Such facilities are particularly vulnerable to earthquake destruction and disruption unless very carefully designed. The Federal Reserve Systems inter-bank service is partially back in service; however, there are major problems in restoring individual banks systems. The financial condition of many banks is in question and the ability of these banks to provide the financial resources and services necessary for the restoration of the commercial sector are severly lacking.

Electrical power, communications, transportation and other utilities are the life blood of business. Currently, the first priority for allocation of these services is to households. Without a change, the business sector could be crippled for some time to come. It is of the upmost importance that industry be given priority access to these important life lines.

The distribution system for raw materials, intermediary products, and finished goods has been severly disrupted. Rail, river, and highway transportation is in poor condition and many routes are impassable. Without rapid restoration of a means to move products, the commercial and manufacturing sectors will be crippled.

<u>Business Round Table Recommendations</u>

Business build Utah and business can rebuild Utah--If it is given the chance. Business needs priority for the allocation of fuel, transportation, electricity and building materials now. But most of all it needs the latitude to act efficiently in an environment that is predictable, constant and unbiased to competing interests,

Recovery of Utah businesses must begin now and receive the vigorous support of the public and government, whether local, State or Federal. If we do not get on with the process, then out of State interests will come in and wipe us out. The impact on personal income and the tax base of the State will be devastating, more so than the earthquake itself. Our ability to control our own destiny will be effected for a number of years, possibly generations. We need to rebuild as rapidly as possible and practical. We are worried that we could become a consumer State and thus a "third world, poor region".

Restoration of the employment base of the community should be the top priority after maintenance of the family. As decisions are made over the next few months it must be recognized that business through provision of employment, serves individual and social needs just vitally as does housing. We are concerned that our human capital will leave unless our skilled people can find meaningful employment that satisfies their's and their family's needs. People are the most important asset for the future.

The viability of the State of Utah is intricately tied to the functioning capability of its industrial and business community. Between them, the manufactures, processors and retail distributors of the State have been a source of 60% of all the wages earned in Utah. Unless business can be back in operation within 6 months, competition from other areas will take over our markets and the entire economy of the State will collapse. With this in mind, the Business Round Table asserts its need for representation on the Governor's Commission and makes the following recommendations to this body.

1. Commission Membership--The addition of ten members to the Commission is necessary to adequately represent the interests of Utah businesses.

2. Recovery Priorities--The LDS Church be asked to assess the current status of business throughout the State, both in impacted and unimpacted, develop priorities from their recovery needs, and recommend actions that will hasten the recovery of the economy.

3. Banking--Highest priority must be given to the recovery of the banking system. We recommend that the Governor request Federal assistance and relaxation of stringent interstate banking restrictions so that the capital and financing necessary for all aspects of recovery are available both to business and to the public. Allocation of emergency generators and available electricity to restore data processing facilities for banking is critical and of the highest priority.

4. Electrical Power--The shortage of electrical power is a hardship for the entire State. For industry, however, it is a critical element--factories cannot function without it. We therefore recommend that electricity be brought in from outlying, less-effected areas, that private agencies be permitted to buy electricity from the Bonneville Power Administration and other Federal power authorities at cost, insofar as available, and that business and industry be given priority in allocation.

5. Communications--Of the several State emergency communications networks now operating, we recommend that one be allocated to business and industry as they work to rebuild, repair facilities, reestablish

supply relationships among manufactures and distributors, and restore production.

6. Transportation--The Governor take a leadership role in directing the restoration of transportation routes important to commerce. Only the Governor has the authority to organize the available equipment and personnel, both military and private, throughout the State so that repairs proceed in a logical and efficient manner.

7. Labor-Management Cooperation--Now is the time for labor and management to recognize that they are each vital components in the industrial equation. We urge that labor and management reopen, in good faith, their existing contracts and work rules to assure that the joint objective that each share in continuation of businesses is achieved. In many cases this may require wage and work rule concessions. We urge that these be examined carefully and expeditiously outside the usual confrontation environment. We urge that business assure its employees that they will benefit from concessions, if they are necessary, in the future when the firm returns to a healthy, competitive State.

8. Funding for Reconstruction--The capital needs of business far exceed that available from within the businesses community. Losses far exceeds the amount of insurance coverage. Without access to additional capital, many businesses will be unable to reopen, severely crippling the economy of the State. The following measures are recommended:

   a. A national, State guaranteed industrial bond issue to provide capital for business restoration;

   b. A moratorium under the State's Uniform Commercial Code on business debts for a period of one year;

c. A moratorium on State taxes for business which have suffered greater than 25% loss or damage for a period of 5 years, or until recovery of the amount of uncompensated damage; and

d. That the Governor recommend a 35% cut in Federal corporate taxes for impacted businesses until full recovery is achieved.

Through these immediate actions, the disastrous effects of the recent earthquake can be moderated. Rebuilding of the State's economy can proceed taking advantage of improved machinery, processes and techniques as well as re-structuring to make better use of the natural and people resources of the Great State of Utah. These actions are recommended as a package to assure that the State has the opportunity to prosper in the future and maintains the values that have made our State great.

Ski Development Council

The ski industry is one of the largest industry in the State. It is a business not recreation. It not only is a major employer, but also pays substantial taxes and, through the spending skiers, supports many industries, restaurants, and motels throughout the State.

Three major problems have been identified. The first is rumor control. This industry is very susceptible to bad press. It relies on out of State information dissemination and word of mouth for promotion. We need to let the public know that we are still in business, indeed we were not effected in any major way and that aftershocks pose no essential risk. There are no lines and excellent powder.

Our second major problem is transportation. The State's decision that the reopening of roadways to ski resort areas is of lowest priority leaves the industry isolated. While some slides on public roads have been cleared with our equipment, we can not clear the large rock slides blocking most access roadways. In addition emergency fuel supplies are nearly gone and the industry is not high enough on the list to receive additional supplies. The FAA restriction of all air traffic in the area has prevented us from flying in skiers willing to pay the added costs of helicopter service from airports still capable of commercial operation. They indicate that such private, non-emergency use of the airways is still some time off - probably after the powder has melted. This situation is doubly detrimental: first, it deprives the industry of revenues that could be earned and thus provide employment for the many who depend upon this industry for their livelihood. Second, it allows our competitors in California, Colorado and Idaho to seize our market share. It may be difficult for us to recapture skier loyalty. Once lost, these skiers may not return next season.

Our third major problem is that our market presence has been damaged by the out of State electronic press who have given the impression that Utah is totally destroyed and a dangerous place to go. We will be here next year, we have suffered minor damage and we are vital to Utah's economic well being in the future and we are currently being economically disadvantaged by the States apparent disinterest in our future. We are pleased with the Commission's initiative to establish rumor control centers in San Francisco and Denver. There is a systemic problem in rumor control in that there is a lag time in the correction of miss-information. After the center is closed, the impression that Utah is still in trouble is likely to persist. Thus we think that it is vital for the State as a whole for a vigorous, well funded Utah development publicity campaign to be nationally mounted to inform the rest of the country that Utah is in business, its fundamental assets are unaffected and that we are in business now.

With the Jordan and Deer Creek Aqueduct out of service, the major water supplies for Salt Lake City and environs come from the Big and Little Cottonwood Canyons, which also happen to be the principal areas for ski resorts. We must begin to ascertain what the sources of pollution are for these creeks so that they can be corrected. We must open the roadways into the area so that the monitoring and repair equipment can get into the area to correct these pollution sources before the water shed is permanently effected. Our pollution monitoring equipment indicate that there is a lot of Pollution coming from private sewage facilities in both of these canyons. They must be checked immediately or you will loose these canyons for the near term as water supply areas.

Ski Development Council Recommendation

1. Rumor Control--We want a seat on the San Francisco Rumor Control center staff to assure that the interests of the industry are well and properly represented.

2. Air Access--The ski industry and the tourist industry in general should be partners with the State on the committee that sets the terms for access to the region prior to resumption of full commercial air access.

3. Transportation--The industry needs the immediate clearance of roadways to the east, providing access to areas currently threatening the water shed of the Big and Little Cottonwood Canyons and giving both access to ski areas.

4. Environmental Safety--Assistance in restoring sewage treatment in the mountainous area is required, since these areas provide the water shed for Provo, Salt Lake City and Ogden as well as any other communities in the area.

5. Waive Fees--The industry recommends that fees for licenses, property taxes and other charges be waived for this year, or until the industry is economically whole again. While skiing was good over the Christmas season, there is none now. The industry does not want to avoid safety licensing but ask that it be given the latitude to achieve safe reconstruction in the most economic manner available to us rather than to meet prescriptive, not performance, standards. The industry wants to recover and become, once again, an important part of the tax and business base of the State.

6. Loans--The ski industry depends upon loans as the principal source of capital to operate. The damage done to the banking system, and particularly the impaired financial condition of rural service banks presents a special hardship to the tourist industry. We recommend several direct actions:

Low cost loans for at least three year period to help us recover. The Governor should make a special effort with the Department of the Interior to assure that Utah gets special treatment under existing programs and that inappropriate regulations are suspended.

Low cost loans for capital improvements be made available to operators as they are to small businessmen under Federal and State programs.

7. Fuel--Current fuel allocation programs discriminate against the tourist industry. We recommend that the Governor give first priority to allocating fuel supplies under his control and authority first to life saving functions and second to business. Without adequate fuel all the other actions recommended will have limited effects.

STATE REPUBLICAN LEGISLATIVE LEADERSHIP

This is no time for the traditional rivalries between and among different political interest groups to impede the strong, united effort of the people of this great State to recover from the devastating blow dealt by the recent earthquake. We reaffirm our commitment to the principal that government exists to serve the people. We call upon all interests to join in a truly humanitarian effort of public service that sets aside the petty differences of the past. We pledge that we will not engage in any actions that takes partisan advantage of situations that are attributable to the earthquake and call on others to make the same public pledge.

The Republican Party hereby makes available to the State and to the several public service associations now serving the State so admirably the full assistance of its organization. As most will attest we are well organized to the grass roots level and have the ability to muster great effort for and by the people.

The Republican State Committee has meet several times since the earthquake. During the emergency period, the public had a common goal of protecting life and property. Now that the emergency period is ending, the public is starting to observe their individual losses and sorting out who is gaining and who is losing. Politically, this is a time of ferment. The next State-wide election will be held in eight months. Scapegoating has started, and the Governor is under heavy criticism for the inadequacy of State and Federal response. While this may not be justified, it portends severe political problems as the various impacted groups start to press for advantage. Some have already suggested that the Governor be abandoned by the Party since there is a high likelihood that the public will blame him for everything that goes wrong, is not done, or is inequitable. Running against this situation is a lot easier than defending it.

The appointment of the Commission has deflected some of the political heat but it will not act as a shield for long. The Republican Party is rumored to be preparing an aggressive plan to seize political control of the State. Various minority groups are claiming that the poor and disadvantaged are not receiving equitable treatment and are unlikely to receive their fair share as benefits are channeled to the middle class and business. Regional tensions are starting to be observed as those sections of the State not particularly affected are seeing virtually every resource available to the State channeled to the impacted area.

State Republican Legislative Leadership Recommendations

As the criterion for the decisions that this Commission must make, we propose the first concern be given to the preservation of the family and its values. It is the cornerstone on which Utah is based and must not suffer by and through the actions of the State to recover.

The goal for the State's government should be, as it is for the Republican Party, to restore the State as soon as practical. To accomplish this the stresses caused be lack of fuel, food, transportation, communications, all those things necessary for the restoration of the community. We call upon this special Commission to:

1. Liaison--Establish a liaison between the State and its functioning units and the LDS Church in order to help identify where the most pressing human

needs are, assess these needs and recommend actions to fulfill them. While the LDS Church has been active in the emergency period as part of the State team, it is not planning to continue in the recovery period. The Church has the most effective access to the State's population at the family level of any institution and thus represents a unique resource.

2. Federal Coordination--Call upon the President to appoint the Vice-President as the Federal Coordinating Officer to coordinate and manage all Federal assistance which this State needs and deserves in its recovery. In particular we want to be able to open national forest lands for wood cutting for the purpose of home heating without permits. We have confidence that Utahans will exercise this allowance with care and do concern for environmental values. We want to be able to use military personnel to assist in clearing debris, restoring power and opening roads to those places most in need. We want to be able to establish credit resources in those areas where private rebuilding is needed. And we want this panel to recommend national legislation where needed to provide that special legislation needed to restore the State's economy.

3. Preservation of the Family--Clearly a key to recovery under the criterion of preservation of family values is to discover what the families needs are. This can only be achieved with the restoration of communications systems and collection of information so that we can find out what the real needs of the people are. When these needs are discovered, the people can respond through direct family to family action. For example, this great State has stored food for a year at every location. While much of the contents were damaged, much survived and can be used to fill the void. There are plenty of ways in which these resources can be mobilized by individuals when there is clear understanding of where the need is.

4. Unified Recovery--All recovery efforts be must be unified across party lines. No one should exploit the situation to advance any political cause or individual interest at the expense of the public. The Governor should appoint a bipartisan Council of citizens to observe governmental officials to monitor their actions and recommend steps to assure that they are ethical, non-partisan and in the public interest and should represent all

the diverse interests of the State. The Council should have the all the authorities and resources needed to assure its success.

5. Critical Facilities--The restoration of critical facilities should receive the highest priority for competing resources. Hospitals, emergency communications, hazardous materials containment, and emergency operations centers are at the center of our ability to respond to another earthquake, which the scientists tell us is likely.

6. Recovery Resources--The Governor request a clear, concise and realistic assessment of the total assistance likely to be available under Federal programs, both as a proportional share and absolute amount among the several impacted States. We specifically counsel that the Governor and our Congressional delegation push for aggregation of recovery support into block grants and loans for administration by the State. It is quickly becoming apparent that neither the public nor its elected leadership would allocate resources among competing interests in the way that Federal program officers are indicating they will. We must control our future, not delegate it to others who are not from our State or who will have to live with the results.

7. Governmental Consistency--The Governor should personally take responsibility for consolidating and solidifying the efforts of all cabinet offices and departments of the State to assure consistent and appropriate action during recovery.

8. Responsibility--Establish within this Commission a Subcommission whose purpose is to discover who is responsible in the Federal government for the failure to provide in advance for the possibility of this disaster and in particular who is responsible for not having established an earthquake prediction effort in the State. And why was it that FEMA had not established a mandatory earthquake insurance program to provide in advance for the financial resources to recover? Why was local Federal aid for civil defense allowed to lapse? We think it was because the Democratically controlled House of Representatives has failed to respond to repeated Republican lead efforts to provide adequate resources. Our

party is people oriented and wants to know what went wrong so that errors of the past can be rectified, not find scapegoats for the failures of the past.

Now is the time for the public as individuals and families to recognize the extraordinary capacity it has demonstrated to help itself during this stressful time. The future will be a time of great testing of their resolve to prosper. We urge that the Governor give great emphasis to calling upon the people, individually, as family groups and through their churches and community organizations to foster self reliance and initiative. To recognize individual initiative and efforts we recommend that the Governor establish a recognition program of awards for exemplary accomplishments. The creativity, energy and capacity of the people is unbounded. Sustaining the public's extraordinary effort through the balance of the recovery can and will create a better Utah--one for which we can all take pride and credit.

Concern was expressed by one Commissioner that reliance on the LDS Church to establish priorities for the allocation of aid: first, violates the separation of church and State; second, places the church in conflict of interest in the establishment of priorities for aid to non-church members; and, third, may disproportionately aid church partially or wholly owned enterprises. Upon inquiry, the witness indicated that they had already asked party workers all over the State to become part of this information retrieval process and to report any cases of preferential treatment to it. The Church has been diligent thus far in assuring that there is no prejudice and has given of its resources to other groups, both religious and secular, that had need and were providing public service and relief to those not desiring to have dealings with the LDS.

The Party spokesmen were asked if they supported the suggestion of the Acting Governor that a Constitutional convention be called to amend the Constitution to allow the State to go into debt and thus to finance emergency and recovery costs? The Party does not support this suggestion. We have asked for Federal credit resources and think that they will be sufficient. We want Federal legislation and financial support in such quantities that will not require us to go into debt. We do not think that this step is necessary now and would not support such a convention.

To avoid the dependence that might occur of Utah on Federal programs we would funnel all Federal support through the State. Indeed we feel that all funds and resources should be funneled through State accountable bodies and not through the individual Federal program offices. We feel strongly that in this time of need that the people of Utah should set their own priorities and not be subject to some one else's aspirations or desires. While this may be difficult for the Federal government agencies to accept and may reduce the total amount of Federal support available, we feel that we must insist upon such projections to assure that the State retains its unique character and redevelops in a way consistent with its values.

A Comissioner asked if the witness would support granting of subpoena powers to the commission to help determine calpability at all levels of government for their actions prior to the disaster. The witness concurred as long as it does not interfere with the recovery process and that it remain constructive, not degenerate into a witch hunt.

COMMISSION'S INITIAL RECOMMENDATIONS

The Commission recommended high priority actions within 14 days to the Governor. Their overwhelming view is that the people of Utah have the resolve, the adaptive capacity and the will to recover and prosper following this massive event.

The Governor has extended membership of the Commission to eighteen by adding eight new members to represent business - two representing small businesses in the impacted area, two representing big business, one representing businesses not effected by the earthquake, one representing interstate business interests, one banker and one representing the utility industry.

The first recommendation of the Commission, given 10 days ago has already been acted upon. The Governor has met with the Mayors and County Commissioners of the impacted areas. The have jointly and unanimously agreed:

1. To jointly foster recovery of the impacted areas;

2. To avoid competition among their jurisdictions for recovery assistance and industrial investment;

3. To cooperate to foster an economic resurgence of the region;

4. To enforce building codes, inspection procedures, and land use requirements that contain appropriate levels of earthquake protection to assure that various interests do not use lesser requirements as a means of attracting capitol, jobs and people to locate in one area versus another; and,

5. Not to sacrifice long term preparedness for the expected aftershocks to achieve more rapid recovery.

They have agreed to meet regularly and have each assigned a senior advisor to communicate daily with their counterparts.

The Commission has thus far recommended specific actions in five distinct area--Federal Relations, Resources, Finance, Life Lines, and Administration. They are enumerated below.

FEDERAL RELATIONS

Request that the President issue public assurances to the Governor that all programs, actions, and activities of the Federal government influencing or directly affecting recovery will be subject to review and approval of the Governor or his designee. Also request that the State's Congressional representation introduce and press for passage as soon as possible legislation that forces the passage of all recovery funds to the State through block grants to be controlled by State officials under the direction of the Governor and the Legislature.

RESOURCES

Establish recovery information clearing houses in several regions of the State to assure that information is available to everyone on the same basis. These clearing houses should be vertically integrated with the central State office providing both information to the regional centers and aggregating needs for communications to the Governor.

Request that available Federal military personnel focus their assistance to the State on the restoration of flood control works, particularly levees. The potential for flooding poses such a severe threat to urban areas that this is one of the highest priorities. It is felt that focusing such Federal assistance in one area will improve performance substantially.

Undertake the sale of $500 million in State guaranteed Industrial Development Bonds to provide financial assistance to State business. The recommended interest rate is 9% with the first year's interest deferred. Equity participation is considered a condition for such loans, since the State should not incur the risk of loss without the potential for gain.

FINANCE

Declare a moratorium on financial obligations under the State's Commercial Code until June 10th, at which time an extension may be considered. The legal status of many claims is in doubt, and the value of many assets questionable. The delay will afford the community the opportunity to better assess the condition of loans and forestall legal disputes that could be injurious to the financial future of the State.

Remove the State's restrictions on interstate banking. The condition of many banks is in question, and there have been several offers from eastern and western banks that, if the interstate banking restrictions are lifted, they are prepared to move into the State in a big way. They are prepared to make the appropriate assurances that they will be good and productive additions to the State's economy.

LIFELINES

The Corps of Engineers should be assigned as its principal task the opening and restoration of transportation routes. Restoration is needed quickly to allow commerce and business to reestablish itself, particularly in the eastern portion of the State. The primary focus should be on commercial, business, farm access and tourist assess roadways. Residential restoration is definitely a secondary priority and should only be undertaken where absolutely necessary for life safety.

Emergency approval by the State Utilities Commission of a raise in electrical rates to four times their pre-earthquake level for use in excess of 150 kwh per month. Current capacity and distribution networks are limited, and some mechanism must be found to allocate power among the competing users. The pricing mechanism is judged to be the most equitable one available. The 150 kwh level was selected as the amount needed to operate refrigerators, and other essential household appliances. While it will pose some hardships on householders, these are deemed by the Commission to be within an acceptable level.

ADMINISTRATION

Call an emergency session of the State Legislature to amend the State's Constitution to allow State debt. Currently the State may not run a deficit. Current law severly limits the State's ability to meet emergency life saving needs or to foster recovery, especially in light of expected low revenues for the coming year.

Add 10 people to the staff of State's Liaison Office in Washington to assure that the State has access to what is happening in Washington and to assure that the State's interests are adequately presented and defended before the Congress and the Administration.

Provide an emergency grant to the LDS Relief Society and cooperating relief agencies. They have rendered assistance of unquestioned value to the State's citizens. They have exhausted their meager resources and need aid if they are to continue. It is the Commission's conclusion that they are the lowest cost mechanism for the equitable provision of aid to those in need.

Provide a grant to the Tourist Development Council to develop and sponsor an aggressive publicity campaign to assure the country that Utah is a great place to visit and that now is a good time to do so.

Institute wage and price controls for 90 days.--There are widespread reports that gouging for services and products is being practiced. Controls are felt by the majority to be the only effective means to put an end to such practices. A minority of the Commission feel that there are already adequate legal means to prosecute flagrant violator and that the price mechanism is the only equitable way to allocate scarce resources.

AFTERWORD

This disucssion has been purely hypothetical. If its speculative nature troubles you, remember Voltaire, who said that doubt is an uncomfortable condition, but certainty is a ridiculous one. The purpose of the exercise was to illuminate the political nature of reconstruction policy and to initiate a process of accommodation. It was solely meant to stimulate the participants and the reader to think about the problems posed by a massive earthquake in terms other than the direct damage or the immediate emergency problems of life saving, both of which are vitally important.

As the Workshop proceeded, the participants became more involved and began to show signs of understanding that the environment in which decisions will be made is one where parochial interests will be aired and political interests not only presented but served. After all, the political process is first and foremost the process wherein differing interests express themselves and work toward resolution of problems that are not well posed and have no optimal solutions.

Time and time again, we have learned that we can not effectively respond to problems that have not been thought through prior to the need for immediate action. While emergency life and property saving functions are pressing and tax our resources, they are none the less straight forward. We know how to respond - only our lack of materials or management skills will prevent satisfactory action. The difficult problems are those where we cannot rely on our instincts or the goodwill of others and the public will not have a consistent view of satisfactory performance. These are problems that have no simple solutions--indeed, they probably have no best solution at all. But our ability to recognize, diagnose and react to these complex socio-environmental issues is critical. This paper has attempted to start a process of examination of Utah's earthquake hazards problems that can bring these problems out into the open where they can be calmly and rationally discussed and functional relationships that lead to effective earthquake preparedness can be developed. It continues a process begun by the author in his papers "The Charleston Earthquake: A Prospective Assessment" and "Recovery Following an Earthquake: A Prospective Assessment for Arkansas Following a Central United States Earthquake". Hopefully it will achieve this purpose.

ACKNOWLEDGEMENTS

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PREPAREDNESS PLANNING ALONG THE WASATCH FRONT FOR EARTHQUAKES AND OTHER NATURAL HAZARDS

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INTRODUCTION

An analogy can be drawn relative to two value indicators which will give a perspective to the amount of funding and effort being spent on earthquake preparedness and planning along the Wasatch Front.

In 1982, when the Federal Emergency Management Agency gathered information from the Departments and participating Agencies and put together the draft Five-Year Plan for the National Earthquake Hazard Reduction Program (covering Fiscal Years 1983 through 1985), it cited the funding suggested to carry out the program elements. Taken from that draft plan is a summary of the funding recommended for FY 1985, in each of the five program elements, and at the lower levels of emphasis:

I	Hazard Delineation and Assessment	$ 14,900,000
II	Prediction and Prediction Dissemination	10,490,000
III	Seismic Design and Construction	91,775,000
IV	Preparedness Planning and Hazard Awareness	4,075,000
V	Fundamental Studies	32,750,000
		$153,990,000

Of the amount in Element III, $90,300,000 is a projection of on-going earthquake proofing being done to Veterans Administration Medical Facilities. (The retrofit of the VA Medical Center in Salt Lake City cost $13,000,000).

It is realized that the figures shown above may have little comparison to what may be appropriated or allocated, but they do give an indication of emphasis, or relative scopes of perceived activities within the five elements of the overall program.

Another view of quantitative values can be taken from the costs of damages experienced from Utah's 1983 and 1984 flooding and landslide disasters.

1983	Damage Costs	$478,098,555
1984	Damage Costs	41,413,479
		$519,512,034

With these two reference to cost values, it can be noted that the FY 1985 funding proposed in Utah for preparedness planning for earthquakes and multi-hazards is:

Earthquake Preparedness	$ 33,455
Multi-Hazards Mitigation Project	94,800
	$128,255

IMPORTANCE OF EARTHQUAKE PREPAREDNESS AND MITIGATION

Along with the economic aspects of earthquakes and other natural hazards, a more serious concern is that of threats to people, or the potential of lives lost. The USGS Open-File Report 76-89, A Study of Earthquake Losses In The Salt Lake City, Utah Area, estimates the impact of an earthquake of a Richter magnitude 7.5 along the Wasatch Fault, considering damages in Weber, Davis, Salt Lake and Utah counties.

Deaths	2,266
Seriously Injured	9,064
Homeless	29,569

With the added impact of a secondary threat from a dam break, such as Deer Creek, the estimates rise to:

Deaths	11,900
Homeless	44,369

If an attempt were made to compare the 1983 Lake Thistle mountainslide to a major earthquake along the Wasatch Fault, it may illustrate the magnitudes of impacts involved.

When the mountainside in Spanish Fork Canyon began slipping on April 12, 1983, there were 22 persons living in the area which was eventually covered by the 70,000 acre foot lake. The event was slow moving and the victims were relocated. Fortunately, in this catastrophic natural event, along with the flooding and debris flows throughout northern Utah, no lives were lost, no hospitals were disabled, and no major metropolitan lifelines were disrupted.

If the Thistle mountainslide had suddenly occurred without warning; if the total movement of the land mass, the formation of the dam, and the filling of the lake, had all occurred in less than three minutes (longer than the time of damaging earthquake shocks); if all 22 residents of the area had lost their lives,----though tragic, that would yet have been only 22, not 2,266----as estimated for a Richter 7.5 earthquake along the Wasatch Fault. Putting it in perspective, to deal with a natural hazard of the magnitude threatened by a Wasatch Fault major earthquake is a very serious and worthwhile endeavor. If planning and preparedness can reduce and prevent losses, whatever meager funds and efforts are expended to achieve it will reap pay-off benefits beyond many other things for which funding and efforts are spent.

PREPAREDNESS PLANNING AND MITIGATION PROGRAMS

Utah is well on the way to completing a joint-use State/Four County Earthquake Response Plan. This plan is to be an operational management tool to be used whenever a damaging earthquake occurs along the Wasatch Fault. It will integrate all available response resources and capabilities and employ them with coherent control and management throughout Weber, Davis, Salt Lake, and Utah counties. The State/Four County Plan will be used as a common reference guide at community, county, and state levels by officials, emergency response forces, and volunteer organizations. It will be backed up by mutual aid agreements sufficient to support unencumbered employment of appropriate resources where needed most.

Much effort has gone into making it site specific and in telling users readily:

What to do.

Who will do it.

How to do it.

and

What resources will be used.

This operational plan is developed under the mandate and authorities of Utah's Disaster Response and Recovery Act of 1981 and Utah's Emergency Management Act of 1981. It's development is supported by funding through the Federal Emergency Management Agency.

Special activation procedures are established to be applied at state level if notifications arise from the seismograph station system of the University of Utah or from the National Earthquake Information Service at Golden, Colorado. County or community level activation can also be done to respond to damages or threats of damage.

Provisions are made for:

Emergency Communications, which emphasize the use of radio links from on-scene locations of damage or response to the all-important control and management centers. An all-inclusive radio frequency list is developed to provide a common reference tieing together the government emergency use frequencies with state agencies and county agencies. It includes, the expanded resources of private sector volunteer radio communications resources.

Reconnaissance Operations, which establishes mechanisms and resources for immediate evaluation of damages and hazards. Pre-disaster contacts and reporting formats are established. Inspection of critical facilities will be initiated by local emergency inspection teams. Specific areas or objectives will be covered by aerial surveillance from the Utah National Guard, Civil Air Patrol, etc.. Broad area aerial reconnaissance with preplanned essential elements of information has been set up with the U.S. Sixth Army and the Idaho Air Guard. The Idaho Air Guard has a tactical reconnaissance organization equipped with high level, high speed, remote sensing aircraft, imagery production, and interpretation laboratories.

Monitoring and Warning: Emphasis is placed on the responses needed to evacuate, or take safety measures in advance of secondary threats, such as deluges from dam breaks. Precisely, Pineview, Mountain Dell, and Deer Creek Dams and their downstream metropolitan areas are given unique procedures. To the extent possible, existing 24-hour alert centers are used, such as the Sheriff's Dispatch Centers and Utah Highway Partol Dispatch Centers. Procedures cover conditions with telephone or without telephone capabilities. Other life-saving warning provisions relate to the hazard areas surrounding the four oil refineries in Davis County, which have a combined storage capacity of over 5 million barrels of petroleum products.

Emergency Public Information procedures are preplanned to broadcast emergency guidance for specific hazard areas or general instructions to populations affected by power outages, gas main failures, water system failures or route blockage isolations. Means for activating the Emergency Broadcast System at state, county or community levels are given. County Emergency Operations Centers, as well as the State Emergency Operations Center, have remote radio pick-up linkages to designated Primary Common Program Control Stations in the Emergency Broadcast System.

Fire Fighting and Search and Rescue are life-saving demands where pre-planning and training pay off. In addition to the combined utiliza- tion of all available municipal and county fire fighting resources, mutual support agreements have been adopted for all of the oil refineries. They have their own foamer trucks and trained fire suppression crews. They have established quick response procedures from the nearest municipal fire stations. Response resources for use throughout the four county area include the foamer and special equipment from Hill Air Force Base and Salt Lake City International Airport (above the airport needs at the time), and aerial fire retardant units managed by the Inter-Agency Fire Control Center, based at the Salt Lake International and Ogden Airports. When not involved with fire suppression, fire fighting crews provide one of the best resources for searches in damaged buildings and the rescue of entrapped victims. Primary responsibility for search and rescue rests with the Sheriffs' Departments. They will be augmented with Rocky Mountain Rescue Dogs, a unit on 24-hour alert with access to 20 dog teams throughout the four counties; Sheriffs' Jeep Posses having over 160 four-wheel drive and radio equipped vehicles; and the Civil Air Patrol with eight squadrons of trained search and rescue resources.

Evacuation, Sheltering, and Feeding are established as responsibilities at local community and county levels, supported by the state agencies. First demands will be evacuations from areas threatened by a dam failure. The inundation areas, evacuation procedures, routes, and shelters are predesignated in the plan. Unique transportation resources will be coordinated by the State Emergency Operations Center to provide helicopters and ambulances. Evacuations from heavily damaged building areas and high rise buildings, hospitals, nursing homes, and schools are treated. Shelters are to be quickly inspected by local inspection teams. The most likely shelters within the four counties are listed. Large volume public and commercial shelters in contiguous areas, such as Park City and the ski resorts are considered. Mass feeding and shelter management will be coordinated by local and state agencies and supported by the American Red Cross.

Health, Medical, and Sanitation: Managing and employing the undamaged and uninjured medical resources will be one of the most crucial factors of earthquake response. As summarized from the USGS Open File Report, 76-89, there could be over 12,000 persons with injuries serious enough to require hospitalization. A compilation of hospital/medical facility resources in 1984 carried 4,668 bed spaces within the four counties. In their emergency medical plan, the State Department of Health considered that they could accept an augmented capacity of 150 percent of normal for emergencies. This would equate to an augmented figure of 7,000 bed spaces. The above quoted USGS Open File Report, 76-89, estimated that earthquake damages would result in a bed loss of 2,937, or almost half of the available spaces. Priorities for emergency treatment and physician/ nurse care will no doubt be more critically short than bed spaces. Massive adjustments and coordination will require state level management. Unique resources, such as helicopters and ambulances will need to be pooled and allocated by priorities. Emergency Medical Collection Points will need to be established. Massive patient evacuations to regional hospitals outside the area will need to be considered. The aspects of health, medical care, and sanitation are planned to the depth of detail permissable. They will be expanded and refined as exercises and experience give us more knowledge.

Response To Lifeline Systems Damages will be crucial to support relief operations and to sustain the disrupted and recovering populations. Each of the lifeline systems are vast and unique. To a certain extent, the private sector or utility agencies who operate the systems will manage the restoration of services. For example, in the USGS Open-File Report, it was estimated that following a 7.5 earthquake, Mountain Fuel Supply could repair most natural gas line damages within 24 hours. Yet lifeline disruptions will probably be massive, widespread in their impacts, and may last days or longer. To the greatest detail allowable, and within proprietary rights, this section establishes the processes for restoring the lifelines. Direct links between the lifeline operators and the State and County EOC's are best covered by having respresentatives from the lifeline agencies in the appropriate emergency operations centers.

Debris and Wreckage Removal take on a more critical importance then in normal disasters because of the likelihood of entrapped victims. Controlled demolition could be required, in some cases. Procedures and authorizations are guided by the life-saving demands and in accordance with provisions given in Utah's Disaster Response and Recovery Act of 1981.

Military Support will be a major contribution. Resources from the Utah National Guard have proven their responsiveness and sizable capabilities during the 1983 and 1984 flood and landslide disasters. Other nearby military resources from Hill Air Force Base and Tooele Army Depot will consititute vital flexible capabilities. In the event the State's Emergency Operations Center is disabled, the Alternate EOC will be located in facilities on Hill Air Force Base. Sixth US Army at Presidio has established a specific Earthquake Response Plan for the Great Salt Lake City Area. It provides for the deployment of Disaster Control Elements at the outset of a damaging earthquake from the Ogden Air Logistics Command, from Fort Carson, Colorado, and other military resources. The Tactical Air Command has an Operations Plan "Sea Nature" which provides Tactical Air Reconnaissance in support of natural disasters. For the Wasatch Front earthquake, reconnaissance objectives have been specified, essential elements of information listed, and required reports formats coordinated to facilitate automatic operational response to the earthquake event.

Volunteer Support is an extraordinary resource in Utah. It coalesces and brings in the specialized, trained, and organized capabilities of the American Red Cross, Salvation Army, Civil Air Patrol, Rocky Mountain Rescue Dogs, Sheriffs' Jeep Posses, Amateur Radio organizations, and the churches, especilly the L.D.S. Church. Putting to work their responsive structure, during the 1983 flood and landslide disaster, 139,537 members of the L.D.S. Church (in organized and managed groups) performed 1,271,443 hours of volunteer labor. They have developed neighborhood resource lists of response specialists, such as doctors, nurses, etc..

Mutual Aid Agreements are being negotiated to facilitate flexible application of resources. Though negotiations are sometimes fraught with protective reluctance, progress is being made in many areas. As mentioned above, the four oil refineries, AMOCO, Chevron, Husky, and Phillips, have mutual aid agreements with themselves and nearby Fire Departments in Davis County wherein they will combine to handle a massive emergency at one or more of the refineries. The Military Assistance To Traffic support agreement for life-threatening emergencies negotiated with the Helicopter Rescue Detachment of the 40th Air Rescue and Recovery Service at Hill Air Force Base, is another example of achieved mutual aid. Three of the four counties in the above mentioned response plan have concluded Mutual Aid Agreements.

Training of Emergency Response Forces, such as Fire Departments, emergency Medical Teams and volunteer organizations will take on a more meaningful scope as the Earthquake Response Plan is exercised and used as hub around which to focus and vector the training and drills. The Division of Comprehensive Emergency Mangement's Training and Education Section has annually sponsored an Earthquake Preparedness Month throughout all channels of the media. The recent formation of the Public Awareness/Education Resource Committee is intended to generate classroom quality instruction on earthquake preparedness and inject it into homes and businesses through PBS television and other media outlets.

MULTI-HAZARD MITIGATION PROGRAM

Utah's Multi-Hazards Mitigation Project goes beyond the threshold of earthquake preparedness and includes the hazards of dam failures, deluging floods, and landslides. More than one of these events could occur simultaneously or in triggered sequence. The Multi-Hazard approach was adopted to enable planners and mitigation authorities to treat all four hazards in a parallel, formal manner, with equal cognizance of all risks.

The Multi-Hazard Mitigation Project is supported by funding from the Federal Emergency Management Agency. However, since the Project evolves long-haul mitigation measures which actually implement life saving and property loss reductions within jurisdictional areas, the objective is to develop a partnership between FEMA and the local jurisdictions. Hazard analyses and mitigation strategies evolve from the Multi-Hazard Project developments.

Application of the mitigation measures and bringing to culmination the hazard reduction benefits will depend upon efforts contributed by the affected jurisdictions in the way of funding, legislation, preparedness, zoning, structural modifications, etc..

Certain catalysts which will clarify the view of mitigation authorities are the Probabilistic Risk Analysis, Economic Impact Analysis, and Demographic Risk Analysis. The Probabilistic Risk Analysis applied by Jack R. Benjamin, Associates, Inc., (who developed the Stanford University's Engineering risk assessment techniques for dams) precisely quantifies the risks from the four hazards within a designated project area. From the three analyses mentioned, jurisdictional authorities are able to assess the impacts of the hazard events and grasp the scope or urgency of mitigation requirements.

As has been shown in the costs mentioned above, and from the 1983 and 1984 floods and landslides damages, potential savings from responsible mitigation efforts can be immense, both in terms of dollars as well as in lives saved.

To initiate the Multi-Hazards Mitigation Project and focus the implementable hazard reduction results, the Pineview Dam and the Ogden Metroplitan area were selected for the pilot effort.

Pineview Dam is an earthfill structure located six miles up Ogden Canyon and 600 feet in elevation above the Ogden City area. It was first constructed in 1935 to a height of 65 feet with an impoundment volume of 44,000 acre feet. In 1957, the height of this earthfill dam was increased to 94 feet, giving it a reservoir capacity of 110,000 acre feet.

The initial project in the Multi-Hazards Program has dealt with a Richter magnitude 7.5 earthquake or maximum credible earthquake along the Wasatch Fault in Ogden; a partial or complete failure of the Pineview Dam; the hydrologic event of a maximum credible storm of 10 inches within 6 hours over the 298 square mile watershed draining into Pineview Reservoir; and the risks of hazardous landslides.

As the probabilities are annunciated, as the risks are assessed, and as the impacts are evaluated, the Ogden Area Administrative Review Committee (made up of Weber County/Ogden City officials, members of private industry, the banking community, and academic community) will develop and pursue the myriad hazard reduction potentials.

The Multi-Hazard Mitigation model will then be applied to other areas which urgently need similar hazard reduction implementations. These areas are: Salt Lake City and Mountain Dell Dam, Provo/Orem communities and Deer Creek Dam, and other specific sites of major populations in Utah.

LIFELINES IN A URBAN POST-EARTHQUAKE ENVIRONMENT

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INTRODUCTION

Lifelines, as used in this paper, refer to those facilities which are required to transport people, things, energy, and information. They are a necessity for a community in a modern industrial society to survive and prosper. They include power, communication, water, sewage, oil, gas, and transportation systems. Many of the lifeline systems have associated with them what are called critical facilities such as dams and gas storage facilities. They are also indispensable elements to other facilities and services that are critical in a disaster setting such as hospitals, fire fighting, and emergency operation centers.

The disruption associated with the loss of any of the lifelines would constitute a disaster in its own right. When this occurs in conjunction with a generally disruptive event such as an earthquake and several lifelines are disrupted concurrently, their loss of function can greatly exacerbate the situation and can seriously compound the loss of life and property.

In this paper the following topics are discussed: characteristics of lifelines; lifeline damage experience and expectations; the realation between disaster preparedness, response, and lifelines; the role of utilities in mitigation and preparedness; assessing societal needs and establishing acceptable risks; translating performance criteria into design specifications. The discussion of the above topics will be in general terms without making qualifications when a specific comment may not be applicable to some of the systems referred to. There also has been an attempt to put the discussion in a context of the situation in Utah. Since earthquake experience has been obtained from other regions, certain aspects of these experiences may not be applicable to the local situation.

CHARACTERISTICS OF LIFELINES RELATED TO EARTHQUAKE

Several characterists of lifeline are of particular significance when considering the earthquake problem. Most lifelines have a moderate to high degree of redundancy. This has the effect of significantly improving system reliability since the system can experience some damage without effecting system performance.

Lifelines represent a significant part of the total capital investment within a community. Thus, damage to their facilities can have a significant direct economic impact on the community. More important, however, are the secondary effects that the loss of lifeline function can have. Their impact is more keenly felt by the society rather than the utility. While there are numerous anecdotal examples of secondary effects in the post-earthquake environment, little has been done to thoroughly document secondary effects associated with lifeline damage.

LIFELINE DAMAGE EXPERIENCE AND WHAT CAN BE EXPECTED

The discussion of lifeline damage from past earthquakes must start by noting that no major metropolitan area of a modern industrial society has been subjected to a great earthquake since that advent of modern lifeline systems. Given this limitation, the experience to date has shown that system performance has generally been good. However, there are numerous examples of specific facilities being severely damaged by both moderate and strong seismic excitations. This suggests that a great earthquake could damage enough facilities so that system performance would be unacceptable and a bad situation could be made significantly worse as a result of the poor performance of lifelines.

EARTHQUAKE DISASTER RESPONE AND LIFELINE

Several lifelines play a crucial role during the disaster response phase following an earthquake. Effective communications is probably the most important factor that will determine how disaster response works. As the telephone system can become saturated with calls for even a small earthquake, dependence on this vital function for emergency response is highly risky.

Power systems are also of particular importance since so many things in the community are dependent on power. Unfortunately, power systems have been proved to be very vulnerable to earthquake damage.

The lack of warning, the rapid onset, the creation of numerous large impact secondary hazards, and the fact that most lifelines are adversley effected by earthquakes creates a negative synergism that makes coping with earthquakes much worse than most other disasters. Utilities often respond to disasters that befall them; however, the unique way in which earthquakes effect utilities and the lack of exprience in dealing with them highlights the need for disaster mitigation and preparedness.

THE ROLE OF UTILITIES IN EARTHQUAKE MITIGATION AND PREPAREDNESS

Because of the physical plant of most utilities is so large, any wholesale effort to implement massive mitigations measures will be beyond the resources of most utilities and the communities that they serve. Since the cost of mitigation is low for new construction, sound earthquake practice should be exercised for new facilities.

Experience has shown that in regions of low seismic awareness, utility personnel often under estimate the vulnerability of their systems to earthquakes. Thus, it is important to not only get the attention of utilities that there is earthquake risk, but to make sure that the required expertise is brought in to assess the risk. It should be noted that most utilities do not use formal cost-benefit analysis in determining what mitigation measures should be implemented. As secondary effects primarily impact the society and they are difficult to quantify they play little if any role in the decision process. This suggests the need for a public policy that will address societal needs.

As noted earlier, utilities deal with disasters on a regular basis. Even for an earthquake, standard response plans will be activated and will attack the problem. Utilities will normally prioritize critical facilities and attempts to restore service to the most customers in the shortest time. In the post earthquake environment this practice may not be the best for the community perspective so that it is vital that major utilities have a representative familiar with utility operations present at emergency operation centers so that they can be informed of the communites needs and these can be transmitted to the utility in an appropriate manner.

ACCEPTABLE RISK AND SOCIETAL NEEDS

At the present time, where earthquakes are given any consideration, the approach is to use sound installation practices and have equipment meet seismic specifications. System response is given little consideration as it is both difficult and costly to assess. Thus, to the extent that societal needs are addressed, they are a byproduct not a direct objective. Of course, it is inappropriate for societal needs to be specified by engineers in utilities. What is needed, is for public officials with the assistance of emergency palnners and utility personnel to establish levels of acceptable risks keeping in mind that it is probably not prudent or possible to have a disruption free system. If acceptable risk can be stated in terms of performance criteria, such as the duration and extent of disruption, then meeting the requirments can be left to the engineers to meet. It should be emphasized that the detailed, highly technical decisions are best left to utility personnel.

TRANSLATING PERFORMANCE CRITERIA INTO DESIGN SPECIFICATIONS

Because of the complexity introduced by system redundance and the difficulty in designing some equipment to withstand earthquakes, the problem of translating performance criteria into system and equipment specifications is still an unsolved problem. Given the mandate and public support there is little doubt that utilities will continue to meet societies needs.

WHERE DO THINGS STAND AND WHAT SHOULD BE DONE

The items discussed below while closely related to lifelines also form part of the general approach to earthquake mitigation and preparedness.

1. A clear signal should be given by government that it recognizes earthquakes as a hazard to the community and that earthquake effects should be an integral part of lifeline plans, construction, and operations.

2. An earthquake scenario should be developed which is based on a uniform description of a specific earthquake. The description should consist of seismic hazard maps showing intensity, ground shaking parameters, and soil stability. It should be emphasized that this material is to only be used for initial emergency planning purposes so that accuracy is not as crucial were they to be used for administrative purposes.

   The description of the seismic environment that is developed would then be distributed to each concerned organization so that it can estimate how it will perform. For lifelines these estimates would include the extent and duration of disruption and the assumptions as to the availability of other lifelines and emergency services used in developing the scenario. Two types of estimates should be provided; a) a centered best estimate of the system response, and b) a reasonable worse case situation. This should be an iterative process which incorporates external expert review at some point. This scenario provides the basis for implementing lifeline mitigation and preparedness measures and community emergency response planning.

3. Emergency governments at various levels should develop their own response plans which should include lines of communications (both organizational and physical) to community lifelines.

This provides one initial step in the process of addressing the problems of earthquake mitigation and planning as they relate to lifelines.

REVIEW OF THE ACCOMPLISHMENTS AND RECOMMENDATIONS OF THE UTAH SEISMIC SAFETY COUNCIL

by

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INTRODUCTION

The Utah Seismic Safety Advisory Council (SSAC) was established by an act of the Utah Legislature in 1977. The council was charged to prepare a comprehensive State plan for earthquake safety. The plans and recommendations were developed over a 4-year period from 1977 to 1981 by an appointed council of eleven memebers assisted by a small fulltime staff.

Studies of earthquake risk dealing with an extensive list of safety and property-loss issues were prepared along with associated recommendations for risk reduction to Utah's Governor and the two houses of the Legislature in 1981. These studies and recommendations are contained in fourteen technical reports plus a summary report.

The purpose of this paper is to review the recommendations made by the advisory council and to comment upon the status of their adoption and/or implemention during the three years since they were presented to State officials. The paper concludes with an assessment of the current validity of the recommendations--i.e., are the recommendations still needed, or has the earthquake risk situation changed in ways that render the recommended actions unneeded?

SCOPE OF THE STUIDES AND RECOMMENDATIONS

An overview of the subjects of study by the SSAC is presented first for the benefit of readers who may be unfamiliar with the array of issues that are involved in a comprehsensive plan for earthquake safety. The scope of the studies and recommendations is most evident in the titles of the individual technical reports. The titles of the reports plus an abbreviated indication of individual recommendations are listed below.

For each of the study subjects, the advisory council made specific recommendations aimed at reducing earthquake risk or at improving State and local government capabilities to deal with earthquake-related problems. Typically, several recommendations applicable to each study subject were made, because, we believe, a sharply focussed statement directed to a specific problem or issue would be most helpful to those persons who might have follow-up involvement. In all, 48 specific recommendations were made that essentially are of a mitigation type, and 39 recommendations were made dealing with emergency managment and preparedness issues.

<u>Tiles of Study Reports and Abbreviated Associated Recommendations</u>

A. Seismic Risk Assessment of Utah Primary and Secondary Schools.

1. Recommended that standards for earthquake safety be established for design of school buildings.

2. Recommended that earthquake safety for certain high-risk existing school buildings be evaluated.

3. Recommended that the State establish an on-going program for retrofit of hgih-risk school facilities.

B. Seismic Risk Assessment of Utah Health Care Facilities.

1. Recommended that earthquake safety standards for health-care facilities be established.

2. Recommended that siting of health-care facilities relative to known fault zones be a consideration for licensing of new or expanded hospitals.

3. Recommended that older portions of existing health care facilities be reviewed for earthquake risk and high-hazard facilites be phased out, as may be feasible.

4. Recommended actions to deal with high earthquake risk at the State Mental Hospital.

5. Recommended that future construction at the Utah Training School include earthquake-resistant features.

C. Seismic Hazards and Geologic Hazards Related to Comprehensive Planning in Utah.

The report outlines considerations and procedures for including earthquake safety in land-use planning. No specific recommendations were introduced, since the entire report is a guideline for action by local planning agencies.

D. Seismic Safety Considerations for Dams and Reservoirs in Utah.

1. Recommended that analysis of earthquake hazards be completed for water impoundments 25 ft. or more in height.

2. Recommended that water impondment facilities of 25 ft. or more in height be designed for seismic resistance when seismic analysis indicate a need.

3. Recommended that a preliminary report on seismic risk be submitted to the State Engineer before new dams and reservoirs are approved for construction.

4. Recommended that independent review of earthquake-resistant design be conducted for certain water impoundment facilities.

5. Recommended that dam review criteria under a program funded by the Corps of Engineers be expanded to provide increased attention to earthquake safety.

E. Seismic Strong-Motion Instrumentation for Utah: Current Status, Needs, and Recommendations.

1. Recommended that the State establish and fund a stong-motion instrument array. Specific details for the array and its operation are included in the recommendation.

F. Seismic Risk Analysis of State-Owned Buildings in Utah.

1. Recommended that State owned buildings be designed and constructed in complete compliance with current seismic standards of the Uniform Building Code.

2. Recommended site inspection procedures pertaining to earthquake risk for State buildings.

3. Recommended that supplemental information relevant to earthquake safety be added to the State inventory of buildings.

4. Recommended that plans be developed for expeditious correction of earthquake risk conditions in existing State buildings.

5. Recommended that special attention be given to earthquake safety during planned renovations of buildings at the State Fair Grounds.

6. Recommended that earthquake safety be a required consideration when historic buildings are so classified.

G. Seismic Risk Analysis of Fire Stations, Police Facilities, and Other Critical Municipal Facilities in Utah.

1. Recommended that earthquake risk be a consideration in the design of new fire stations.

2. Recommended that earthquake risk be evaluated for existing fire stations.

3. Recommended that earthquake safety be incorporated into police communications facilities.

4. Recommended that confinement facilities (e.g., jails) be constructed in compliance with current earthquake safety standards.

5. Recommended that the State assist to survey earthquake risk conditions in public buildings of local government units.

H. Seismic Risk Analysis of Public Culinary Water Supply Systems in Utah.

1. Recommended that geologic evaluations be prepared for new culinary water supply systems before they are designed and constructed.

2. Recommended that alternative flow paths be designed for water conduit systems as a means to insure against complete loss of water supply to populated areas as a result of a strong earthquake.

3. Recommended that design of water conduit systems be given special attention at fault crossings.

4. Recommended that bypasses be provided at water treatment facilities to insure against earthquake-induced interruptions of service.

5. Recommended that pumping stations be designed with earthquake resistance.

6. Recommended that piping inlet and outlet connections be designed with earthquake resistance.

7. Recommended that underground piping materials be selected with consideration to their seismic resistance.

8. Recommended that water supply districts stockpile replacement parts for essential portions of their systems for emergency use.

9. Recommended that individual components of water supply systems be anchored to resist earthquake-induced movements.

I. Seismic Risk Analysis of Electric Power Systems in Utah.

1. Recommended that Utah Public Service Commission assert its regulatory role to include consideration of earthquake resistance in the design of electric power systems.

2. Recommended that standards be established for earthquake resistance in electric power systems.

3. Recommended that earthquake resistance standards be established for electric sub-stations.

4. Recommended that the State provide education and information programs on earhtquake risk for the benefit of operators of utilities systems--especially municipally-owned systems.

J. Seismic Risk Analysis of Oil and Natural Gas Systems in Utah.

1. Recommended that operators of oil and natural gas systems in Utah be required to include emergency planning and preparedness for earthquake events in operational plans.

2. Recommmended that standards be established for storage tanks of petroleum products to provide improved resistance to earthquake damage.

3. Recommended that pipelines carrying petroleum products be valved at or near all crossings of known or suspected faults.

4. Recommended that the Utah Public Service Commission establish standards for natural gas connections to buildings and other structures that provide optimum safety from earthquake effects.

K. Emergency Management Planning for Earthquake Disasters in Utah.

1. Recommended that the State Division of Comprehensive Emergency Management (CEM) include in its State Emergency Operations Plan a section dealing with earthquake mitigation.

2. Recommended that CEM encourage or require the preparation of earthquake disaster mitigation plans for the State and local governments.

3. Recommended that CEM prepare and present information to local officials on local earthquake hazards mitigation responsibilities and procedures.

4. Recommended that each local emergency management agency designate and train a hazards mitigation coordinator as a part of the local staff.

5. Recommended that an "Earthquake Survival Guide" for the general public be prepared and published.

6. Recommended that CEM prepare an earthquake response plan to be a part of the Utah Emergency Operations Plan on Natural Disasters.

7. Recommended that CEM lead in forming a public information advisory committee to coordinate efforts and develop materials for an emergency public information system.

8. Recommended that CEM and other agencies concerned with earthquake hazards continue to work toward annual designation of a statewide "Earthquake Preparedness Day."

9. Recommended that camera-ready materials and information packets for print and broadcast media be parepared ahead of time and stockpiled for distribution immediately after an earthquake to meet anticipated heavy post-event demand for earthquake information.

10. Recommended that an earthquake speakers bureau be established and public information presentations be prepared.

11. Recommended that educational and informational materials be prepared on individual emergency preparedness actions the public might take to prepare for a disasterous earthquake.

12. Recommended that CEM, in cooperation with the Utah Office of Education, continue to engage in training programs to insure that teachers and children know how to respond an earthquake occurs.

13. Recommended that CEM supplement the organizational information in its Emergency Operations Plan for Natural Disasters to include prototype checklists, standard operating procedures, and contingency plans for an earthquake disaster.

14. Recommended that emergency planning agencies identify high-risk structures and facilities in their jurisdictions so that emergency response time is reduced.

15. Recommended that inundation zones resulting from earthquake-induced dam failures be mapped and plans developed to meet such hazards.

16. Recommended that State and local governments begin preparations to respond to earthquake predictions.

17. Recommended that CEM prepare and publish an earthquake prediction response plan for use by State and local government agencies.

18. Recommended that local governments in the high-risk seismic areas of the Wasatch Front develop their own local response plans for earthquake prediction.

19. Recommended that CEM develop an earthquake prediction scenario for use in exercises by emergency management agencies.

20. Recommended that model earthquake mitigation ordinances be compiled or prepared for hazardous buildings and other earthquake safety dangers that may be of concern to local governments.

21. Recommended that earthquake emergency exercises be scheduled for State agencies.

22. Recommended that CEM develop training programs to prepare for the recovery period after a disasterous earthquake.

23. Recommended that businesses in the private sector be more directly involved in earthquake disaster preparedness planning.

24. Recommended that local emergency services agencies plan for and develop a heavy-rescue capability and readiness program.

25. Recommended that CEM establish a heavy-rescue training program and conduct exercises in subjects related to earthquake disasters.

26. Recommended that CEM, in cooperation with the State Department of Health, develop and distribute a disaster medical procedures manual and guidelines for treatment and movement of large numbers of casualties resulting from an earthquake disaster.

27. Recommended that CEM initiate and support efforts by State and local health agencies to train health professionals and social workers in earthquake disaster response.

28. Recommended that techniques for providing earthquake protection for communications equipment be made available to State and local agencies whose communications systems would be critical in an earthquake emergency situation.

29. Recommended that CEM assist in developing a Statewide health and medical services communications system and an operations manual for the system.

30. Recommended that guidelines for law enforcement emergency response dealing particularly with earthquake emergencies be prepared as a joint effort between emergency management agencies and law enforcement agencies.

31. Recommended that the Utah Department of Public Safety develop and conduct training for law enforcement managers in resource utilization for earthquake emergencies.

32. Recommended that law enforcement agencies give special attention to security of communications equipment from earthquake-induced damage.

33. Recommended that CEM assist local governments in the high-risk Wasatch Front regions to prepare mutual-aid plans for mobilizing heavy-rescue and debris-clearance equipment and personnel.

34. Recommended that a building inspection mutual-aid plan be developed in cooperation with local building inspection agencies, the private sector engineering profession, and the construction industry.

35. Recommended that CEM assist local governments to organize building inspection mutual-aid programs and provide training for earthquake damage inspection.

36. Recommended that CEM establish a program to obtain qualified personnel from other State agencies to serve as a reserve force to augment State and local personnel for operation of disaster assistance centers for earthquake response.

37. Recommended that the State encourage assistance from other organizations, such as EERI, as a means of learning lessons from other earthquake disasters, and that plans be developed to establish an earthquake investigation clearinghouse to be activated when an earthquake occurs.

38. Recommended that the State establish a long-term Recovery Task Force to prepare appropriate recovery phase public policy for earthquake disasters.

39. Recommended that the State establish standards for long-term recovery that are to be applied when State resources and assistance are rendered to local communities impacted by earthquakes.

L. Seismic Risk Analysis of Utah Transportation System.

1. Recommended that designs for new highway bridges and other such structures be in accordance with state-of-the-art engineering techniques pertaining to earthquake standards.

2. Recommended that engineering evaluation be made by the Utah Department of Transportation to determine the seismic resistance of existing bridge structures along the major arterial and expressway routes.

3. Recommended that a program be established for retrofit of existing important highway structures determined to have questionable seismic resistance.

4. Recommended that potential soil liquefaction be considered in the design of new bridge structuress for Utah highways.

M. Seismic Risk Analysis of Principal Communications Systems in Utah.

1. Recommended that State policy be established to recognize the importance of communications during emergency periods and that facilities housing essential communications equipment used during emergency periods be designed to resist earthquakes of strengths expected in the regions of the facilities.

2. Recommended that telephone and radio broadcast transmission systems equipment be braced or anchored to prevent damaging displacement resulting from an earthquake.

STATUS - IMPLEMENTATION AND/OR ADOPTION OF RECOMMENDATIONS

It is important and significant to note at the outset of this portion of the discussion that the Utah Legislature chose not to act upon the recommendations made by the SSAC. The leadership of the Legislature simply received the materials and recommendations that were prepared by the advisory council and gave them no further consideration.

Notwithstanding the failure of the Legislature to act, it also must be noted that not all of the recommendations require legislative action in order to be implemented. Indeed, most of the recommendations could be implemented by administrative action coupled with budget appropriations needed for increased work loads that would be entailed. Thus, most of the recommedations could be implemented or adopted by administrators committed to earthquake safety and with only legislative blessing in the form of budget approvals.

Why, then, if legislative action is not needed in most instances to carry out the recommendations, is the advisory council dismayed by the Legislature's failure to take any action after spending nearly one-half million dollars to obtain the recommendations? Primarily, the council's dismay is because, by failing to consider the recommendations, the Legislature has signalled that it is disinterested in earthquake safety for the State. This signal of disinterest necessarily carries over the executive branch of government and, consequently, to the various agencies of government where administrative actions for earthquake safety might be taken.

Given the observation in the preceding paragraph, it should be no surprise that very few of the recommendations made by the USSAC have been implemented or adopted. Public policy for earthquake safety has not been set forth by Utah's elected officials; no requirements to achieve improved earthquake safety planning, mitigation, and response have been incorporated into State laws; and administrators of public agenices have not felt compelled, in general, to undertake mitigation efforts on their own.

Although the blanket indictment of governmental nonaction is generally accurate, isolated instances of progress have been observed during the past three years since the council's three years since recommendations were submitted. For example, the State Building Board (now the Division of Facilities Construction and Management) has given increased attention to earthquake safety for the facilities under its jurisdiction, the City of Ogden has adopted an ordinance dealing with earthquake resistance of existing buildings, and earthquake safety has been a factor (both in a positive and negative sense) in debates from which other public policies have developed. Preparedness planning for earthquake safety also has progressed in the State, and some of the preparedness recommendations made by the council have been implemented. The caveat here, however, is that this progress in emergency planning has occurred more because of federal assistance than because the State of Utah has supported the work through pertinent public policies.

There is yet another weakness in follow-up attention to the work of the advisory council by the State. This weakness is that there has been extremely limited distribution of the recommendations--including the abbreviated recommendations as a whole and the detailed recommendations dealing with specific subjects. At the conclusion of the advisory council's statutory period, only a small number of copies of the recommendations were distributed. Most of the copies went to legislative and exective agencies of the State, with just a few distributed to other interested parties plus major libraries in the State. Original copies of the reports were furnished to an agency of the State for follow-up printing as might be needed or desirable, but little follow-up distribution has occurred. The net result is that the recommendations are not widely known to the State's citizenry, and so they have no basis for formulating their own opinions regarding the significance either of the earthquake risk in which they live or of the possible remedies available to them for reducing the risk.

Overall, follow-up actions on the four-year effort of the Seismic Safety Advisory Council are dismal and suggest that conditions within government in Utah are not yet right for undertaking concerned efforts and programs to improve earthquake safety.

The above indictment of government in Utah with respect to consideration of earthquake safety cannot be taken as the complete picture of concern or lack of concern in Utah. There are others besides government officials and government agenices which have a stake in the matter as well as opportunities for involvement. So far, I have not commented on parallel efforts in the private sector nor on efforts by agencies of the federal government aimed at reducing seismic risk. Both of these groups have been involved in earthquake safety matters in Utah, and both have contributed meaningfully to improving risk conditions in the State.

Within the private sector, earthquake mitigation has been improved through efforts by professional architects and engineers. Especially, the Structural Engieers Association of Utah has worked to broaden the expertise of its membership and others in the building industry in earthquake-resistant design techniques. Seminars and workshops on earthquake safety conducted by or sponsored by this group are showing results, with an increasing inventory of new facilities desinged or retrofitted for seismic resistance. This, coupled with greater expectations by local and State building regulatory agencies for meeting the seismic design standards contained in adopted building codes, is helping to assure that we are not adding to the State's inventory of sesimically unsafe building structues.

Federal support for advancing Utah's capabilities to respond to damaging earthquakes also must be recognized. This support is of several types--among them, continued and expanded funding for the University of Utah's program for monitoring earthquake activity in the State, support for geologic investigations that broaden the information base regarding earthquake potential in the State, funding support for conducting training workshops on the design of earthquake-resistant buildings, and funding support to State agencies that permits them to carry on limited earthquake preparedness and response planning.

CURRENT VALIDITY OF THE SSAC RECOMMENDATIONS

Given that more than three years have elapsed since the recommendations on earthquake safety in Utah were completed and submitted by the SSAC, it is fair to question whether that information is valid today, whether the prior work should be updated before further efforts are made to see the recommendations implemented, or even whether the recommendations are without merit and should be discarded.

One consideration in assessing the current validity of the recommedations of the Seismic Safety Advisory Council for earthquake safety in Utah is whether or not information about the earthquake hazards or associated earthquake risks have changed during the past three years. It is this author's view that nothing about the hazard has really changed which would lead to alteration of the recommendations. No doubt, on-going geologic studies have yielded improvements in information about earthquake risk, but these improvements are incremental and significant changes would be needed to alter the basic recommendations for risk reduction. There have been some new studies on earthquake risk, such as the work by L. Anderson on liquefaction. These studies help greatly in refining priorities of action but do not appear to affect the basic recommendations. To the author's knowledge, no new studies of earthquake losses have been undertaken in Utah since the work by the SSAC was completed. Thus, we have no new information that suggests greater or lesser potential earthquake losses than set forth in studies by the council.

Based upon the paragraph above, the author concludes that the recommendations made by the advisory council are as valid today as they were when submitted three years ago.

Looking at the recommendations in another way, it is possible that priorities should be altered in deciding which of the recommendations ought to be implemented first. However, even a reevaluation of priorities is unlikely to change the recommendations much. The SSAC three years ago placed priority, first, upon the need for a State office to direct the earthquake safety program; second, upon a need to give emphasis to seismic-resistant practices in the construction of new facilities (mitigation action to halt further additions of unsafe facilities); and, third, upon land-use planning practices intended to reduce earthquake risk through proper siting. These suggested actions are so basic to a comprehensive earthquake safety plan for the State that their priorities are unlikely to change no matter what improvements in information may be made. In the absence of significant justification, priorities should be changed only after the basic elements of the comprehensive plan are in place.

In summary, this author concludes that the basic plan and recommendations prepared by the Utah Seismic Safety Advisory Council for comprehensive Statewide policies and actions dealing with earthquake safety are sufficiently broad and remain sufficiently valid to serve as the framework for State and local government participation in earthquake risk-reduction planning and implementation programs. Governmental units of the State need only to proceed with the task of following the comprehensive plan that has been set forth.

ARCHITECTURAL ACTIONS TO IMPROVE SEISMIC RESISTANCE

by

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INTRODUCTION

In the United States the architect's role in seismic design has been overshadowed by that of the structural engineer. The causes of this are two: U.S. structural engineers have maintained strongly that seismic design is an engineering problem, and architects have, by default, been willing to accept this position. In consequence, seismic design tends to be delegated by the architect to his structural engineer, and U.S. architects are not well educated in seismic design issues. Since this situation applies even in high risk zones, such as California, it is safe to assume that seismic design issues would have very low priority in moderate to low risk areas.

However, in recent years, it has become clear that the architect has a major role in seismic design, even if largely unrecognized by many practitioners. This paper outlines the areas where building seismic performance is influenced by architectural design decisions and steps which can be taken, from an architectural perspective, to improve performance in new or existing buildings.

BUILDING CONFIGURATION

In recent years - particularly following the 1971 San Fernando, California earthquake - it has become clear that architectural configuration (the size and shape of the building) makes a major contribution to the success or failure of the building's seismic performance. Long recognized by engineers, this factor assumed additional importance through the use of new configurations in the 1950s, made possible by the widespread use of steel and concrete frame construction. At present this ability to construct almost any building configuration, combined with the determinants of urban building sites and planning requirements, characteristic planning solutions, and the efforts to provide interesting and unique architectural images, has resulted in a number of building typologies - building occupancy types combined with configurations - that have led to some serious problems.

While configuration alone is not likely to be the sole cause of building failure, it may be a major contributor. Historically, before the use of steel and reinforced concrete frame construction, good configuration was one of the major determinants of good seismic performance. Building plans tended to be symmetrical, spans were short so that there was a high density of supporting walls, and the need for massive load bearing construction, although it increased earthquake forces in the building, tended to keep unit stresses in the materials to very low values. These are some of the reasons why load bearing, unreinforced masonry structures have survived for centuries even in seismic areas.

With the use of modern framed structures, or combinations of walls and frames, in which a much smaller amount of structural material is very highly stressed, irregularities of configuration will tend to result in dangerous stress configurations. Although our knowledge of materials and forces is much more precise than in historic times, our designs are much less conservative and we demand much more from our materials and connections.

The configurations that cause concern are those characterized by plan irregularities that will accentuate the development of torsional forces, and by vertical irregularities that tend to produce structural discontinuities and stress concentration. In addition, variations of strength and stiffness, whether horizontal or vertical, tend to overstress the stiff elements and understress the more flexible, resulting in a structure in which a small number of elements may receive an undue proportion of the forces.

In plan, the most dangerous forms have proven to be those in which there is a wide variation of strength and stiffness between various building elevations. The performance of the Penney Department Store in the Alaska earthquake of 1964 was a notable example of the poor performance of these forms. In the area of vertical structural discontinuity the problem of the 'soft first story' and in particular a sub-class of this configuration, the discontinuous shear wall, have been revealed as the most vulnerable. The performance of Olive View Hospital in the San Fernando earthquake of 1971, and the Imperial County Services Building, in Imperial County, 1979, are text book examples of the problems associated with these configurations. Both these types of vertical configuration are characteristic of modern building style and are twentieth century inventions only made possible by modern steel and reinforced concrete structural technology.

These problems of configuration apply both to existing buildings, and new buildings. In existing buildings a common instance of a soft-story is that of hotel, office, or commercial building that has, at some later date, had much of the first floor structure removed to accommodate store front glazing.

NONSTRUCTURAL COMPONENTS

Buildings contain many nonstructural elements and assemblies that may suffer severe damage in earthquakes, and present a real hazard to life in more severe earthquakes. In a typical commercial or institutional building the value of nonstructural components will average somewhere between 3 - 10 times that of the structure. Of these, many will be selected and designed by the architect: exterior wall, glazing, partitions, ceilings, etc.

These are the elements that transform the engineer's "structure" into a building. They provide the building with its environment, and they surround the occupant at work or play, at home, office, or institution. The idea that these nonstructural elements played a very important role in building seismic performance began to become apparent in the 1964 Alaska earthquake, and even more clearly in the 1971 San Fernando earthquake. Experience in the 1972 Managua, Nicaragua earthquake highlighted the extreme differences in damage to nonstructural components depending on the structural design of the building. Two adjoining office buildings suffered relatively light and comparable structural damage, well below collapse or life-threatening levels. But the Banco de America, a stiff shear wall structure, suffered minimal nonstructural damage, whereas the Banco Central, a moment resistant frame, suffered tremendous nonstructural damage. This contrasting behavior showed to a startling degree that structural and nonstructural performance were interrelated.

The influence of nonstructural components is four fold: first, their presence may modify the structural behavior of the building in detrimental ways; that is the building structure no longer behaves the way it is designed because nonstructural components change the strength and, most frequently, the stiffness of the main structure. Second, damage to nonstructural components may make the building non-functional - or useless - even though the building structure performs adequately. Third, damage to nonstructural components may cause death and injury, through falling light fixtures, exterior wall elements, file cabinets and the like. Four, the direct economic loss in nonstructural components, combined with indirect loss of revenue caused by lack of function, may create serious problems for the owner - and for society - even though no lives are lost and no injuries are incurred.

These are major problem areas, cutting to the heart of the physical, human, and economic interrelations that create the earthquake hazard; much thought needs to be given to these issues in the design of new buildings and in assessing the hazards of existing buildings in the seismic environment.

CONCLUSION

From the above discussions, it is clear that architectural decisions and architectural materials (those selected by the architect rather than the engineer) are major determinants of seismic hazard, and property loss.

It has been suggested that this issue is not fully appreciated even in high risk seismic areas: if this is so how can the architect in areas of lesser risk be encouraged to think in terms of seismic design and trained to do so. Architects have many things on their mind - and it is quite unrealistic to suggest that the kind of commentary outlined above will cause an architect to change the habits of a lifetime and elevate seismic design to a major priority.

First, the issue must be thought in terms of long term goals. Second, the long term goal should be expressed not solely, or even primarily, in terms of designing for the seismic environment but in terms of a general improvement in design and construction practice. This improvement is aimed at the provision of building that will better meet the normal attacks of weather, thermal stress, differential settlement, and long-term maintenance. In dealing with these traditional architectural problems it is a small step to introduce some rational architectural and structual thinking that will make the building perform better in the occasional moderate earthquake that it may encounter.

Finally, in addressing the aims and responsibilities of our own profession, can we afford to ignore the issue that only small areas of the world are not earthquake prone, and that knowledge of earthquake effects and how to design against them must be part of the professional training and understanding of any responsible architect.

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EXAMPLES OF EARTHQUAKE HAZARDS MITIGATION TECHNIQUES AVAILABLE TO PLANNERS AND DECISIONMAKERS

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INTRODUCTION

Actions to reduce earthquake hazards can be divided into five phases: two before the event, one during the event, and two after the event. These five phasea are: (1) pre-event mitigation techniques which may take 1 to 20 years, (2) Preparedness measures which may take 1 to 20 week, (3) response during the event, (4) recovery operations following the event which may take 1 to 20 weeks, and (5) post-event reconstruction activities which may take 1 to 20 years. Obviously, those times will vary depending upon the magnitude of the earthquake and the resources available to the community and metropolitan area.

Preparedness is just one phase of hazard reduction; personal preparedness is just one aspect of that phase. For example, the Council of State Governments (1976) suggests an outline for a comprehensive state emergency preparedness plan and the Western States Seismic Policy Council (1984, Appendix A) reports on the status of states' earthquake preparedness projects. The Southern California Earthquake Preparedness Project (1983), through "planning partner" arrangements with selected public jurisdiction and private entities, has developed prototypical planning guidelines for responding to, and recovering from, an earthquake. The Federal Emergency Management Agency recently funded the Central United States Earthquake Consortium -- the nation's first effort to develop and coordinate earthquake preparedness activities in a region composed of several states. Corporate, utility, and governmental preparedness (as well as mitigation, response, recovery, and reconstruction) can be very complex; discussion of these is beyond the scope of this paper.

A prerequisite to personal preparedness is familiarity with and concern about all hazard-reduction phases. For example, strengthening the structure of the home, storing water, and showing family members how to shut off the electric-, gas-, and water-supply lines are only a part of one phase -- personal preparedness. Equally important are the other phases which might include picking up children from an evacuated school, securing heavy objects at the work place for the safety of a spouse, and retrofitting the commuter-highway overpasses needed to reunite a family. For purposes of this paper, we will introduce all five hazard-reduction phases.

MITIGATION TECHNIQUES

Many techniques for reducing earthquake hazards before the event are available to planners, engineers, and decisionmakers. Some of these techniques are well known to the planning profession, such as public acquisition of hazardous areas; or to the engineering profession, such as designing and constructing earthquake-resistant structures. Others are obvious, such as warning signs and regulations. Still others have been successfully used in solving landslide, flood, and soil problems, but have not heretofore been applied to earthquake hazards.

These and other techniques are listed in Table 1 under the general headings of discouraging new development, removing or converting existing unsafe development, providing financial incentives or disincentives, regulating new development, protecting existing development, and ensuring the construction of earthquake-resistant structures.

These techniques may be used in a variety of combinations to help reduce both existing and potential earthquake hazards. Most of them are long range, taking from 1 to 20 years or more to prepare, adopt, and execute. Many of the techniques have been discussed and illustrated by William Spangle and Associates, and others (1980), Brown and Kockelman (1983), Kockelman (1983) Blair and Spangle (1979), Nichols and Buchanan-Banks (1974), and Jaffee and others (1981).

Table 1.
Some mitigation techniques for reducing earthquake hazards

Discouraging new development in hazardous areas by:

Adopting seismic-safety or alternate-land-use plans
Developing public-facility and utility service-area policies
Disclosing the hazards to potential buyers
Enacting Presidential and gubernatorial executive orders
Informing and educating the public
Posting warnings of potential hazards

Removing or converting existing unsafe development through:

Acquiring or exchanging hazardous properties
Clearing and redeveloping blighted areas before an earthquake
Discontinuing nonconforming uses
Reconstructing damaged areas after an earthquake
Removing unsafe structures

Providing financial incentives or disincentives by:

Adopting lending policies that reflect risk of loss
Clarifying the legal liability of real-property owners
Conditioning Federal and state financial assistance
Making public capital improvements in safe areas
Providing tax credits or lower assessments to property owners
Requiring nonsubsidized insurance related to level of hazard

Regulating new development in hazardous areas by:

Creating special hazard-reduction zones and regulations
Enacting subdivision ordinances
Placing moratoriums on rebuilding
Regulating building setbacks from known hazardous areas
Requiring appropriate land-use zoning districts and regulations

Protecting existing development through:

Creating improvement districts that assess costs to beneficiaries
Operating monitoring, warning, and evacuating systems
Securing building contents and nonstructural components
Stabilizing potential earthquake-triggered landslides
Strengthening or retrofitting unreinforced masonry buildings

Ensuring the construction of earthquake-resistant structures by:

Adopting or enforcing modern building codes
Conducting appropriate engineering, geologic, and seismologic studies
Investigating and evaluating risk of a proposed site, structure, or use
Repairing, strengthening, or reconstructing after an earthquake
Testing and strengthening or replacing critical facilities

PREPAREDNESS MEASURES

Preparedness measures are necessary because long-range mitigation techniques can not completely reduce all damage and all threata to life safety. In addition, preparedness is applicable to home, school, and place of work and enhancea disaster response. Important personal preparedness measures include:

- Storing emergency supplies for survival, sanitation, safety, and cooking.
- Knowing first-aid and water-purification procedures.
- Developing or being familiar with evacuation routes and deciding on a place for the reunion of the family.
- Learning how to shut off gas-, electric-, and water-supply service lines.
- Securing valuable and nonstructural objects to prevent damage or personal injury.
- Keeping portable extinguishers and garden hoses ready for fighting fires.

Preparedness measures can be taken anywhere from 1 to 20 weeks or more before an event. An excellent booklet by Lafferty (undated) on earthquake preparedness includes: suggested topics for family discussions, family-member assignment check list, community-awareness check list, list of food items for a 2-week emergency supply, suggested replacement periods for stored food, and sample menus for the first 72 hours after an earthquake. Another booklet, by the American Red Cross (1982), includes: extensive lists of home-emergency supplies, procedures for purifying water, first-aid instructions, and an earthquake-survival test. These preparedness measures provide not only for increased safety and reduced damage, but have the additional value of giving people confidence in their ability to cope with a disaster.

Many of us are overwhelmed by the broad range of techniques, measures, operations, and activities available for reducing earthquake hazards; this feeling is completely justified. However, we should make an effort to be personally prepared. There are several reasons not to be prepared for an earthquake; those reasons are restated (and refuted) in Figure 1.

Three personal preparedness measures are discussed here: inspecting and strengthening the home; organizing the neighborhood, school, church, or civic group; and securing heavy or valuable objects around the home, school, or workplace.

Inspecting and Strengthening the Home

The 1971 San Fernando earthquake provided lessons in the types of home structures most likely to fail. Potential weaknesses include numerous cracks that penetrate the entire foundations, unbolted sill plates, cripple walls, lack of solid sheeting or shear panels, unreinforced masonry chimneys, poorly attached masonry veneer, lack of diagonal bracing, large window openings, and untied terra cotta or slate roofing tiles.

A special report by Sunset Magazine (1982) on **Getting Ready for a Big Quake** provides general instructions on how to check your home for both structural and nonstructural safety, and how to make it more earthquake resistant. Additional reference material includes **The Home Builders Guide for Earthquake Design** by Shapiro' Okino, Hom, and Associates (1980), **An Earthquake Advisor's Handbook for Wood-Frame Houses** edited by Chusid (1980), and **Peace of Mind in Earthquake Country** by Yanev (1974).

Organizing the Neighborhood

State and Federal assistance takes days to organize and mobilize; see Figure 1, reason nos. 2 and 3. However, immediate help is usually available from your neighbors and friends. According to Popkin, a study by Haas and others (1977, p. xxix) suggests that "families in the United States rely on institutional support for post-disaster assistance, with help from relatives and friends or self-help playing only a small part in their recovery." Neighborhood groups can very often bridge this gap and can influence government decisionmakers in order to expedite recovery operations and reconstruction activities. Sunset Magazine (1982) gives an outline for organizing a neighborhood preparedness group and provides a sample registration form. The Southern California Earthquake Preparedness Project (1983) has developed a neighborhood self-help planning guide which tells how to set up a community program.

Figure 1. -- Seven Reasons Not to Get Ready for an Earthquake

Reason #1 If a bad earthquake hits, we'll all be dead anyway. Not true. There may be a lot of fatalities, but, many more people will be alive--and your loved ones may be among those who need your help. This is similar to the "why wear your seat belt" response: defeatist.

Reason #2 If I had food, I'd have to defend it with a gun against all the people who wouldn't have food. Deciding to store emergency supplies is a personal decision. Some people store much more than they will need, in order to be able to give to others. Other people are organizing their entire block or neighborhood so they aren't the only ones with food. Cooperation is a key to survival. Naturally, you will have to make up your own mind. But ask yourself honestly: how would you react if faced with a life or death situation? Would you steal or kill for your family members? Why not prepare, and spare yourself that predicament.

Reason #3 The rest of the country will come to our aid. Helicopters will be here in no time to drop food and water. Take a second to think about recent disasters in this country. First of all, none have been on the scale of a good-sized earthquake--the kind we already know can happen in the Bay Area. Federal or state aid takes days to organize and mobilize; meanwhile, you are on your own. Transportation of emergency supplies will be hampered by destroyed highways, overpasses, train tracks, etc.

Reason #4 I have enough food in my house to last quite a while. Take another look. In many homes, much of that food is perishable (in your refrigerator or freezer, which may no longer work) or unsuitable (requires cooking or is nutritionally forgettable--marshmallows, chocolate chips, etc.). Water is even more important. You can live for awhile without food, but it is curtains if you don't have water. If you have a pool in your back yard and a water filter in your emergency kit, you are in A-1 shape. Don't depend on a water heater tank; pipes may rupture and the water may leak out.

Reason #5 I don't have any room to store emergency goods. Some kits are quite compact and can fit in a linen closet or under a bed. In a small apartment, emergency food and equipment may mean making some changes. But what is more important? 15 pairs of shoes on the closet floor, or food and water that could save your life???

Reason #6 Storing food in your house is useless, because the house will fall down on it. It could be inedible, or impossible to get to. Possible. If you have a garden shed or a free-standing garage, that might be a safer storage area. But again, wouldn't you rather be trying to figure out how to get to the food after your house falls down, than trying to figure out where to buy, beg, or steal water and food?! If this is a big concern to you, you could have your house inspected to see how likely it is to withstand an earthquake, and what structural changes could improve those chances.

Reason #7 It will never happen to me. Talk to someone from Coalinga.

Source: Mele Kent (1983) from an interview with Randy Shadoe; reprinted by permission.

Securing Nonstructural Objects

People have been hurt by falling light fixtures, flying glass, overturning shelves, and spilled toxins. The Federal Emergency Management Agency (1981, Table 2) estimates that one-third of the property lost in future earthquakes in California will be attributed to building contents. Such contents are only one part of the nonstructural portion of a building.

Nonstructural damage is caused by object inertia or building distortion. For example, if an office computer or file cabinet is shaken, only friction will restrain it from overturning, falling, or impacting against its user. As the structure bends or distorts, windows, partitions, and other items set in the structure are stressed, causing them to shatter, crack, or spring out of place. Numerous protective countermeasures are available, including:

- Bolting down pedestal bases of sharp or heavy office machines, equipment, and fixtures.
- Tying fragile artwork to the walls.
- Connecting filing cabinets together at the top and tying them to the wall.
- Zigzagging free-standing, movable partitions.
- Using smaller, operable, and wood-frame windows to accommodate structural drift.
- Installing locks on cupboards.
- Boxing classroom carboys that contain hazardous liquids.
- Strapping hot-water heaters to wall studs with plumber's tape.

An excellent book on reducing the risk of nonstructural earthquake damage was prepared for The Southern California Earthquake Preparedness Project (Reitherman, 1983). It describes typical conditions found in office, retail, and government buildings. Measures are suggested for restraining over 20 nonstructural building components, such as office machines, electrical equipment, file cabinets, built-in partitions, suspended ceilings, exterior ornamentation, elevators, piping, stairways, and parapets. Each component is rated for existing and upgraded vulnerability for life-safety hazards, percent of replacement-value damaged, and post-earthquake outages for three levels of shaking intensity (Figure 2).

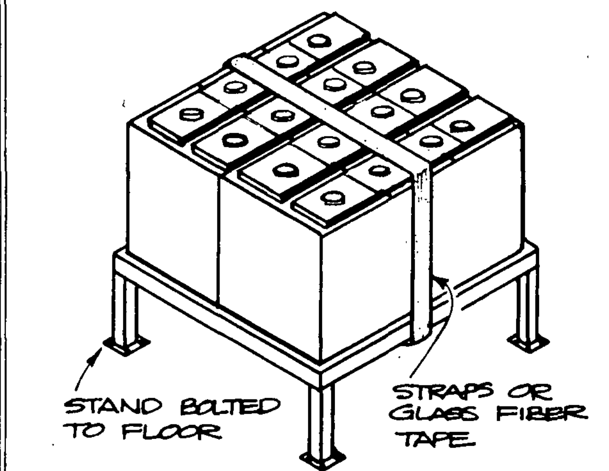
RESPONSE DURING THE EVENT

According to Blair and Spangle (1979) "individuals are virtually helpless during the course of an earthquake. They must ride it out wherever they happen to be at the time the earthquake strikes..... Helplessness is confined to those seconds when the ground is shaking; man has the knowledge and ability to avert many of the damaging effects of earthquakes." An enlightened response can occur during and immediately following the event. It includes short-term emergency assistance, and should be geared to reduce secondary damage and speed recovery operations. During and immediately after an earthquake, appropriate responses could include:

- Ducking under a desk, table, or bed; or standing in a doorway.
- Remaining calm and reassuring children and pets.
- Avoiding window openings, high buildings, power poles, heavy tile roofs, and overhanging structures.
- Fighting fires, escaping, or evacuating.
- Drawing and conserving water.
- Shutting off gas-, water-, and electric-supply lines.
- Checking for injuries.
- Listening to radio and television for emergency bulletins.
- Checking for damage to buildings, sewers, and drains.
- Cleaning up broken glass and spilled toxins.
- Assisting in neighborhood or workplace search-and-rescue operations.

Brochures such as **When an Earthquake Strikes** by the Santa Clara County Girl Scout Council (undated), **Safety Tips for Washington Earthquakes** by the Washington State Department of Emergency Services (undated), and **Earthquakes - How to Protect Your Life and Property** by Gere and Shah (1980) contain excellent advice.

EMERGENCY POWER GENERATORS

DAMAGE EXAMPLE	PROTECTIVE COUNTERMEASURE
	
earthquake: 1971 San Fernando credit: John F. Meehan	APPROXIMATE COST: $10 per rack for strapping $50 for bolting

EXISTING VULNERABILITY

SHAKING INTENSITY	EFFECTS	✚ (life safety hazard)	$ (% of replacement value damaged)	Post-earthquake outage
LIGHT	slight chance of piping connection break	low	0-5%	mod
MODERATE	slight shifting of equipment; batteries slide	low	5-20%	high
SEVERE	lurching of generator off supports; batteries fall	mod	20-50%	high

UPGRADED VULNERABILITY

SHAKING INTENSITY	EFFECTS	✚ (life safety hazard)	$ (% of replacement value damaged)	Post-earthquake outage
LIGHT	no damage	low	0%	low
MODERATE	no damage	low	0%	low
SEVERE	damage to rest of electrical system more likely than generator damage	low	0-5%	low

✚ LIFE SAFETY HAZARD $ % OF REPLACEMENT VALUE DAMAGED [outage chart] POST-EARTHQUAKE OUTAGE

Figure 2. Excerpt from Reitherman (1983, p. 39) showing how to reduce risk from earthquake damage for one type of nonstructural building component.

Lafferty (undated) provides a check list of responses for when an earthquake strikes, safety rules to be followed during an earthquake, and a form for authorizing medical treatment of minors. The American Red Cross (1982) also provides advice on coping with childrens' reactions to earthquakes and instructions for turning off gas-, electric-, and water-supply lines.

RECOVERY OPERATIONS

Recovery operations take from 1 to 20 weeks and may continue until all public facilities, institutions, and utilities return to normal. Repair of critical facilities* usually has first priority in a community or metropolitan area. Personal-recovery activities include:

- Ensuring safe ingress and egress to-and-from the home and its rooms.
- Repairing power and telephone lines.
- Repairing water-, gas-, and sewer-service lines.
- Inspecting structures and posting warning signs if found unsafe for habitation.
- Assisting neighborhood or community work parties that are assigned burial, temporary-shelter, vaccination, and transport tasks.

Personal recovery is difficult to separate from the recovery of the community or metropolitan area. For example, Rubin (1978) has written a helpful booklet on **Natural Disaster Recovery Planning for Local Public Officials** which includes: a discussion of the impact of a disaster on a community, warning signs that indicate insufficient community preparedness, and examples of successful community recovery. The Pan-American Health Organization (1981)

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*The term "critical facilities" is used here to include:

(a) Lifelines such as major communication, utility, and transportation facilities, and their connection to emergency facilities;

(b) Unique or large structures whose failure might be catastrophic, such as dams or buildings where explosive, toxic and radioactive materials are stored or handled;

(c) High-occupancy buildings, such as schools, churches, hotels, offices, auditoriums, and stadiums; and

(d) Emergency facilities such as police and fire stations, hospitals, communications centers, and disaster-response centers.

has provided easy-to-read comprehensive procedures for emergency relief including: management of mass casualties; disease control; management of relief supplies; and the planning, layout, and management of temporary settlements and refugee camps. Examples of continuing response and recovery activities for a volcanic eruption were given in a series of **Technical Information Network** bulletins released by the Federal Coordinating Office (1980).

RECONSTRUCTION ACTIVITIES

The reconstruction phase usually involves strengthening weakened or damaged structures, razing irreparable or obsolete buildings, or commencing a neighborhood or community redevelopment program. This phase, taking from 1 to 20 years or more, provides a unique opportunity to reduce future damage and loss of life from similar events by:

- Relocating structures to less hazardous areas; for example, out of a fault-rupture zone or landslide area.
- Constructing earthquake-resistant structures, particularly critical facilities.
- Reducing population densities in hazardous areas.
- Realigning infrastructures, such as pipelines power lines, and transportation routes, thereby minimizing the transversing of hazardous areas.
- Introducing redundancy into critical facilities; for example, alternate transportation and pipeline routes across fault-rupture zones.

The post-event reconstruction phase can also be considered a mitigation technique (see Table 1). Other techniques which may be used in conjunction with this one are moratoriums on rebuilding, regulations concerning land-use, location of capital improvements, and financial incentives and disincentives.

William Spangle and Associates, and others (1980) describe reconstruction plans and actions taken after the following earthquake disasters: 1971 San Fernando Valley, California; 1964 Alaska; 1969 Santa Rosa, California; 1963 Skopje, Yugoslavia; and 1972 Managua, Nicaragua. In addition, their discussion of the San Fernando and Alaska earthquakes includes issues, options and opportunities seized or missed. Popkin in **Reconstruction Following A Disaster** (Haas and others, editors, 1979, p. xxix) notes:

> Most policy issues involving reconstruction arise because some element of the community wants to avoid a similar future disaster. This usually happens shortly after the disaster and may cause conflict with the widely-held desire to return to normal as quickly as possible. The strongest pressure of all for prompt return to normalcy comes from the existence of displaced families and businesses. Such pressures do not necessarily make for orderly, well-planned reconstruction processes.

CONCLUSION

Many ways to reduce earthquake hazards are available, including: long-term mitigation techniques, preparedness measures, responses, recovery operations, and reconstruction activities. However, a prerequisite to their effective use is public awareness. Turner and others (1980) make the following recommendations for improving public awareness:

- o Carefully prepared and selected advice concerning earthquake preparedness for individuals and households should be given widespread and repeated public distribution through the media as well as other channels.
- o This preparedness advice should come from some authoritative government agency and should be endorsed by well-known local government officials and public personages.
- o Each recommended preparedness measure should be presented in conjunction with a brief but credible explanation justifying that recommendation and suggesting how it can be implemented.
- o Some responsible state agency should develop a program to promote earthquake safety in the household making use of local government, private agencies, and citizen groups. An especially useful program of this type would be one that conducted household safety inspections.

Successful programs promoting public awareness include this conference; SEISMOS '83, a City of Los Angeles simulated seismic event and metropolitan response (Manning, 1983); the 12th Annual Japanese National Earthquake

Preparedness Week and Drill (Bernson, 1983); the 1983 National Seismic Policy Conference (Western States Seismic Policy Council, 1984); the South Carolina Seismic Safety Consortium conferences (Bagwell, 1983); and the Governor's Conference on Geologic Hazards (Utah Geological and Mineral Survey, 1983).

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NEAR-SURFACE FAULTING ASSOCIATED WITH HOLOCENE FAULT SCARPS, WASATCH FAULT ZONE, UTAH: A PRELIMINARY REPORT

by

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INTRODUCTION

Abundant geologically young, fault scarps are clear evidence of recent major vertical displacements on the Wasatch fault zone in Utah (Swan and others, 1980; Schwartz and Coppersmith, 1984). Earthquake hazard assessments assume that the formation of these scarps was associated with earthquakes of magnitude 7 or greater (Bucknam and others, 1980). However, it is uncertain how these scarps relate to subjacent near-surface faults and to deeper faults that may be the source of damaging earthquakes. Understanding the relationship of the scarps to deeper structures formed in high strength rocks and to the regional structural framework can provide a better basis for realistic earthquake hazard assessments.

During the past two years, we have collected high-resolution seismic reflection data with a MINI-SOSIE[1] system across Holocene fault scarps at several locations along the Wasatch Front (Fig. 1). These profiles clarify the relationship between the scarps and the subjacent faults, and reveal the distribution of near-surface buried faults. From these data we can identify areas adjacent to the scarps where ground rupture might occur during future large earthquakes. Where available, deep structural information from

[1] Use of this name is for descriptive purposes only and does not constitute an endorsement by the U.S Geological Survey.

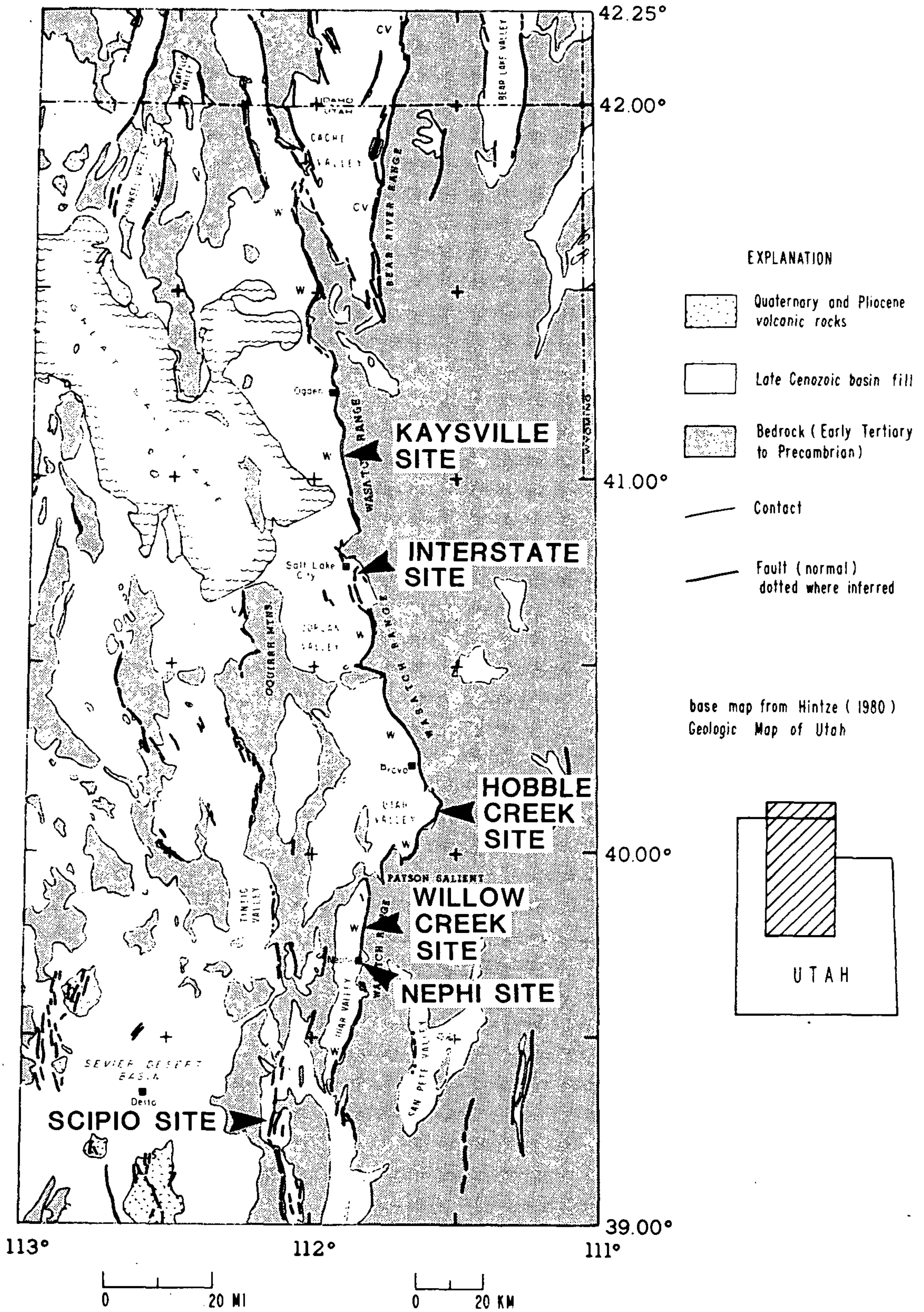

Figure 1.--Generalized geologic map of the Wasatch Front and environs, north-central Utah, and location of Mini-Sosie profile sites. Wasatch fault zone is indicated by "W". Modified from Zoback (1983b).

conventional reflection profiles can be used to relate the shallow buried faults and the scarps to deeper structures and to the regional structural patterns.

DATA COLLECTION AND PROCESSING

The MINI-SOSIE (MS) system is a small, versatile, high-resolution reflection technique that uses earth-tampers as energy sources. The foot of each tamper is fitted with a source sensor that identifies a time break for each impact of the foot. Time breaks for the impacts are transmitted to a recording truck by radio. The tampers have a peak energy input at about 45 Hz but they also supply higher-frequency energy above about 100 Hz (Wiles, 1979) that improves the resolution of shallow reflections.

Time breaks from the tampers are cross-correlated in the field with the signals received by the geophones. The cross-correlated data are electronically stored while data from succeeding impulses are cross-correlated. Vibration point (VP) spacing is 16 m. For each vibration point, sufficient cross-correlated data are stacked and autocorrelated to yield a good signal-to-noise ratio; in these surveys, a total of 1200 to 2400 impulses from three simultaneously operating tampers were stacked for each VP.

The field data were processed with a standard sequence of processing steps at the U.S. Geological Survey facilities in Denver. Processing steps included tape re-format and gain recovery, common-depth-point (CDP) sort, velocity analyses, normal moveout correction, datum and residual statics corrections, band pass filtering, final CDP stack, and, for some profiles, wave migration. For consistency, only unmigrated secetions are discussed here. The resulting record sections consist of one-second, two-way travel time of 12-fold CDP data.

The MS technique has several distinct advantages over conventional reflection-profiling methods. Because of its small size, the system can be easily transported into remote, poor access areas, a particularly useful advantage along some parts of the Wasatch Front where access is limited to steep, rugged roads and trails. The system is also capable of collecting reflection data in seismically noisy areas, a useful feature when working in urban areas. Where ambient seismic noise is a problem, the number of impacts stacked for each VP can be increased until the reflected signal can be distinguished from the undesireable noise. Another advantage of the MS is that it can operate in populated areas without the threat of the induced ground motion damaging nearby structures. Thus, the MS can fill gaps in conventional reflection data associated with areas of cultural development.

REFLECTION PROFILES

To date, seven MS reflection profiles have been collected at six locations along the Wasatch Front (Fig. 1). All of the times cited in the discussion of these profiles are two-way travel times as shown on the figures. Estimates of depth and displacements on faults were calculated from the stacking velocities used to process the profiles. Because of uncertainties in the velocities, the estimates should be regarded as only approximate.

Kaysville Site

Two parallel, east-west seismic lines about 0.3 km apart, were run across the large fault scarps located approximately 3 km southeast of Kaysville (Fig. 2). There, an approximately 22-m-high, west-facing scarp marks the location of the most recently active major strand of the Wasatch fault; a 1 to 2.5-m-high antithetic fault scarp lies west of the main scarp.

Relationships exposed in exploratory trenches and detailed surface mapping by Swan and others (1980) have documented several episodes of Late Pleistocene and Holocene surface faulting at this site. The stratigraphy in the trenches indicates at least three surface faulting events in the past 6,000 yrs producing a net vertical displacement of 10 to 11 m. Each event resulted in an estimated 1.7 to 3.7 m. of vertical displacement. Swan and others (1980) estimate a late Holocene recurrence interval of about 1000 yrs for surface faulting.

The 0.75-km-long Kaysville-2 MS line (Fig. 2), located about 150 m south of trench A of Swan and others (1980), crosses the main fault scarp at VP 1029 and an antithetic scarp at VP 1023. Line Kaysville-1, 0.61 km long (Fig. 2), crosses the main scarp at VP 925 and an 1 to 2-m-high antithetic fault scarp at VP 919. At both lines, the graben formed by the two scarps is about 96 m wide (16 m/VP x 6 VP).

On Kaysville-2, a strong, two-cycle (doublet) reflection (labeled A in Fig. 3) between 0.1 and 0.2 s extends across much of the profile and shows the amount and distribution of near-surface faulting in this area. Beneath and

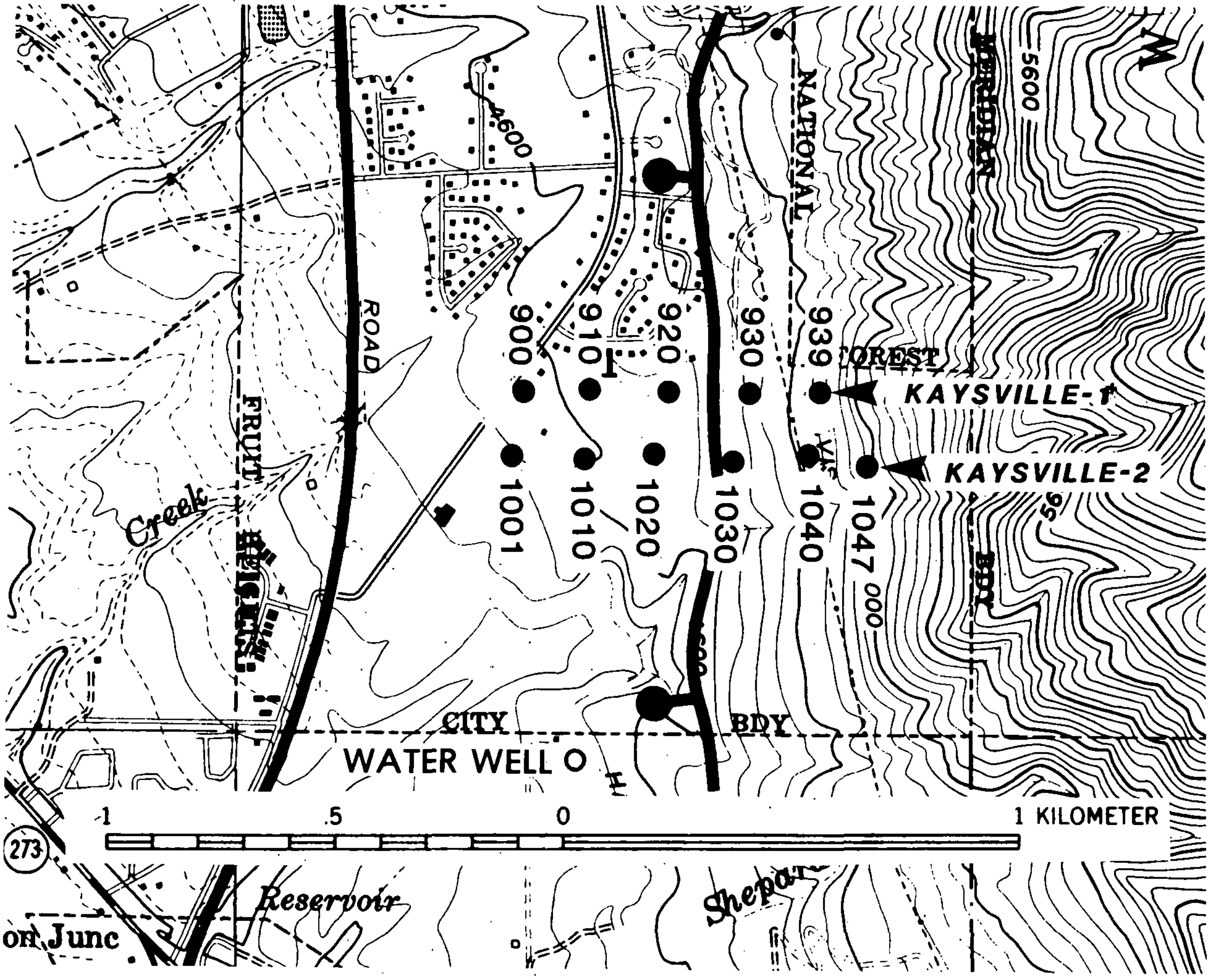

Figure 2. Vibration point (VP) map of Kaysville-1 and Kaysville-2 MS profiles plotted on the Kaysville 7.5-minute topographic quadrangle. Generalized location of main fault scarp from Cluff and others (1970) shown by heavy line; bar and ball on downthrown side. Antithetic fault west of main fault scarp not shown. Kaysville trench discussed by Swan and others (1980) was located at the scarp approximately midway between the two MS profiles. Distance between VPs is 16 m. Open circle is location of water well discussed in text.

east of the scarp, reflection A at about 0.095 s between VP 1027 and VP 1031 indicates that the fault associated with the scarp cannot be vertical. Just west of the main scarp a similar doublet reflection is at about 0.15 s. As will be discussed later, it is doubtful that all of the reflections labeled A

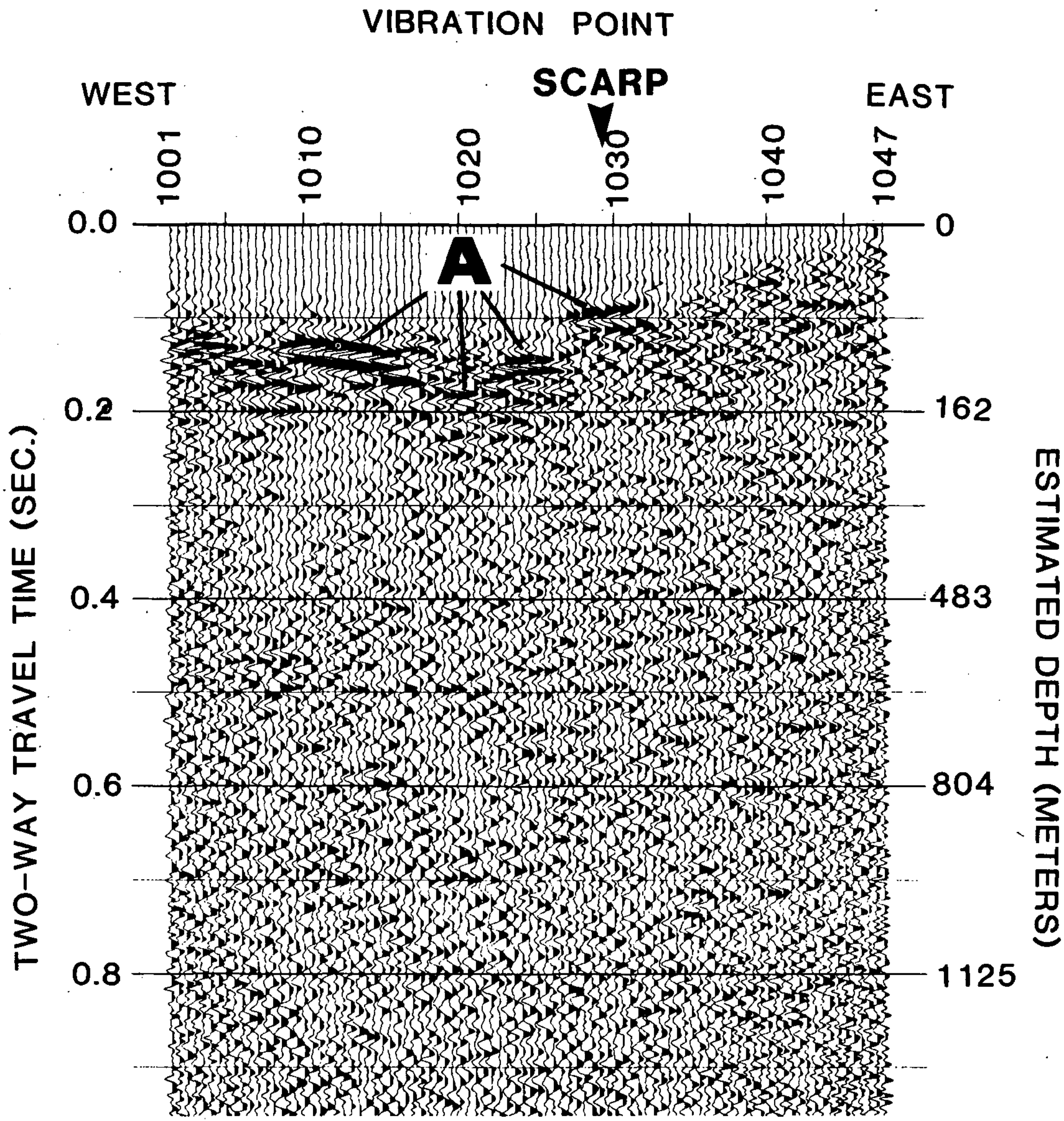

Figure 3. Kaysville-2 MS profile. Main scarp crosses the profile at vibration point (VP) 1029 and antithetic scarp (not shown) at VP 1023. Distance between VPs is 16 m. Reflection A is discussed in the text.

originate from the same stratigraphic horizon. Nevertheless, the displacement between reflections A at VP 1027 and at VP 1025 (±40 m) does identify the location of the main fault. If the western termination of reflection A at VP 1027 is projected upward to the scarp, the inferred near-surface dip of the fault is about 62^{o} to a depth of approximately 76 m.

West of VP 1027 reflection A is broken by a series of faults that form a broad graben. Down-to-the-west faults between VP 1023 and 1020 displace the reflection about 37 m to the low point of the graben. West from the low point, there may be antithetic faults near VPs 1017 and 1014. The total displacement between the low point and the shallowest reflections west of the graben is about 72 m. The subsurface graben is about 250 m wide, approximately 2.5 times as wide as the graben on the surface.

Data from a water well, located about 0.6 km south of the west end of the Kaysville-2 line (Fig. 2), combined with criteria developed by Arnow and others (1970) in Salt Lake Valley to the south, suggest that reflection A west of the main fault marks the base of the unconsolidated Quaternary sediments on the MS line. In Salt Lake Valley, Arnow and others determined that the Quaternary-Tertiary contact (i.e. base of the Quaternary sediments) is marked by a distinctive carbonate cemented horizon, interpreted to be the remanents of the soil that formed on the Tertiary sediments prior to burial by Quaternary sediments. The well penetrated a sequence of unconsolidated sands, clays and gravels and, at 88.7 m, it penetrated 3 m of cemented gravel in the bottom of the well. A reflector 88.7 m deep would generate a reflection at about 0.13 s, a travel time essentially the same as reflection A at the west end of the Kaysville-2 line.

There are no well data to identify the stratigraphic horizon responsible for reflection A at 0.1 s beneath and east of the fault scarp but it probably is generated by the contact between the bedrock and the overlying Quaternary and/or Tertiary sediments. If this reflection is correlated with the faulted reflections west of the scarp then the net displacement across the entire fault zone on the profile is only about 5-10 m. However the trenches of Swan and others (1980) indicate a net Holocene displacement of 10 to 11 m. Also, the net displacement across scarps formed in late Pleistocene Lake Bonneville sediments is about 20 m. This implies that reflection A east of the fault (VP 1027-1031) must correlate with a horizon that lies beneath the horizon producing reflection A west of the fault and that the net displacement indicated by the MS profile is a minimum value.

The reflections on seismic line Kaysville-1 are generally poor but there is a strong doublet reflection (labeled B in Fig. 4) at about 0.2 s between VP 917 and 909. To the east, there are few coherent reflections although at about 0.11 s at VP 925 there is some strong reflected energy and a suggestion of a weak doublet. Further east coherent reflections are absent. If the eastern termination of reflection B at 0.21 s at VP 920, is assumed to be the

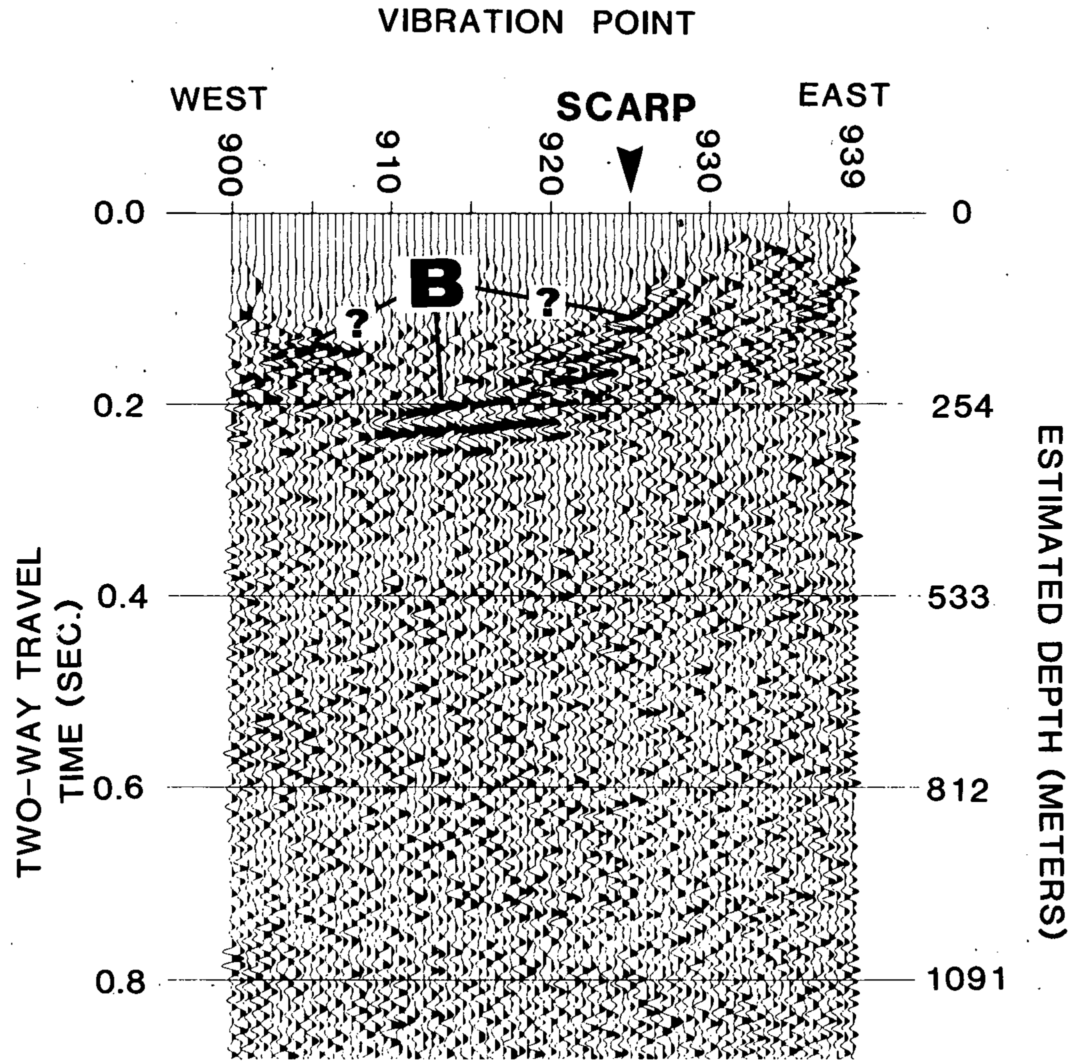

Figure 4. Kaysville-1 MS profile. Main scarp crosses the profile at vibration point (VP) 925 and antithetic scarp (not shown) at VP 919. Distance between VPs is 16 m. Reflection B, discussed in the text, is queried where correlation is uncertain.

location of the fault at a depth of about 240 m, then projecting this point up to the scarp implies a near-surface apparent dip of about 72^{o} for the fault.

West of reflection B, near VP 907, there is also some strong but incoherent reflected energy. Although very speculative, if this energy and reflection B are correlative, they indicate a major down-to-the-east antithetic fault with about 35 m of vertical displacement. This antithetic fault would be the western boundary of a subsurface graben that is a minimum of 176 m wide, about 1.8 times wider than the surface graben.

Reflection B on Kaysville-1 has an apparent west dip whereas the reflections on Kaysville-2 are essentially horizontal or have an east dip. The stacking velocities for Kaysville-1 show that the apparent west dip results from a westward decrease in the velocities across the profile. Depth estimates show that reflection B actually has an estimated 10^{0} to 15^{0} east dip.

The two-way travel times of the doublet reflections on Kaysville-1 and Kaysville-2 are noticeably different. Part of the difference may be real but much of it results from lateral velocity changes between the profiles and possibly variations in statics corrections.

There is a major difference in the number of faults on the two Kaysville profiles. Reflection B on Kaysville-1 is essentially unbroken across much of the inferred graben whereas numerous faults displace reflection A on Kaysville-2. This indicates that large variations in the number of individual faults may occur within short distances along the strike of the fault zone.

Interstate 80-Salt Lake City

Limited geologic information suggests that the East Bench fault scarp, a prominent topographic feature that extends through Salt Lake City and lies west of the main range front escarpment, may be the major structure separating the Jordan Valley graben from the Wasatch Range. East of the fault but west of the range front, a bedrock piedmont lies close to the surface, buried by a veneer of younger deposits (Marsell, 1969). In the Valley west of the fault, the bedrock is several thousand feet below the surface (Mattick, 1970). Locally the scarp is as much as 49 m high, and geologic studies show that some movement has probably occurred on the fault in the past 5,000 yrs (VanHorn, 1972).

A 1.44-km-long MS line was run across the East Bench fault along Interstate 80 between 1300 East and 700 East to clarify the relationship of the scarp to subjacent faults. Despite the extreme amount of ambient seismic noise, the record section shows a series of strong reflections between 0.1 and 0.3 s (Fig. 5).

At several places on the record section, lateral variations in the coherency of the reflections locally result in poor discontinuous reflections. The area of poor reflections between VP 716 and VP 730 is generally coincident with the 1200 East Overpass and is thought to be related

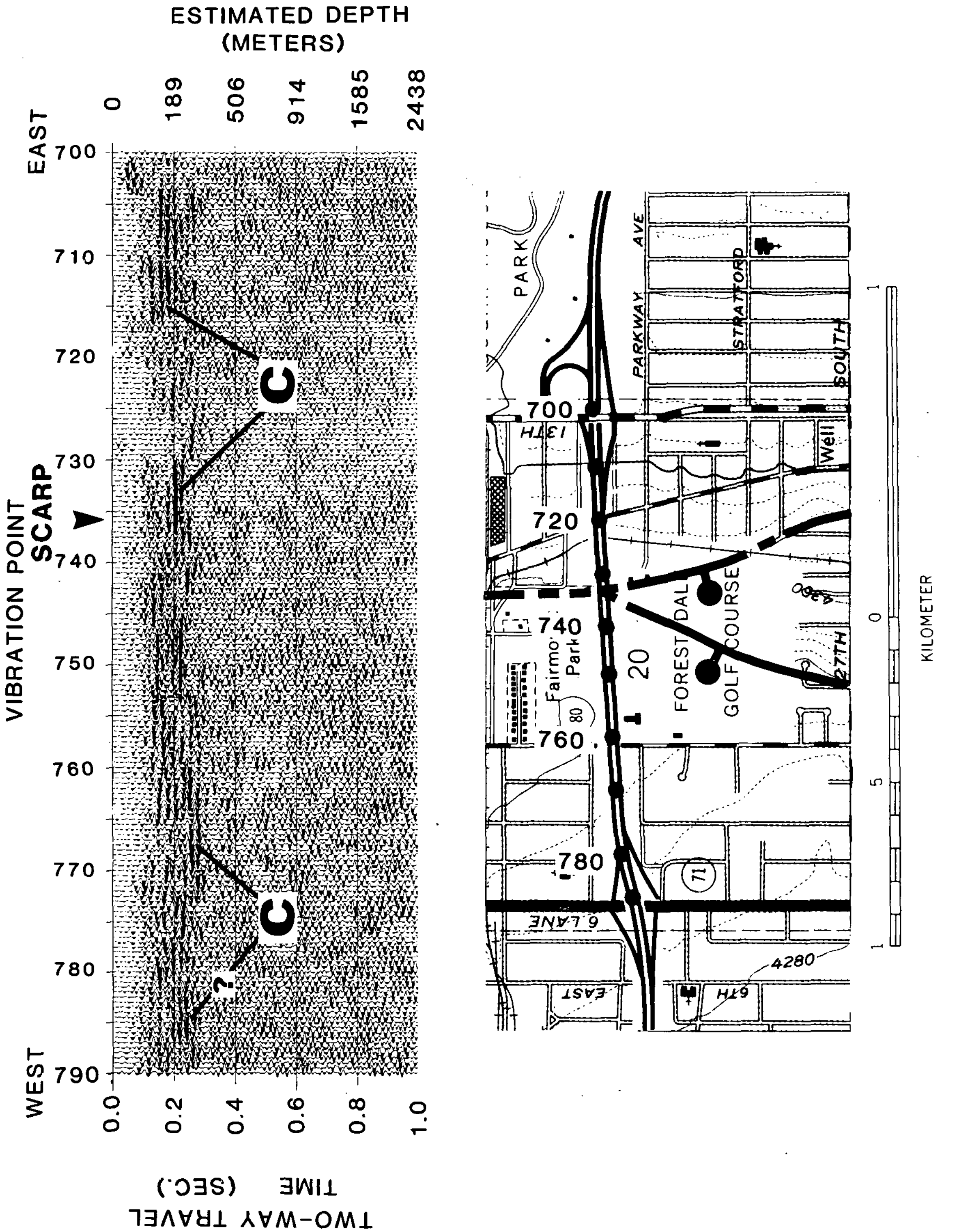

Figure 5. Interstate-80 MS profile and vibration point (VP) map. Fault scarp crosses the profile at about VP 736. Distance between VPs is 16 m. VP map is plotted on the Sugar House 7.5-minute topographic quadrangle. Fault scarps from VanHorn (1972) are shown as heavy line, dashed where concealed; bar and ball on downthrown side. Small solid dots are VPs in increments of ten. Reflections C, discussed in the text, are queried where correlation is uncertain.

to a decrease in the number of common-depth-points stacked near the overpass. Correlation of the strong reflections (labeled C in Fig. 5) at about 0.2 s on either side of the poor data are not definitive but a reasonable correlation suggests no vertical displacement.

The East Bench fault scarp crosses the profile at about VP 736 (Fig. 5) and, westward from this point to about VP 760, the general coherency noticeably decreases and the detailed character of the reflections changes. Within this less coherent zone, there are segments of essentially horizontal reflections but individual reflections seem to be laterally discontinuous. The strong reflections to the east and to the west cannot be traced into the zone. There are no bridges, overpasses or other cultural features that might account for the reduced signal quality in this zone.

West of this poor signal quality zone is a series of coherent reflections at 0.1-0.3 s between VP 760 and VP 770. The strong, two-cycle reflection at 0.25 s in this area is similar to reflection C near VP 734. Correlating these two-cycle reflections across the low coherency zone suggests a vertical displacement of about 85 m. Construction has obliterated the scarp along the highway but, on the golf course directly to the south (Fig. 5), it is conspicuous and about 3-4.5 m high (Marsell, 1969).

The well data near the MS line helps identify some reflections on the profile. A water well 0.9 km east of the east end of the line drilled a sequence of interbedded gravels and clays without encountering bedrock (Iorns and others, 1966), but, from a depth of about 94 m to the bottom of the hole at 175 m, the driller's log reports that the gravels are cemented. These cemented gravels may be part of the Tertiary Salt Lake Group. The 94 m depth converts to a two-way travel time of about 0.12 s, similar to that of the first strong reflection on the eastern part of the profile. The series of strong reflections on this part of the profile may be generated within the upper part of the Salt Lake Group and the shallowest reflection may correlate with the base of the Quaternary sediments. If the identification and the correlation of the reflections are correct then the MS profile indicates that vertical slip on the East Bench fault during the Quaternary has been on the order of 85 m.

Estimates of long-term slip rates on the East Bench fault are very poorly constrained because of uncertainty in the age of the basal Quaternary sediments in the Salt Lake City area. Quaternary sediments in the area are at least 600,000 yrs old (Scott and others, 1982, p. 24). A maximum age for the Quaternary sediments is based on the age of the upper part of the Salt Lake Group which is generally considered to be Pliocene. McDonald (1976, p. 306) reports that a well north of Salt Lake City (T. 3N., R. 1W.) is believed to have drilled into upper Pliocene sedimentary rocks. On the basis of this information, we use a maximum of about 2 million yrs and a minimum of 600,000 yrs for the age of the Quaternary sediments for this discussion. The resultant long-term slip rates are 0.14 m/ka and 0.04 m/ka. These estimated rates are considerably less than the Holocene slip rates (Swan and others, 1980; Schwartz and Coppersmith, 1984) but similar to the pre-Bonneville rates of Machette (this volume).

A water well located less than 0.5 km north of VP 755 penetrated 147 m of interbedded Quaternary gravels and clays (Marine and Price, 1963). This depth converts to a travel time of approximately 0.2 s, shallower than any strong reflections on nearby parts of the MS line.

Hobble Creek Site

The Hobble Creek MS site, located about 12 km southeast of Provo, Utah (Fig. 1), examines the relationship between near-surface structure and faulting, and a deformed late Quaternary (Provo lake-level) terrace that has been backrotated by movement on the Wasatch fault. A topographic profile parallel to but about 250 m to the north of the MS line shows that the originally west-sloping Provo lake-level terrace now slopes to the east for a distance of 385 m from the fault (Profile L-L'; Swan and others, 1980).

Detailed mapping and trench studies near the Hobble Creek site by Swan and others (1980) indicate six or seven surface faulting events in the past 12,000 to 13,000 yrs resulting in a net vertical displacement of 11.5 to 13.5 m. Less precise data suggest that movement on the Wasatch fault has vertically displaced Lake Bonneville sediments 18.5 to 38.5 m.

The Hobble Creek MS line is 1.66 km long and crosses the west-facing main fault scarp at the extreme east end (VP 397, Fig. 6). A two- to three-cycle reflection (labeled D in Fig. 6) occurs at about 0.14 s (approximately 150 m) below VP 397 and continues unbroken with a gentle west dip for nearly 100 m to VP 403. West of VP 403, similar reflections (labeled E in Fig. 5) appear to be downdropped to about 0.2 s. However the stacking velocity for reflection E is much higher than that for reflection D; calculations indicate that

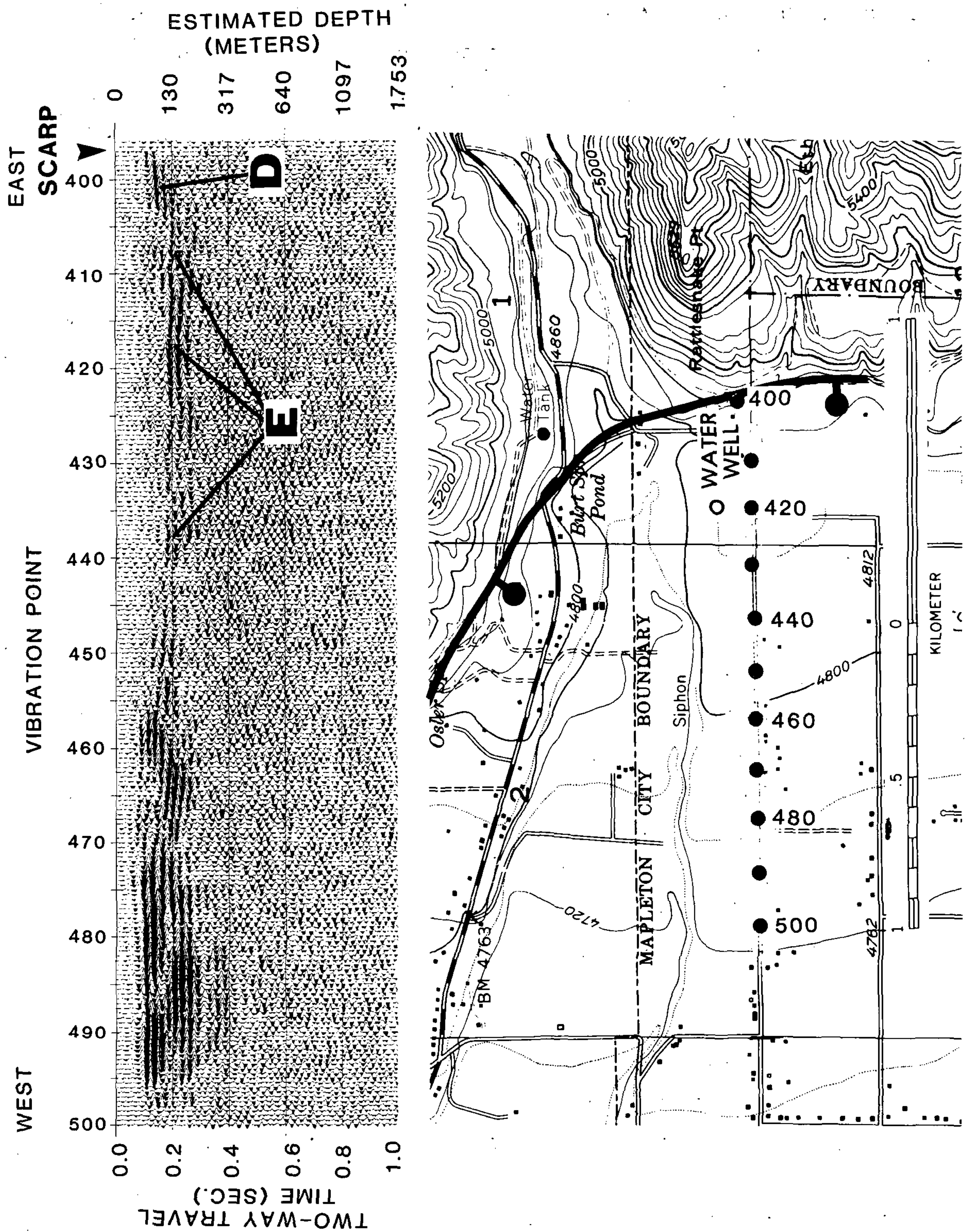

Figure 6. Hobble Creek MS profile and vibration point (VP) map. Fault scarp crosses the profile at the east end at VP 397. Distance between VPs is 16 m. VP map is plotted on the Springville 7.5-minute topographic quadrangle. Fault scarp generalized from Cluff and others (1973) is heavy line; bar and ball on downthrown side. Small dots are VPs in increments of ten. Open circle is water well discussed in text.

reflections D and E are at similar depths. The differences in stacking velocities are probably responsible for the apparent vertical displacement, but the difference also suggests that there may an important structural boundary at VP 403. There are insufficient velocity analyses to determine if the west dip of reflection D is apparent or real.

Reflection D constrains the near-surface geometry of the main strand of the fault. If the fault lies east of the reflection D, it is nearly vertical; if it lies to the west, it has a shallower dip. Although inconclusive, the MS data favor a nearly vertical fault interpretation. The absence of large amounts of vertical displacement between reflections D and E argues against extending the main strand of the fault west of reflection D, especially considering the large amount of post-Bonneville displacement.

The MS profile shows that warping of the Provo lake-level terrace is not simply a surface phenomena but occurs in the shallow subsurface. Westward from VP 403, reflection E is distinguishable to VP 410 where it becomes continuous and coherent to VP 423. Reflection E has a distinct eastward dip and an inflection point that coincides with the inflection point of the overlying warped terrace. This backrotation is similar to the "reverse drag" believed to be associated with listric normal faults (Hamblin, 1965), but the small size of the backrotated block (i.e. distance between the inflection point and the end of the east-dipping reflections) suggests that, if a listric fault is responsible for this backrotation, the fault would probably flatten at shallow depths.

An inflection point in the reflections at VP 474 suggests that a backrotated block larger than the one discussed above may extend across much of the profile. From VP 474, east to VP 403, all of the reflections have a gentle but obvious eastward dip. The east-dipping reflections are broken by several faults between VPs 452 and 472, none with any obvious surface expression. If the correlations are correct, individual faults have as much as 50-55 m of vertical displacement, but the net displacement across all of them is small. If a listric fault is responsible for this broader area of backrotation, it would extend to greater depths and perhaps be tectonically more significant than a listric fault associated with the inflection point of the warped Provo lake-level terrace. However, it is unlikely that even a listric fault with this larger radius of curvature (from the main scarp to the inflection point at VP 474) would directly extend to seismogenic depths.

It should be noted that warping and backrotation similar to that observed on the Hobble Creek MS profile could result from movement along a sinuous fault plane that is concave upward in the shallow subsurface and concave downward at greater depths. Such a fault could then extend to seismogenic depths.

A series of strong, unbroken, flat reflections extend from the inflection point at VP 474 to the west end of the profile. The general continuity of these reflections indicates little near-surface faulting along this part of the MS line.

Well control in the vicinity of the Hobble Creek profile is sparse. A drillers log of a 93-m-deep well located less than 200 m north of VP 420 (Fig. 6) shows prominent lithology changes at depths of 29 m and 73 m but these are shallower than all of the distinct reflections on the adjacent MS line. About 2.2 km south of VP 465, a 205-m-deep well (Cordova, 1969) drilled through interbedded clays, gravels and sands that are probably all Quaternary in age. The 205 m depth converts to about 0.27 s travel time on the MS profile suggesting that all of the reflections on the profile are from Quaternary sediments. The lack of specific age information precludes estimates of long-term slip rates.

Willow Creek Site

There is more than 2.1 km of topographic relief between the crest of the Wasatch Range and the floor of Juab Valley (Fig. 1) near the town of Mona. Displacement on the Wasatch fault zone has probably produced much of the relief although preexisting topography may have contributed to the total (Eardley, 1933). Trenching studies and the morphology of the youthful fault scarp along this part of the range suggest that the last major displacement may have been only 300 to 500 yrs ago (Schwartz and Coppersmith, 1984).

To investigate the near-surface structure associated with this young fault scarp, we collected MS data along a 1.47-km-long line extending generally westward near Willow Creek Canyon, about 2.7 km southeast of Mona (Fig. 7). At the mouth of the canyon at VP 109 the profile crosses an approximately 6-m-high scarp (Machette, this volume). In the canyon east of the scarp, Pennsylvanian-Permian Oquirrh Formation (Hintze, 1980) is covered by a veneer of stream alluvium. In Juab Valley west of the fault, locally as much as 610 m of basin-fill overlies the downfaulted bedrock (Eardley, 1933).

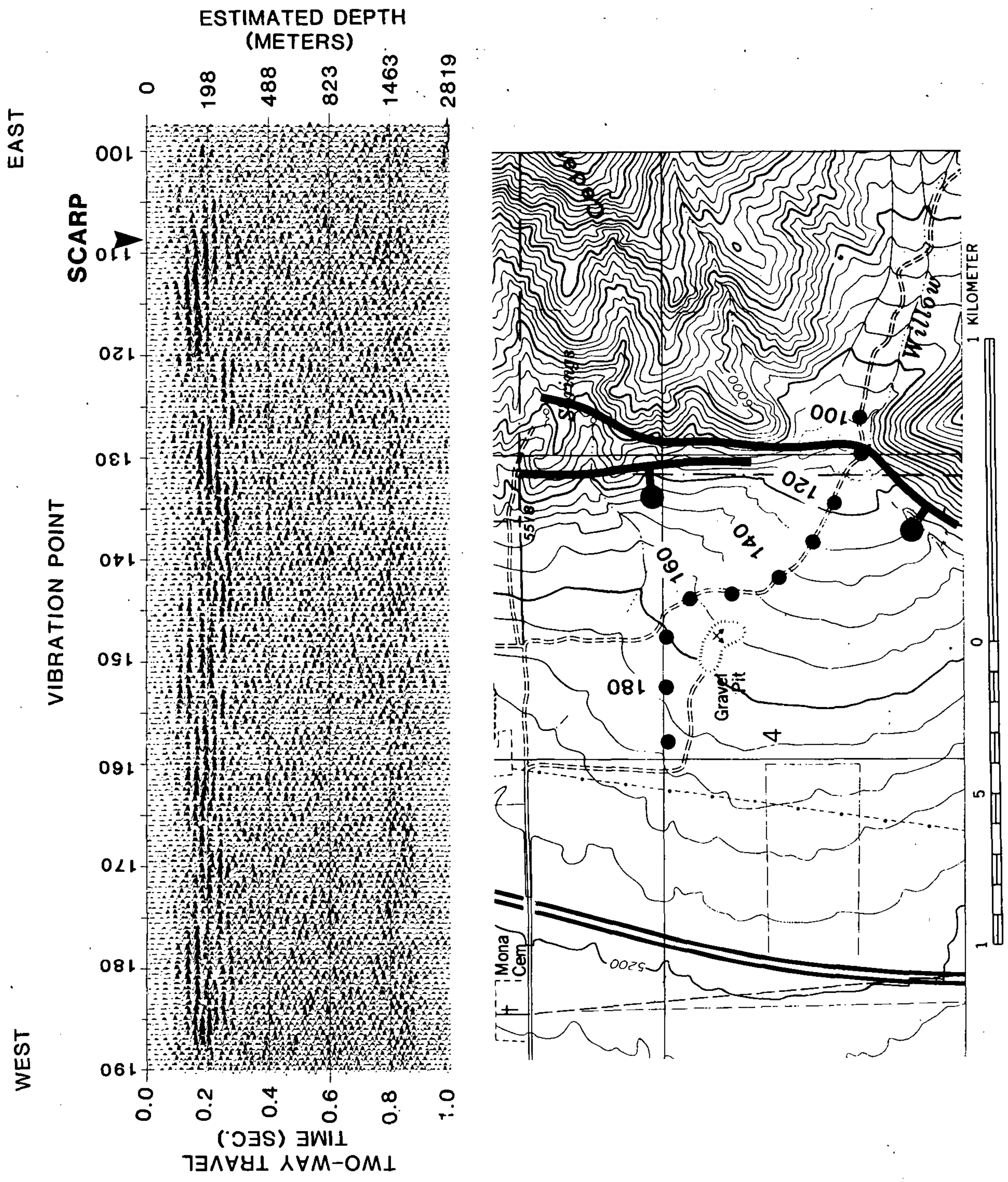

Figure 7. Willow Creek MS profile and vibration point (VP) map. Fault scarp crosses the profile at the mouth of Willow Creek Canyon at VP 109. Distance between VPs is 16 m. The VP map is plotted in the Mona 7.5-minute topographic quadrangle. Fault scarps generalized from Cluff and others (1973) are heavy lines; bar and ball on downthrown side. Small dots are VPs in increments of ten.

The part of the profile in the canyon has few coherent reflections but west of the scarp, there are a series of reflections between 0.10 and 0.25 s (approximately 85-267 m) from within the basin-fill. From the scarp westward to VP 140, correlation of the reflections shows a gentle westward dip of about 2.5^{o} toward the valley. This is interpreted as a primary depositional dip.

The quality of the reflections from the basin-fill clearly deteriorates at two locations west of the scarp, a zone between VP 120 and 126, and near VP 140. The zone of poor reflections between VP 120-126 is perplexing. Good quality reflections to the east and west at 0.15-0.2 s abruptly disappear and, within the zone, a distinct doublet is present at about 0.25 s. The continuity of the doublet precludes large faults within the zone but does not eliminate the possibility of faults at either edge. A reasonable correlation of reflections across the zone suggests little net displacement. Near VP 140 the character of the reflections gradually changes toward the west, making it difficult to confidently correlate the reflections to the east with those to the west. Along the western part of the line, changes in wave amplitude and frequency suggest that facies changes may occur within the basin-fill. The amplitude and frequency variations result in discontinuous reflections that make it difficult to recognize possible small faults, but there is sufficient general continuity across most of the profile to conclude that major near-surface faults other than the fault associated with the scarp are absent.

On the basis of this profile, displacement on the fault zone in the vicinity of Willow Creek seems to be concentrated in a narrow zone, perhaps on a single strand, with little displacement on subsidiary faults. This is consistent with the comparatively simple pattern of fault scarps at the base of the range in this area (Cluff and others, 1973).

Nephi Site

Near the town of Nephi (Fig.1), a major change occurs in the range-front physiography and in the distribution of Holocene scarps. North of town, the range crest towers over Juab Valley, and multiple surface faulting events have produced large Holocene scarps. South of Nephi, the relief between the range crest and valley is much less and there is a 17-km-long gap in Holocene scarps (Schwartz and Coppersmith, 1984). Where present south of the gap, the scarps are small, single-event scarps. These changes suggest that Nephi is located near a major boundary between two segments of the Wasatch fault zone and that the long-term behavior of the two segments is very different (Schwartz and Coppersmith, 1984).

The deep structure at this important boundary has been studied by Zoback (1983a; 1983b) using conventional seismic reflection and gravity data, but these data do not clearly reveal the location or distribution of near-surface faults. Specifically, the conventional reflection profile has no data in the upper 0.2 s and a large "drop-out" of "deep" data in Nephi. To fill this critical gap, we collected 3.97 km of MS data along the route of the conventional reflection line from east of the Wasatch fault in Salt Creek Canyon to beyond the west edge of town (Fig. 8).

An additional objective of the Nephi MS line was to locate areas of potential surface faulting in town during future earthquakes. The prominent scarps north of town die out before reaching Nephi (Fig 8), thus the surface faulting hazard is uncertain.

The general attitude of the reflections on the MS profile (Fig. 9) and the stacking velocities both suggest that there is a boundary between the bedrock in the range and basin-fill at about VP 340. From the east end of the line in Salt Creek Canyon where bedrock is exposed, to about VP 340 (Fig. 8), the reflections at 0.1-0.2 s are locally faulted but have a uniform westward dip (Fig. 9), and stack at velocities of 1981-3048 m/s. From VP 340 to the west end of the line, all of the reflections at about 0.2 s are subhorizontal or have a slight eastward dip and stack at velocities between 1372-1676 m/s. The relatively high stacking velocities east of VP 340 indicate that these reflections are probably associated with the lithified Mesozoic and early Tertiary sedimentary bedrock; the lower stacking velocities to the west suggest that the reflections are probably associated with basin-fill sediments. The record section falsely implies that the reflections east and west of VP 340 are vertically displaced; both sets of reflections have estimated depths of about 122 m.

The bedrock and basin-fill boundary at VP 340 most likely coincides with the location of a buried fault. A broad zone of incoherent noise and weak reflections between VP 340 and 380 on the MS profile supports this interpretation. The noisy zone with poor reflections starts at the boundary (VP 340) and continues to VP 380 where the reflections become strong and distinct. This part of the profile with the poor reflections trends northwestward, subparallel to the local trend of the range and essentially

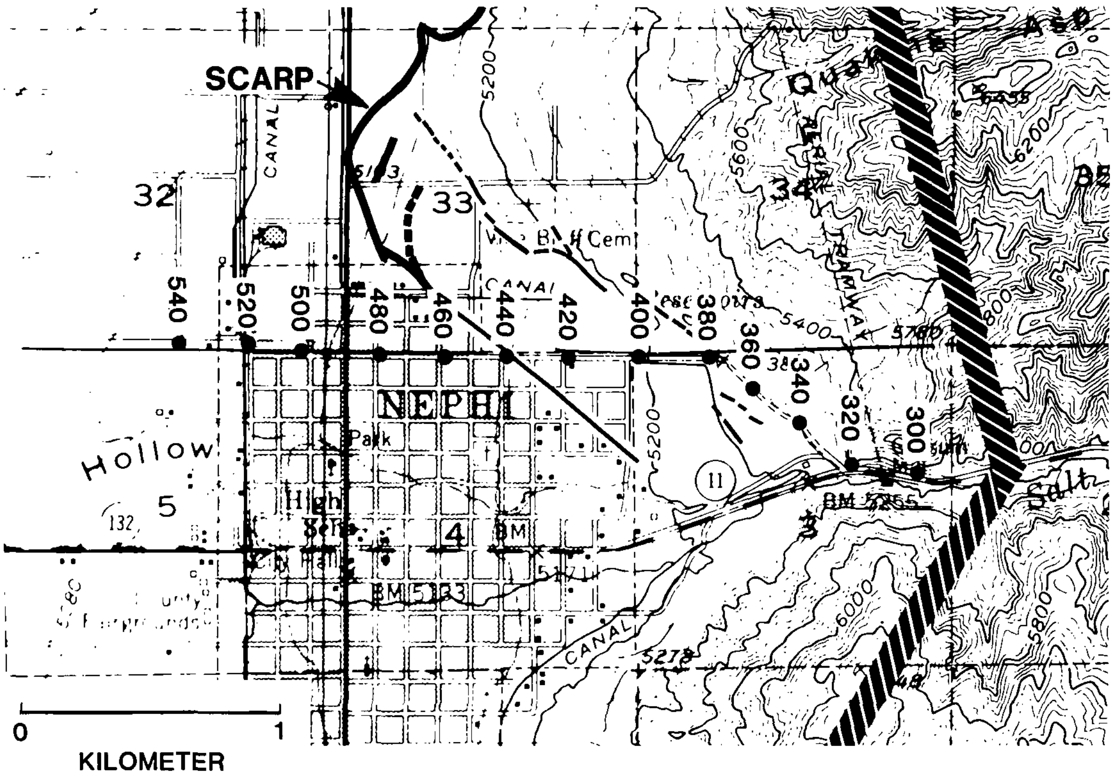

Figure 8. Nephi MS-profile vibration point (VP) map. Map is modified from sheet 10 of Cluff and others (1973). Fault scarps are heavy lines, dashed where approximate. Fine lines are possible surface faults with little or no vertical relief; dashed where approximate. Distance between VPs is 16 m. Small dots are VPs in increments of ten.

parallel to the expected local strike of a fault. The good quality reflections occur where the line turns westward, away from the range and away from the interpreted fault (Fig. 8). The zone of weak reflections and noise is probably related to disruption and "out-of-plane" reflections from this fault zone. The similar estimated depths for the reflections on either side of VP 340 suggest that there has been little recent vertical displacement on this fault.

The fault interpretation for this boundary is also supported by the possible fault-related lineaments (Fig. 8) parallel to and adjacent to the northwest-trending part of the MS line (Cluff and others, 1973). A possible small fault on the MS profile at VP 383 may also be related to these lineaments (Fig. 9). A lineament that crosses the MS line near VP 440 does not appear to be fault related

Correlations of the strong, continuous, two- to three-cycle reflection (labeled F in Fig. 9) at about 0.2 s across the central 1.66 km of the MS

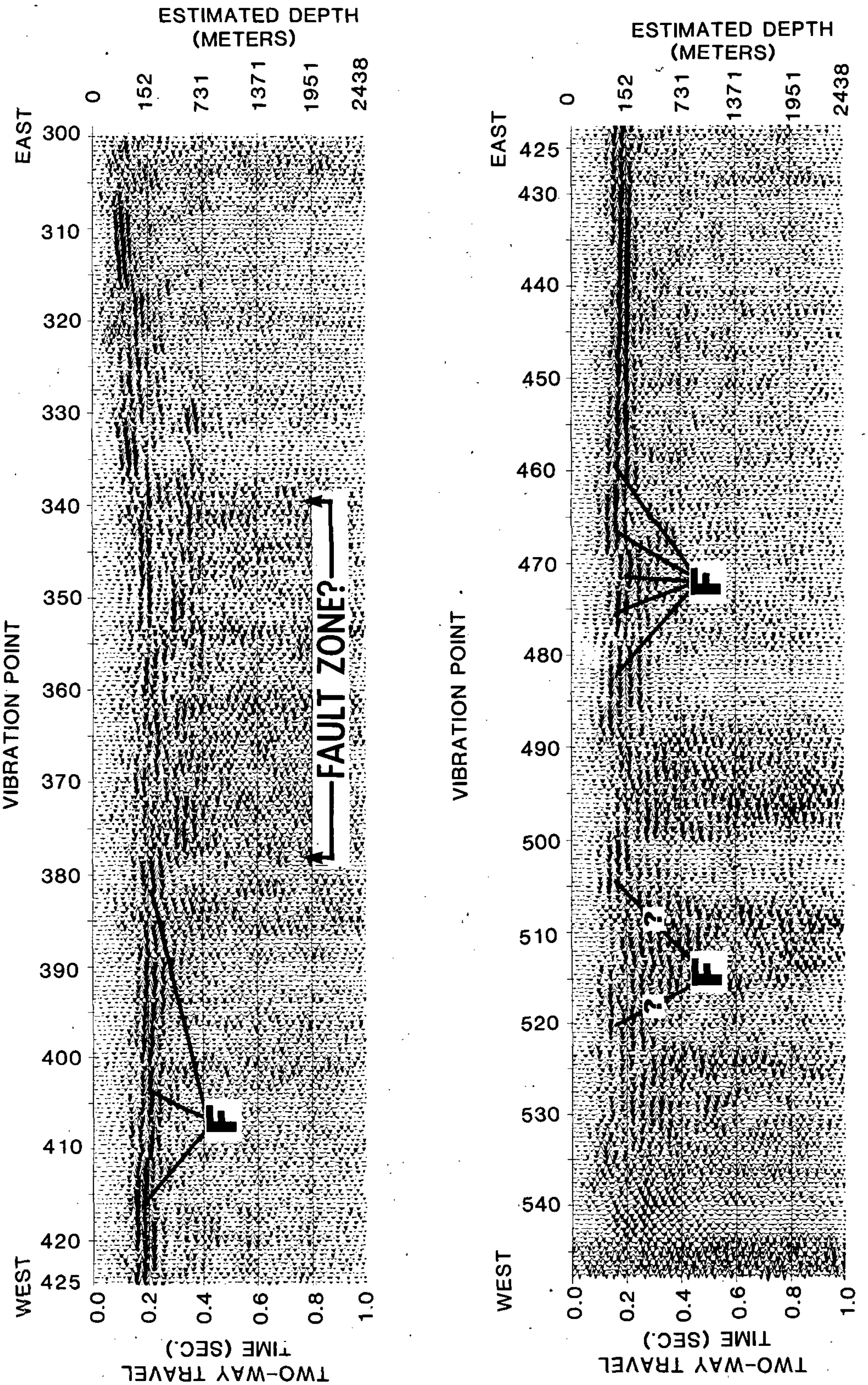

Figure 9. Nephi MS profile. Profile is broken into two segments that overlap between VPs 423-425. Distance between VPs is 16 m. Reflection F, queried where correlation is uncertain, is discussed in the text.

profile indicate probable faults at VPs 468, 473, and 478. The faults at VPs 468 and 473 define a narrow graben; the vertical displacement of about 46 m on the down-to-the-west fault at VP 468 and 35 m on the antithetic fault at VP 473 yields a net displacement of about 11 m across the graben. A small down-to-the-west fault at VP 478 has about 9 m of displacement.

From these faults to the west end of the line, the quality of the reflections varies; in the areas of good data, subhorizontal reflections are visible down to about 0.4 s. The subhorizontal reflections at about 0.3 s on the MS line probably correspond to a reflection at a similar travel time on the conventional reflection profile. Some areas of poor MS data are probably related to junctions with major roads and bends in the line.

Gravity data combined with the MS and the conventional reflection data show that the major fault zone separating the basin in Juab Valley from the Wasatch Range is probably located near VPs 468-478, not near the fault at VP 340. A two-dimensional model of the gravity data shows Juab Valley contains a maximum of 1.2 km of basin-fill just west of Nephi (Zoback, 1983b). Stacking velocities for the conventional reflection profile show that bedrock is not deeply buried on the downthrown side of the fault at VP 340. This requires the presence of another fault zone west of VP 340 that is the major boundary of the east side of the basin. The near-surface faults between VPs 468-478 probably identify the location of this eastern boundary. The MS stacking velocities show that these near-surface faults are formed in the basin-fill, but they occur where the conventional reflection profile constrains the location of the eastern margin of the basin (M. L. Zoback, 1984, oral commun.). Movement on the near-surface faults is probably controlled by movement on the subjacent basin-margin faults. The configuration of this part of Juab Valley indicated from all of these data is a bedrock bench, buried by a comparatively thin cover of basin-fill, that extends westward from near the range front (VP 340) to the eastern basin-margin fault zone located near VPs 468-478. The east edge of the bedrock bench is probably bounded by a fault that has little Quaternary vertical movement.

The near-surface faults at VP 468-478 are generally on strike with, but about 0.3 km south of, the prominent scarps mapped by Cluff and others (1973). Displaced reflections indicate faults as shallow as approximately 58 m. Based on the MS data, it seems likely that the faults associated with the scarps north of Nephi extend southward into the town. Although the most recent movements on this part of the Wasatch fault zone apparently did not produce surface faulting within Nephi, our interpretation indicates that the near-surface faults in Nephi are probably continuous with the faults that have recently formed scarps to the north and are associated with deeper basin-bounding faults that have a long history of movement. Thus, during future earthquakes, displacement on the near-surface faults might produce surface ruptures in town.

Scipio Valley Profile

Scipio Valley is located about 55 km south-southwest of Nephi (Fig. 1) and lies within the transition zone between the Colorado Plateau and the Great Basin. There are numerous scarps in the Valley, some with associated well-defined grabens. A prominent scarp near the northern end of the Valley shows evidence of Holocene movement superimposed on a pre-Holocene scarp (Bucknam and Anderson, 1979).

The 0.75-km-long Scipio Valley profile (Fig. 10) shows that an approximately 5-m-high scarp represents a young displacement on a subjacent fault zone. The fault most directly related to the scarp has an average dip of about 69°E. Segments of coherent reflections only occur in the upper 0.5 s providing no data on the fault geometry below about 400 m. The variable quality of the reflections makes correlations across the interpreted faults tenuous. Reflections G, east of the fault zone, do not have any correlative reflections to the west but if the correlation of reflections H is correct, one strand of the fault has a vertical displacement of about 68 m. This suggests multiple episodes of movement.

In Scipio Valley, the North Horn Formation and Flagstaff Limestone of Late Cretaceous and early Tertiary age underlie the alluvium and locally, sinkholes and collapse features form where accelerated groundwater dissolution occurs in faulted and fractured carbonate bedrock (Bjorkland and Robinson, 1968). It seems unlikely that this process would produce recurrent movement on the long, high scarps described by Bucknam and Anderson (1979) or produce the differential movement on a moderately dipping fault as interpreted on the MS profile. Scarps in Japanese Valley, about 12 km to the east, have been attributed to salt diapirism (Witkind, 1982), but lack of deep data does not permit this possible mechanism to be evaluated at the Scipio site.

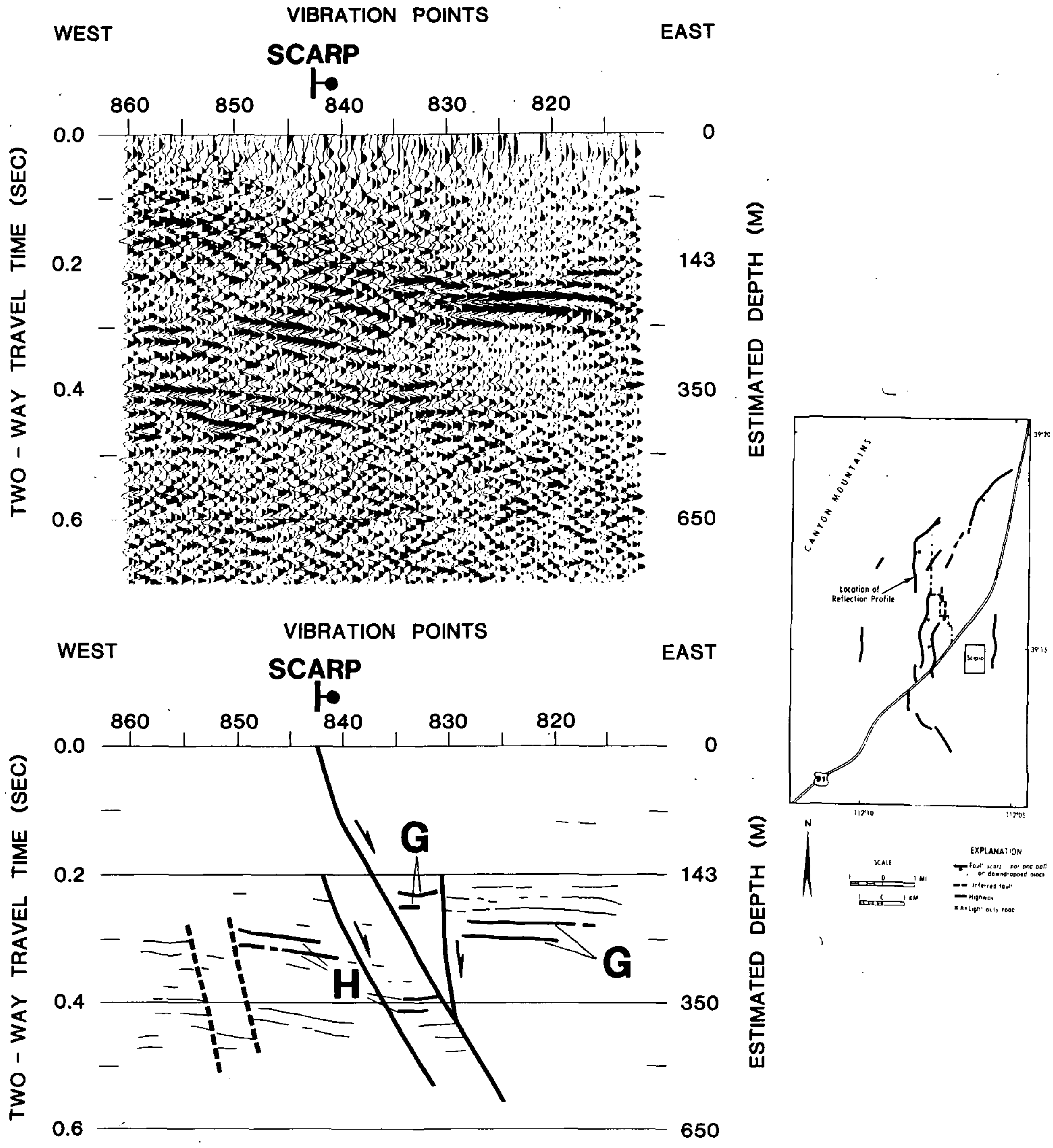

Figure 10. Scipio Valley MS profile, line drawing, and generalized location map. Fault scarp crosses the profile at vibration point 843. Reflections G and H are discussed in the text. Arrows show directions of movement on faults interpreted in line drawing.

CONCLUSIONS

The MS system is an effective means of examining the near-surface structure and faulting associated with Holocene fault scarps along the Wasatch Front. Future studies will examine the near-surface structure at proposed segment boundaries such as at the salient north of Salt Lake City, and investigate the potential for surface faulting in urban areas from movement on intra-basin faults. To date, important observations on the profiles include:

1) The main fault scarps overlie either vertically displaced reflections, zones of incoherent reflected energy, or zones of weak reflections. The MS profiles show that many inferred faults or fault zones, some with substantial vertical displacements, are not associated with scarps in surficial deposits.

2) The area of shallow subsurface faulting and deformation is commonly more extensive than expressed by young fault scarps at the surface . Defining areas of potential surface faulting solely on the basis of recognizable fault scarps may underestimate the surface faulting hazard.

3) The two adjacent profiles at Kaysville show that there can be large variations in the number of individual faults within a short distance along the strike of the fault zone.

4) The East Bench fault at Interstate-80 in Salt Lake City may have as much as 85 m of Quaternary vertical displacement. Although very poorly constrained, the available data suggest a Quaternary slip rate for the fault that is considerably less than the Holocene slip rates estimated from trenching studies of other parts of the Wasatch fault zone.

5) At Hobble Creek a broad area of backrotation in the shallow subsurface extends west of the scarp for more than a kilometer. A more local area of backrotation coincides with the warped Provo lake-level terrace described by Swan and others (1980). The backrotation may be evidence of listric faults. If the near-surface faults identified on the profile are listric faults, their relationship to deeper seismogenic faults is uncertain.

6) At Nephi, the combination of gravity data, the MS line, and conventional reflection data suggest that the major basin-margin fault zone is not located at the range front but, to the west, within the town. Movement on near-surface faults associated with the fault zone could potentially cause surface faulting in the town during future earthquakes.

ACKNOWLEDGEMENTS

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CONTEMPORARY VERTICAL TECTONICS ALONG THE WASATCH FAULT ZONE MEASURED BY REPEATED GEODETIC LEVELING

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INTRODUCTION

Apparent ground-surface tilt and vertical movement can be derived from a comparison of repeated geodetic leveling of permanent benchmark monuments. Elevations have been surveyed by precise geodetic leveling along many main roads and railroads in Utah. The present study has concentrated on repeated surveys across the Wasatch Fault in Weber Canyon near South Ogden (Figure 1) because an apparent ground-surface tilt with a 12-cm vertical component is associated with the fault and developed since a 1958 survey (Wood and Bucknam, 1983). This vertical movement has considerable significance with regard to contemporary preseismic strain accumulation in the fault zone, and implications with regard to the frequency and nature of earthquake occurrence and tectonic deformation. This line and the route from Ogden, Utah to Rock Springs, Wyoming, was releveled by the National Geodetic Survey (NGS), June - October, 1983, using newly developed procedures designed to eliminate the past difficulties with slope-dependent, systematic, cumulative errors in height determination and in vertical crustal-movement studies. The 12-cm vertical movement is based largely upon baseline elevations from leveling in 1958. The 1958 precise geodetic leveling observations have been coded and recalculated using the NGS computer program, REDUC 4, to estimate and apply a refraction correction (Figure 2).

Detailed data on the spatial and temporal nature of vertical tectonic deformation of a region would be extremely useful for earthquake-hazard evaluation and for long-term forecasting and possibly short-term prediction of earthquake occurrence. Repeated geodetic leveling is still the best available

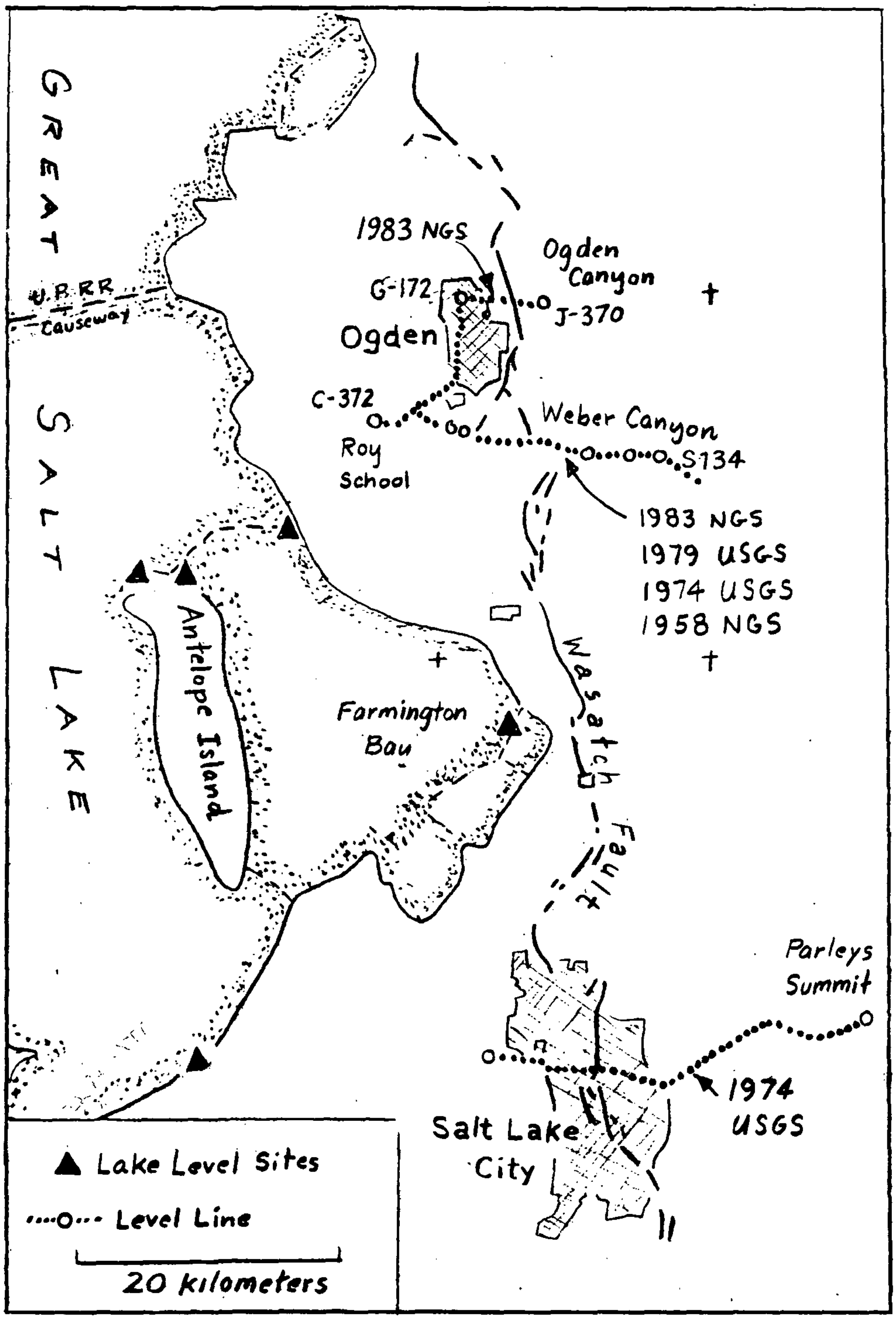

Figure 1.--Network of level lines and lake-level sites for monitoring vertical tectonic movement along the Wasatch Front in the Salt Lake City-Ogden area. (Not shown on this map are the route of the 1903, 1953, and 1967 geodetic leveling surveys of the NGS that run north-south and just west of the fault. These surveys are being re-evaluated for validity of observed elevations).

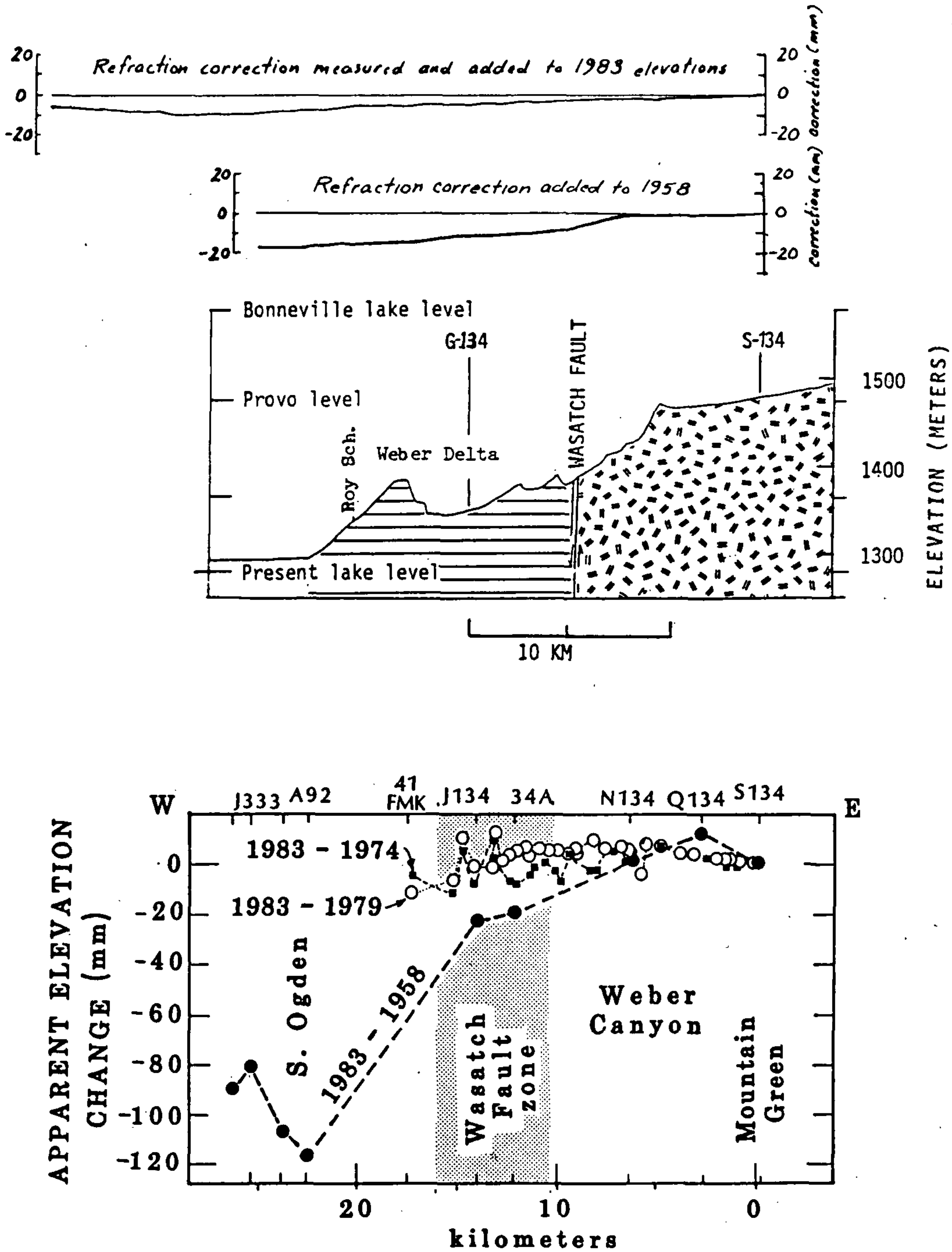

Figure 2.--Profiles of apparent elevation change across the Wasatch fault in Weber Canyon near Ogden (bottom of page). In all profiles, elevations determined in previous years are subtracted from the 1983 elevations and the changes are arbitrarily referenced to bench mark S-134 near Mountain Green, Utah. Above the elevation change profile is a profile of elevation through Weber Canyon along the 1983 leveling route. Profile west of G-134 does not correspond to leveling route. At top of page is a profile of the refraction corrections applied to the 1983 observations, and the estimated refraction corrections applied to the 1958 data. The difference between these two curves has been applied to the 1983-1958 profile at the bottom of the page, and the effect has been to remove a very slight amount of down to the west tilt. The apparent elevation change at the bottom of the page is interpreted to be a down-to-west tectonic tilt.

method for obtaining quantitative profiles of ground-surface tilt and elevation change. New procedures of the NGS have largely resolved problems of slope-dependent systematic errors and can resolve 1 mm/km of vertical movement or 1 microradian of tilt. Limitation on obtaining regional coverage of this kind of data is the current cost of $350/km for single-run, precise geodetic leveling a line of benchmarks. Other systems for obtaining elevation differences of tectonic interest over continental distances are under development (Panel on Crustal Movements, NRC, 1981), but none are routinely used in Utah.

Recovery of older baseline elevation data from past geodetic leveling surveys in the United States is a long-term project of the NGS (Holdahl, 1983). Controversy over vertical-crustal movement measurements by leveling over the past 6 years has now focused largely on the error caused by vertical temperature gradients near the ground that cause bending of the line of sight between the telescopic level instrument and the rod. This refraction error has been found to be considerable, particularly along gently-sloping railroad routes where long-sight lines are possible. Error increases as the square of the sight-length, and prior to 1964, the NGS permitted 70-m sight lengths rather than the 50 meter limitation currently used. This correction was neglected until about 1977. Current field procedures and data reduction of the NGS are designed to correct for refraction and other accumulating systematic errors discussed by Balazs and Young (1982). A method has been developed by Holdahl (1982, 1983) to recalculate older data and incorporate an estimate of the vertical temperature gradient from single temperature measurements and knowledge of typical seasonal meteorological conditions in the United States. Coding and recalculating the repeated surveys for Utah is a considerable task and is not a high priority for the limited staff of the NGS. Therefore we are reviewing the old observed elevations and will request only the most critical lines. We are also coding some of the USGS precise leveling for recalculation.

Lake level of Great Salt Lake and Utah Lake are referenced to shoreline benchmarks from time to time on this project as a means of obtaining an independent set of data on vertical tectonic movement. A site on Farmington Bay within 3 km of the Wasatch Fault (Fig. 1) is being installed with an electronic, digitally-recording water-level monitoring and data transmission system. The time record of water levels will be continuously differenced with data from another site on the same body of water 15 or more km further west. The pair of sites will act as a long-baseline tiltmeter to monitor movement of the earth's surface near the fault with respect to points to the west.

LEVELING DATA ANALYZED ALONG THE WASATCH FRONT

The 1958 elevations have been recalculated using the REDUC 4 program of the National Geodetic Survey. The 1983 elevations were obtained by procedures recently developed to minimize the systematic errors. To illustrate the nature of the accumulated refraction error when it is not considered, this accumulated correction is profiled along the level line discussed in this paper (Fig. 3 and 4). The correction for the 1958 data is based upon an estimation procedure discussed above, whereas the correction for the 1983 data is based upon actual measurement of the temperature gradient at every instrument set-up along the line. The correction applied to the 1958 data accumulates along the line to 17 mm, and appears as a small tilt in a releveling comparison. In all cases, the refraction correction is added to the elevation difference between two points, for refraction of the sight line has the effect of shortening the surveyed elevation difference. The correction applied to the 1983 data is only 5 mm along the same line. It is much smaller because the sight lines are shorter. When refraction corrections are applied, a tilt amounting to 17 mm - 5 mm = 12 mm over the length of the line would appear as an apparent elevation change due entirely to different conditions of sight-line refraction experienced by the two surveys. In this case, this erroneous small tilt is in the same sense as the hill slope because the earlier survey obtained erroneously lower elevation differences when leveling uphill, whereas the more recent survey obtained somewhat greater elevation difference over the same route.

The 1974 and 1979 elevations surveyed by the U.S. Geological Survey (USGS) over the eastern part of the Weber Canyon line have not been corrected for refraction or for possible rod-calibration error, but it is felt that the data is useful and accurate at originally calculated for the following reasons. These surveys used rods calibrated at three points, and had maximum

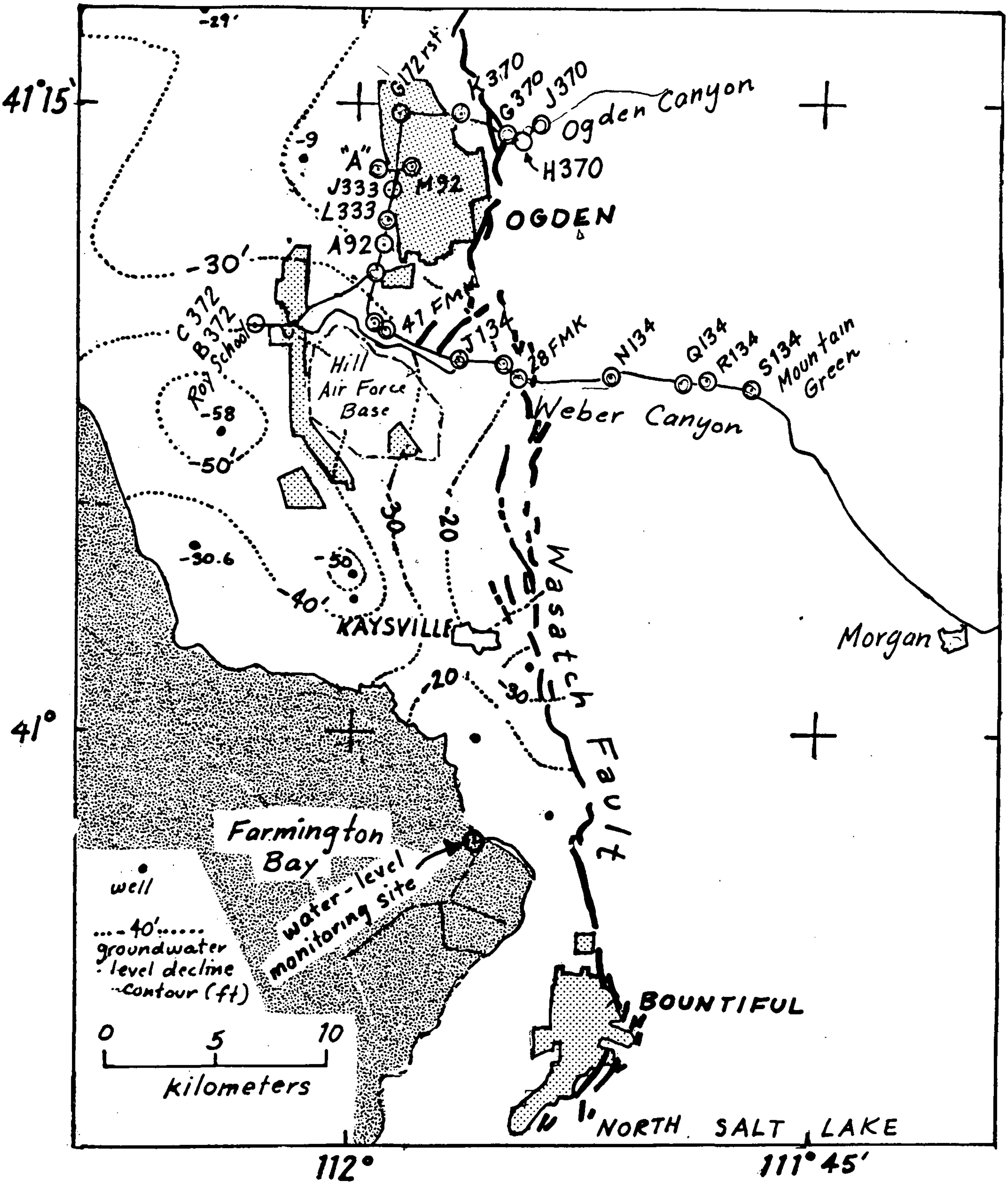

Figure 3.--Map showing benchmark location in the Ogden area. Contours show the water-level declines in confined aquifers in the Weber delta area from 1952 to 1983 (preliminary and unpublished data from Ted Arno, 1982).

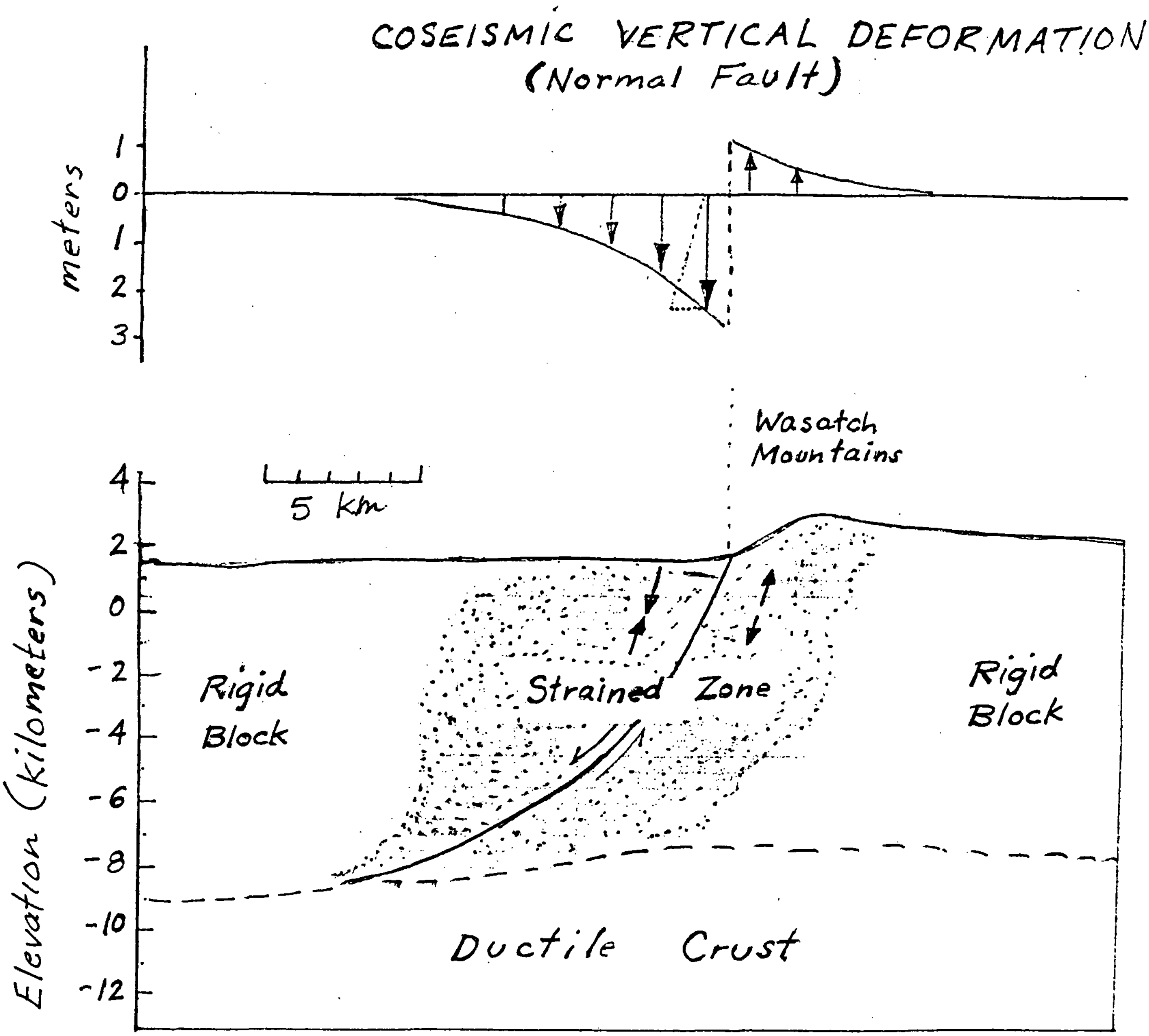

Figure 4.--Conceptual model of the zone of strain accumulation and the anticipated coseismic tectonic deformation from a large earthquake on the Wasatch Fault zone, based upon data in Figure 5. Depiction of the Wasatch fault as a listric normal fault is suggested in articles published by Arabazs and Smith 91979) and Snay and Smith (1984).

permissable sight lengths of 50 m, and otherwise adhered to procedures used by the National Geodetic Survey for precise geodetic leveling. The levels did not contain the magnetic component that has recently been discovered as a source of error in the Zeiss NI-1 type of level. Furthermore, the 1974 and 1979 elevations agree rather closely, and show only a small amount of elevation change when compared (Fig. 2). In fact the elevations agree within 10 mm, except for two marks that are apparently unstable near the western end and have moved upward about 15 mm with respect to other benchmarks along the line in the time interval 1979.4 to 1983.8. Consideration in the previous paragraph of the refraction error actually experienced in surveying along the same line, shows that this type of error is small and should not accumulate to more than about 15 mm. It does accumulate most rapidly between benchmarks 41-FMK and N-134, and the small titlt of the 1979 and 1983 elevation comparison between benchmarks 41-FMK and 34-A could be attributed to refraction error. That tilt indicated by the 1979 USGS data is of interest because it is our most recent measurement and it also occurs within the Wasatch Fault zone. Unfortunately the USGS line was not extended far enough to the west to define the configuration of the tilt. We must rely on the 1983 to 1958 comparison for a measure of the nature of tilting across the fault zone.

The 1983 to 1958 comparison shows an apparent elevation change of about 120 mm across the Wasatch Fault zone. Unfortunately the configuration of that tilt is not known between benchmarks A-92 and J-134, where most of the tilt was developed, because the intervening 1958 benchmarks were destroyed by new construction and road realignment. Nevertheless, the tilt amounts to 100 mm over 10 km, or 10 microradians, which is an order of magnitude greater than any expected random or systematic cumulative error. The tilt is also exactly the configuration expected along a straining normal fault, with the greatest tilt developed in the hanging wall of the fault, and a lesser amount developed in the footwall side of the fault (Fig. 4 and 5).

POSSIBLE CAUSES OF GROUND-SURFACE TILT OTHER THAN TECTONIC STRAIN ACCUMULATION

Other causes of deformation of the earth's surface are (1) continued isostatic rebound of the area of the earth's crust loaded by Pleistocene Lake Bonneville and more recently, subsidence of the crust on account of the load imposed the

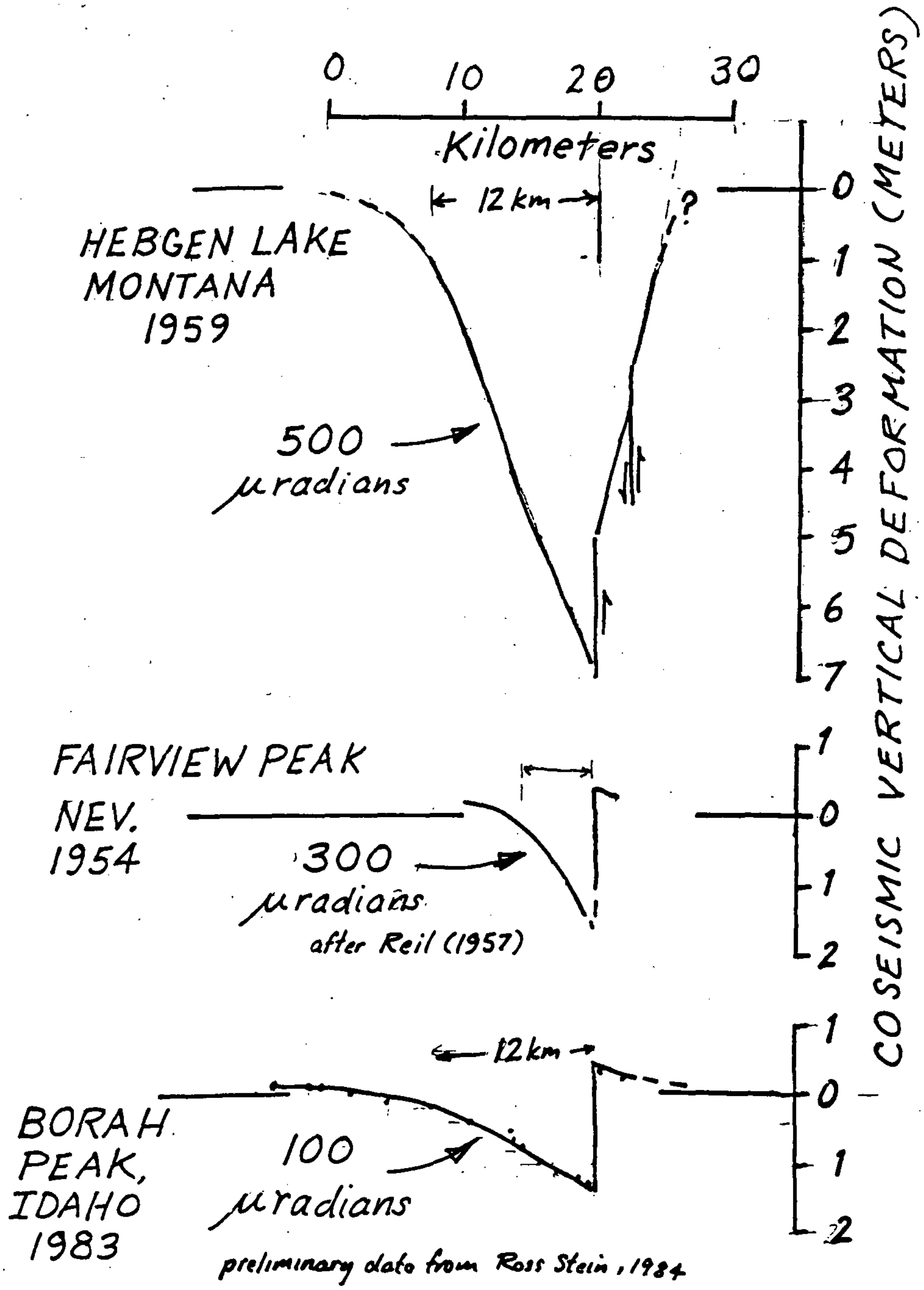

Figure 5.--Profiles of coseismic vertical deformation experienced in three large earthquakes involving normal faulting in the Western United States. Hebgen Lake profile is constructed from data on Plate xx in Meyers and Hamilton (1964). Fairview Peak profile is from Reil (1959) and Savage and Hastie (1969). Borah Peak profile is unpublished and preliminary data furnished by Ross Stein, U.S. Geological Survey (1984).

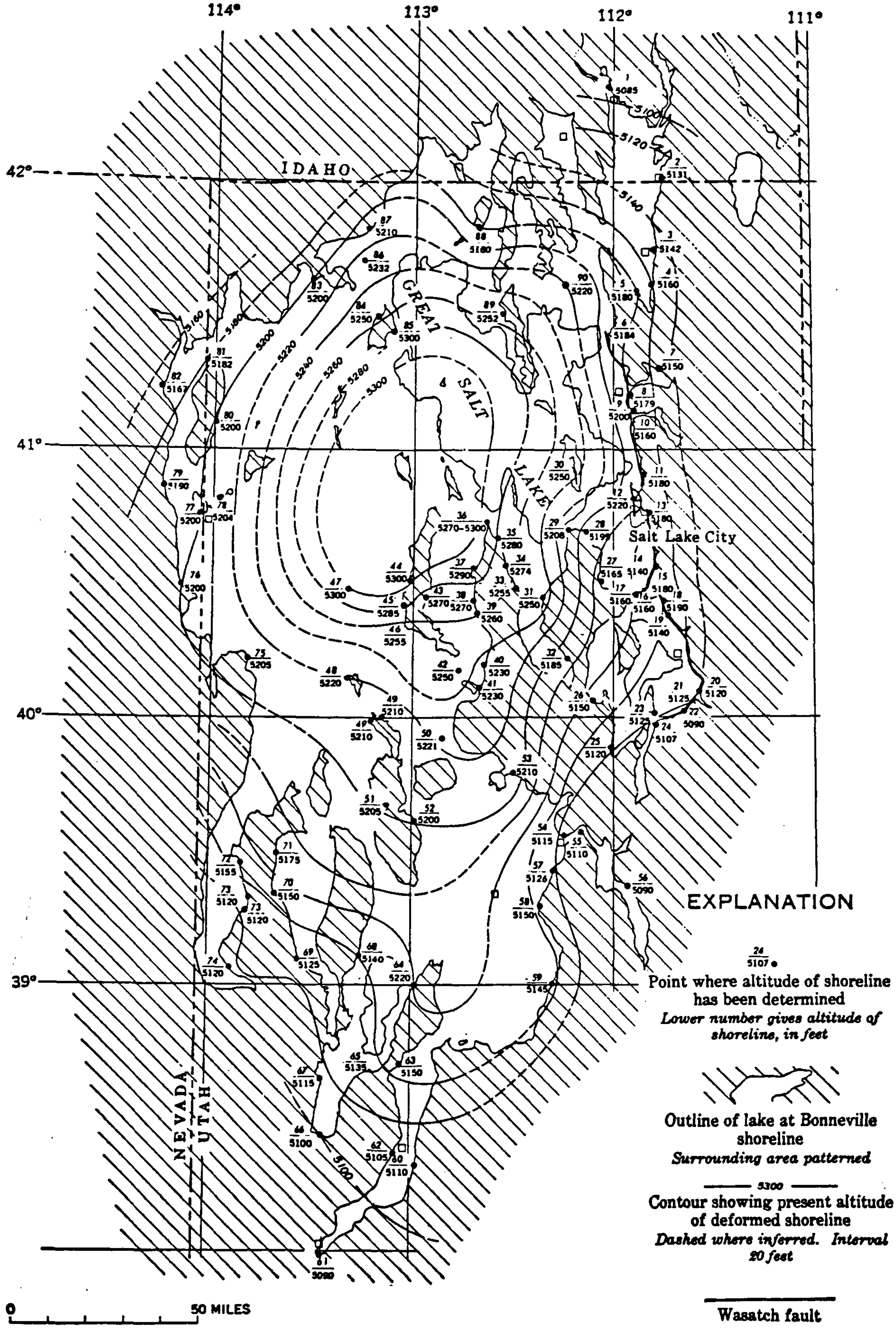

Figure 6.--Map showing deformation of the Pleistocene Lake Bonneville shoreline (from Crittenden, 1963).

3-meter rise in the level of Great Salt Lake from 1982 to present; (2) natural dewatering and compaction of the lacustrine sediments in the Salt Lake Basin in response to the present load of overlying sediments; and (3) artificially induced subsidence in areas of groundwater withdrawal from confined acquifers, particularly in the Weber Delta area.

Deformation of Pleistocene Lake Bonneville shorelines by isostatic rebound is documented by Crittenden (1963, 1967). The main area of rebound is a broad area centered on the Lakeside Mountains along the southwest shore of the Great Salt Lake (Fig. 7) where the total rebound has been 67 m in response to a 290 m lowering of the lake since its high stand about 16,000 yrs ago. Total crustal tilt from isostatic rebound may be 400 to 800 microradians (down-to-the-east). Crittenden estimated that there may be 20 m of rebound yet to go and that the current rate of uplift of the central area should be about 1 mm/yr. The current rate of crustal tilt along the Wasatch front should be about 0.1 microradians per year, down to the east. A level line being run this year (1984) from Brigham City west to the Nevada border should detect rebound when compared to corrected earlier surveys.

The current 3-meter rise in lake level since 1982 should ultimately produce only 0.6 m of subsidence in the central rebound area of which only about 3 per cent (20 mm) might be immediate elastic response (roughly calculated using Crittenden's methods). Viscous response of the mantle is very slow, such that after 10 years, only 0.3 per cent of 2 mm should have subsided. It is therefore unlikely that the current rise in lake level can account for much of the observed tilt in Weber Canyon. It is significant, however, that the magnitude of Holocene tilt from isostatic rebound is of the same order as that typically observed as coseismic deformation from large, normal-fault, earthquakes (100 to 500 microradians) and that the tilt is developed over a length of at least 80 km. Isostatic rebound during the late Pleistocene was very likely a factor in the strain accumulation on the Wasatch Fault and consequently in the earthquake recurrence intervals during the Pleistocene.

Natural compaction of the sedimentary fill in the Salt Lake Basin would probably cause tilt down to the west in proportion to the thickness of clayey sediments upon bedrock. I have not studied the deep section in the Weber

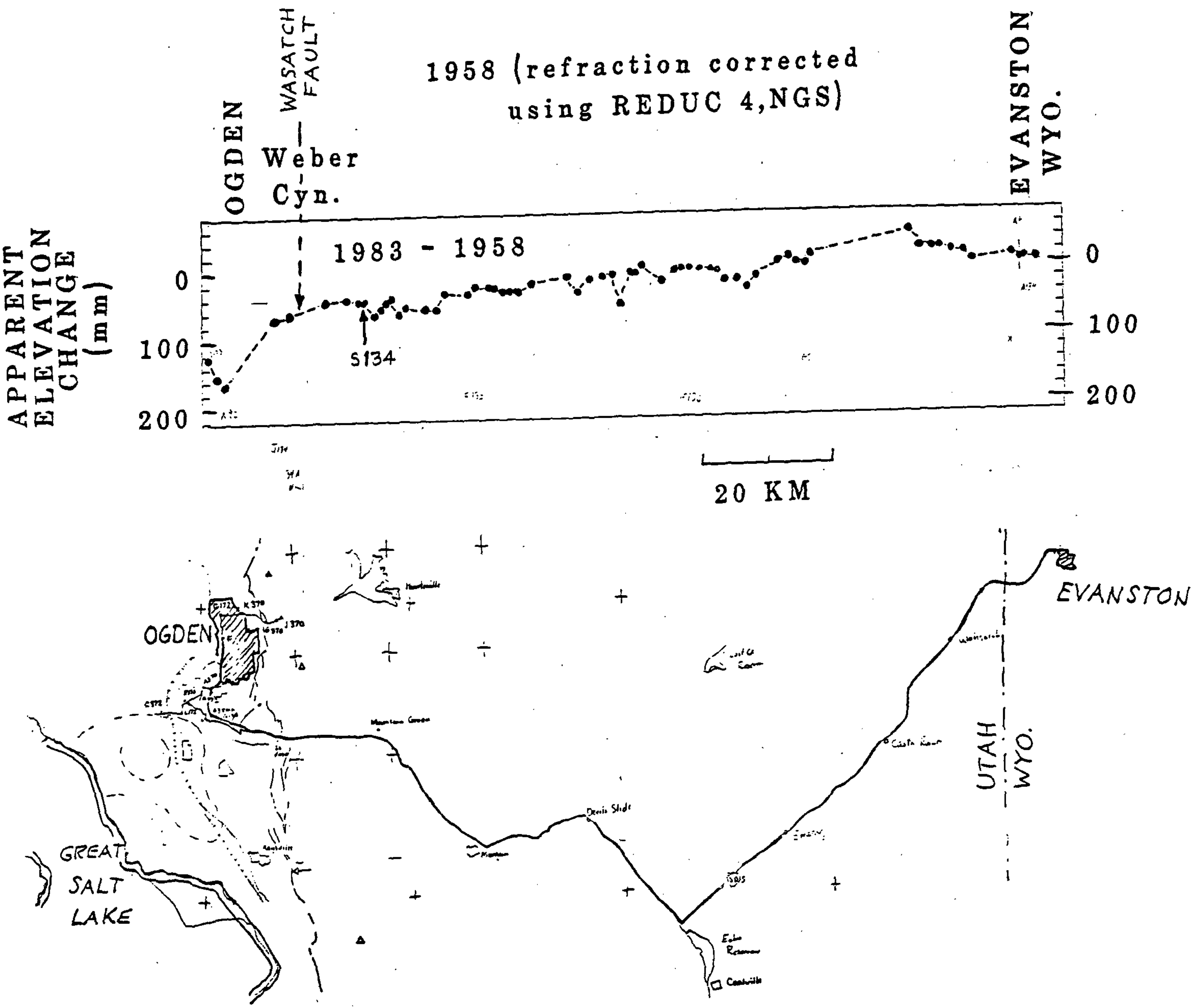

Figure 7.--Profile of apparent elevation change with respect to benchmark S-134 near Mountain Green, Utah. The 1958 recalculated elevations are subtracted from the elevations determined by the 1983 releveling of the line from Ogden to Rock Springs, Wyoming. Only the segment to Evanston, Wyoming is shown.

Delta area and I am not in a position to estimate compaction as a possible cause of the observed tilt in Weber Canyon, although the data to do so is forthcoming in an article containing seismic reflection profiles of the area soon to be published in the Journal of Geophysical Research (R. B. Smith, oral communication, 1984). Older drill hole data is reported in Feth and others (1966). The fact that tilt is also occurring in the canyon directly underlain by Paleozoic and Precambrian bedrock would seem to discount sediment compaction as a possible cause. The rate at which tilt is occurring is also large with respect to the rate at which sediment is known to compact in other basins.

Groundwater is withdrawn from deep wells in the Weber Delta area (Feth and others, 1966). A very preliminary map of approximate water level declines in the confined system, over the period 1953 to 1982, was furnished by T. Arno (U.S. Geological Survey) and is shown in Fig. 3. The control on water level declines is limited to the few wells shown. Water level declines greater than 12 m (40 feet) are indicated in the area west of Hill Air Force Base. It is possible that subsidence on the order of 30 cm (1 ft) could have occurred in the area of greatest aquifer pressure decline, particularly if the aquifers contained a substantial cumulative thickness of thin clayey aquitard layers and lenses (Poland, 1969). In many areas of the Western United States underlain by unconsolidated lacustrine deposits, subsidence has initiated after 15 to 20 m (45-60 ft) of water pressure decline. Further water pressure declines have been known to produce up to 1 foot of land surface subsidence for 20 feet (6 m) of pressure decline (Poland and others, 1975). In the area in which tilt is occurring, the water level declines appear to have been less than 30 feet, and unlikely to produce detectable subsidence. Also, artificially induced subsidence would not affect the area of bedrock in the Wasatch range which is also tilting down the the west.

DISCUSSION

This paper has presented the evidence for relatively large rates of tectonic strain and uplift across the Wasatch Fault. I feel we have exhausted most of the possible objections to this data by recalculating the 1958 data, and releveling the line in 1983. The case rests largely on the validity of the

1958 elevations. The 1983, 1979, and 1974 elevations agree so closely that one cannot argue away their validity.

The 1958 to 1983 comparison indicates an average rate of uplift of 4 mm/yr over the past 25 years. This rate is about four times greater than the rate determined by trenching and dating offset sediments at the Kaysville site, about 15 km to the south. At this site along the Wasatch Fault, Schwartz and others (1983) determined a late Holocene vertical slip rate of 1.3 (+0.5, -0.2) mm/yr. Farther south, at the Hobble Creek site, Schwartz and others (1983) report a Holocene slip rate of 1.0 (0.1 mm/yr). The rate determined in the present study is considerably larger than determined by geologic studies, and supports the idea that strain rates along the fault may differ laterally and episodically. Along this segment of the Wasatch Fault between Salt Lake City and Ogden two events have occurred within the last 150 years as determined at the Kaysville site (Swan and others, 1980; Schwartz and others, 1983). The interval between these events was 500 to 1000 years. Net tectonic displacement for individual faulting events range from 1.7 to 3.7 m. No surface faulting events have occurred on the Wasatch front in the past 136 years, and the last event on the Salt Lake City-Ogden segment occurred within the last 500 years. If uplift is occurring at an average rate of 4 mm/yr as indicated in this study, the net tectonic displacement per event of 1.7 to 3.7 m, would indicate recurrence intervals of 425 to 850 years. Another indication of the total amount of strain accumulation before an earthquake may be taken empirically from measured coseismic deformation from earthquakes with normal faulting in the Western United States (Fig. 5). Maximum coseismic tilt in the hanging- wall block ranges from 100 microradians in the Borah Peak earthquake measurement to 500 microradians in the Hebgen Lake earthquake measurement. The geodetic leveling data in Weber Canyon shows that 10 microradians of tilt accumulated in 25 years, or an average tilt rate of 0.25 microradians per year. Dividing this rate into the measured coseismic tilts at other localities suggests recurrence rates on the order of 400 to 2000 years which is similar to the recurrence rates obtained from slip rates of past events.

PLANS FOR FURTHER RESEARCH

This project is currently limited to evaluating and reporting on available geodetic leveling data and a modest program of releveling of about 15 additional km each year that is not a part of the NGS program, but which takes advantage of that agencies larger releveling program to re-establish the North American Vertical Control Datum, and is done by their crews. In 1983 a line of bench marks was extended west of the NGS route in order to better define deformation in the Wasatch Fault near Ogden. In 1984, the 1974 USGS Parley's Canyon line (Fig. 1) will be partly releveled. A "long-baseline tiltmeter" will also be set up using lake levels of the Great Salt Lake, and about 1 year of data should be available for the 1986 report for the Wasatch Front project.

The National Geodetic Survey is currently releveling parts of northern Utah as a part of its program to re-establish a North America Vertical Control Datum. It is important to encourage the NGS to design and route the new work so that we can monitor vertical crustal movement in Utah and other areas of earthquake hazard concern. If correctly designed, these long level lines are useful in detecting regional warping and also in detecting zones of strain that may not have obvious topographic or geologic expression.

The Wasatch Front offers an ideal situation for a greatly expanded geodetic program to study crustal deformation processes in an extensional tectonic terrane. The face that a major earthquake may be forecasted for the segment south of Brigham City, localizes the area for instrumentation for detecting precursory events that may lead to a short-term prediction, in which geodetic methods to monitor crustal movements will play an important part. Perhaps more importantly, geodetic level profiles offer a means of exploring for other areas of strain accumulation that are not so clearly manifested in topographic or geologic expression as is the Wasatch fault. For instance, in Figure 7, the tilt that involves 4 closely spaced benchmarks just west of benchmark S-134, and the reversal in tilt direction 15 km west of the Utah/Wyoming line may be zones of elastic strain accumulation and not rigid block movement. If significant elastic strain accumulation is detected, such areas are worthy of further earthquake hazard investigations. Seismically active areas are known for surprises. It should not surprise anyone familiar with California earthquake history if a major earthquake occurs on some lesser known fault in the northern Utah area, and not on the Wasatch Fault.

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Constraints on the In-Situ Stress Field Along the Wasatch Front

by

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INTRODUCTION

The in situ stress field is directly responsible for both seismic and aseismic deformation. The sense and style of brittle deformation on a given fault plane depends upon the orientation of the principal stress field and a linear quantity, Ø, that depends on the relative magnitudes of the principal stresses. Knowledge of this Ø value and of the principal stress orientations can be combined with frictional faulting constraints to assess both the style (direction of slip) and the likelihood of slip on any pre-existing fault plane.

Available stress data along the Wasatch front including earthquake focal mechanisms, Holocene slickenside studies, and hydraulic fracturing tests have been integrated with analysis of stress-induced well bore elongation ("breakouts") in six deep wells in the vicinity of the southern Wasatch fault. These data provide a seemingly consistent description of the in-situ stress field which may allow for a better understanding of both seismicity and geodetic strain data as well as providing a foundation for assessing seismic risk associated with pre-existing faults.

DESCRIPTION OF THE IN-SITU STRESS FIELD

As mentioned above, only the orientation of the principal stress field and a value (Ø) expressing the relative magnitudes of these stresses are needed to predict the direction of slip on any given fault plane. The $\emptyset$ value was first described by Bott (1959) and is defined in the following manner:

$$\emptyset = \frac{S_2 - S_3}{S_1 - S_3} \quad (1)$$

where S_1 = maximum principal stress, S_2 = intermediate principal stress, and S_3 = minimum principal stress (all stresses are compressive). Thus, $\emptyset$ may range from 0 ($S_2 = S_3$) to 1 ($S_1 = S_2$). Angelier (1979) presented a simple graphical method for predicting the possible range in slip direction for any arbitrary fault plane for fixed stress axes (see Figure 1). However, unless additional information is known about the absolute magnitudes of the stresses, it is impossible to tell what are likely slip directions, i.e., in which part of this range the maximum resolved shear stress exceeds the shear strength of the fault.

Laboratory and theoretical studies of slip on pre-existing fault planes suggest a linear frictional sliding law of the following form:

$$\tau = \mu(S_N - P) + S_0 \quad (2)$$

where τ = maximum resolved shear stress, μ is the coefficient of friction (generally between 0.6-0.85 for most rocks), S_N is the normal stress across the fault plane, P is pore pressure, and S_o is the frictional cohesive strength of the fault due to some sort of healing mechanism (often zero, generally less than 500 bars). To determine the values of S_N and τ, information on the absolute magnitudes of the principal stresses must be known.

The generally N-S trending, active normal faulting in the northern Basin and Range province suggests a stress regime of the following form:

S_1 = vertical and equal to the weight of the lithostat (S_v)

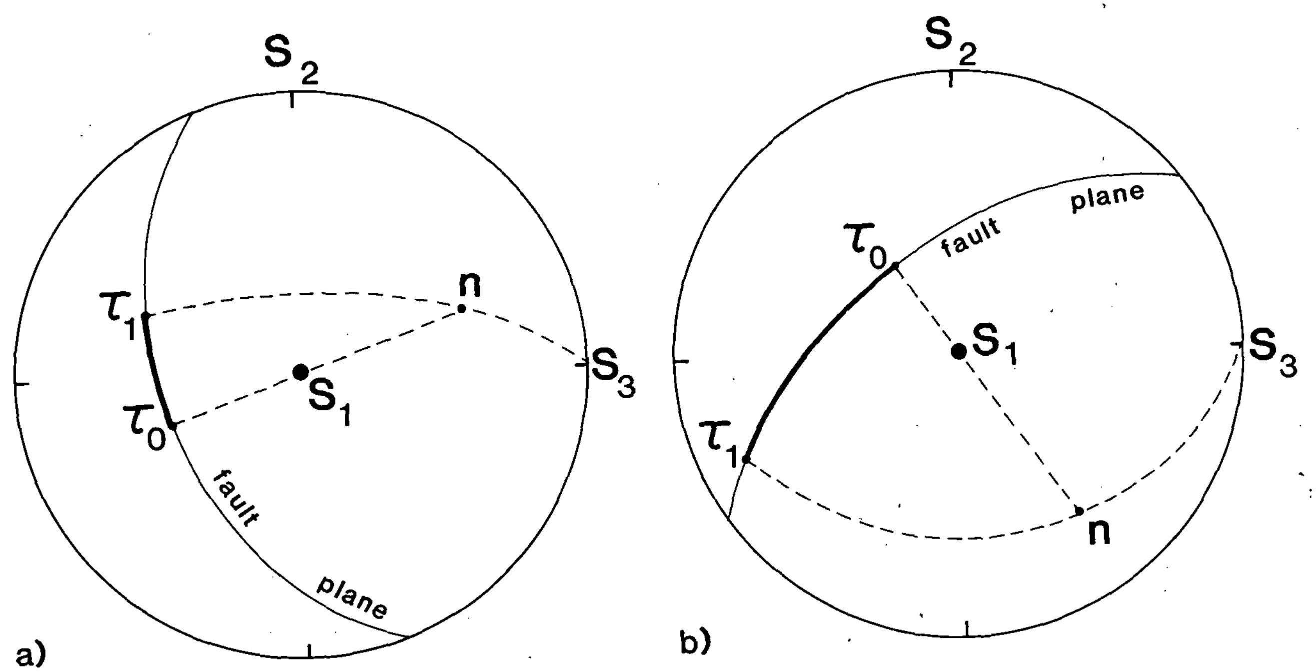


Figure 1. Angular variation of maximum shear stress (slip direction) with $\emptyset$, when stress axes S_1, S_2, S_3 are fixed: n = fault normal; o = projection of S_1 on the fault. When $\emptyset$ goes from 0 to 1, the orientation of the maximum shear stress goes from $_o$ to $_1$. Shown are the range in possible slip directions for two faults in a normal faulting regime where S_3 is oriented east-west.

S_2 = horizontal and approximately N-S

S_3 = horizontal and approximately E-W

For a complete understanding of the stress field in a particular region within the Basin and Range province we need to know the actual orientation of the stresses, the Ø value, and information on the absolute magnitudes of the stresses. There now exists a sufficient amount of geophysical and geologic data for the Wasatch front region to constrain all of these parameters.

ORIENTATION OF THE PRINCIPAL STRESSES

Wellbore elongation (breakouts), analyses of Holocene slickensides, earthquake focal mechanisms, and the orientation of hydraulic fractures all yield data on principal stress orientation. Zoback (1983) presented an analysis of both earthquake focal mechanisms and slickenside studies along the Wasatch front region which suggested an approximate E-W orientation for S_3. The fault slip data described in that report have been reanalyzed (using the iterative fault slip analysis method of Angelier, 1984) with an additional measurement along the Wasatch near Deweyville, Utah. The best fitting stress tensor (Table 1) lies approximately in horizontal and vertical planes with a S_3 orientation of N75^{o}E. (The deviation of the stress tensor from true horizontal and vertical planes is probably largely due to the small number and limited orientations of the fault planes sampled.) The focal mechanisms discussed in Zoback (1983) have also been reanalyzed; in that paper the focal mechanisms were treated as individual faults by selection of one of the nodal planes as the likely fault plane. Angelier (1984) suggests that the best method for analyzing a group of focal mechanisms is to

TABLE 1

Orientation of Principal Stress

Type of data	S_1 Az	S_1 Dip	S_2 Az	S_2 Dip	S_3 Az	S_3 Dip	Ø
Angelier-type analysis of Holocene slickenside data	268°	75°	164°	4°	73°	15°	0.06
Analysis of Wasatch front focal mechanisms	255°	76°	0°	4°	91°	13°	indeterminant
Well bore elongation	no preferred orientation of horizontal principal stresses						assumed 0
Raft River well #4 drilling induced fracture	Vertical?		72°	0°	162°	0°	no information
Raft River well #5 drilling-induced fracture	Vertical?		29°	0°	119°	0°	no information
Roosevelt Hot Springs well drilling-induced fracture	Vertical?		35°	0°	125°	0°	no information
Fifth Water DH103 hydraulic fracture (tests)	Vertical?		163°	0°	73°	0°	0.09-0.50, magnitude of S_2 poorly constrained
Fifth Water DH103 drilling-induced fractures	Vertical?		80°	0°	170°	0°	no information
Fifth Water DH101 hydraulic fracture (tests)	Vertical?		15°	0°	105°	0°	0.29-0.50

include both nodal planes and their possible slip directions, an inversion of this data set yields a reliable estimate of the stress orientation but not the Ø value. Application of this type of analysis to the Wasatch front focal mechanisms yields a S_3 orientation of N91°E (Table 1). The results of both these analyses are not surprising in view of the fact that both data sets reflect normal fault deformation on predominately N-S trending fault planes.

Directions of wellbore elongations ("breakouts") have been analyzed for six deep wells in the vicinity of the southern Wasatch fault (see Figure 2 for locations). Studies in other areas using data from commercially available four-arm dipmeter logs have indicated that the average azimuth of these borehole elongations is very consistent within a given well or oil field (Cox, 1970; Babcock, 1978; Schafer, 1980; Brown and others, 1980). Bell and Gough (1979) and numerous other workers (Springer and Thorpe, 1981; Gough and Bell, 1981, 1982; Plumb, 1982; Healy and others, 1982; Hickman and others, 1982; Blumling and others, 1983; Cox, 1983; and Zoback and others, 1984) have suggested that the consistent azimuth of the long dimension of the hole is parallel to the azimuth of the minimum horizontal stress (S_3 in a normal faulting case).

High resolution four-arm dipmeter logs were provided by Doug Sprinkel of Placid Oil for six deep exploration wells drilled in the vicinity of the southern Wasatch fault. Total depths for the six wells varied from 3704 to 5569 meters (see caption for Figure 2 for details). Major portions of all six wells were extensively washed out (symmetric enlargement of the well bore observed in two perpendicular directions); however, well-defined breakout zones (elongation in only one of two prependicular directions using the criteria of Bell and Gough, 1979 and

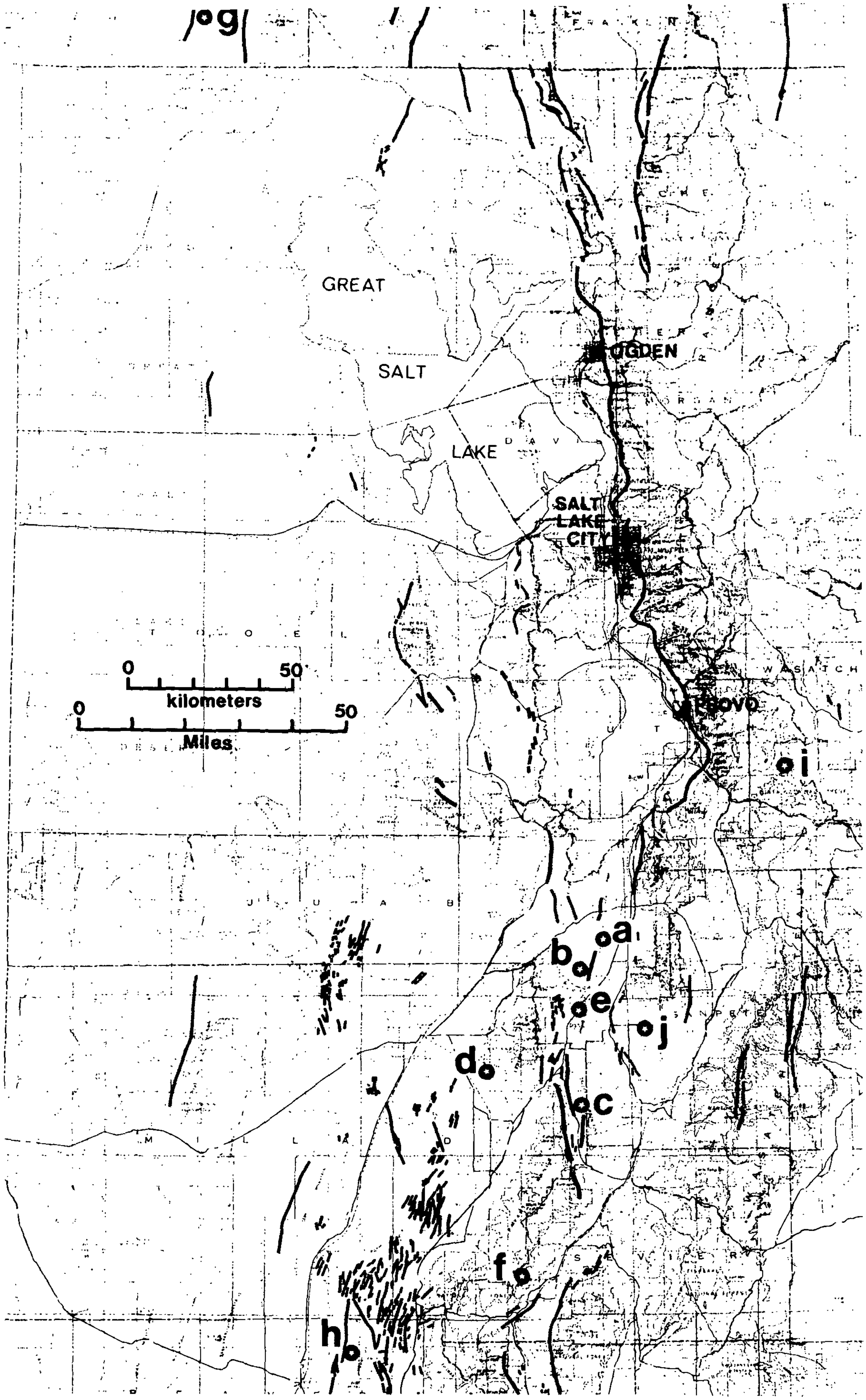


Figure 2. Location map for wells discussed in text. Wells which were analysed for borehole elongation: 2. Howard #1-A (TD=3704m), d.- Henley #1 (TD=3996m), d. Paxton #1 (TD=4520m), e. Monroe #13-7 (TD=4795m), c. WXC USA #1-2 (TD=5569m), b. WXC State #2 (TD=4236m). Wells in which hydraulic fractures were reported: g - Raft River Well 4 and Well 5; h Roosevelt Hot Springs well; i - Fifth Water DH 101 and DH I03; j - Chevron USA #1 Chriss Canyon.

Cox, 1983) were observed in the deeper portions of each well. The washouts are mainly in Mesozoic rocks in the shallow portions of each well and all reliable borehole elongations are at depths greater than 2.2 km, mostly in Paleozoic rocks. Azimuths of well-defined elongation zones for each hole and are shown on rose diagrams in Figure 3.

The breakout azimuths vary considerably from well to well and within some individual wells. Breakouts were found primarily in the northeast and northwest quadrant. A composite of reliable breakout azimuths for all six wells is shown in Figure 4. The azimuths show a wide variation, however there is a slight tendency for them to lie within the northwest quadrant (290^o to 340^o). Interestingly, the percentage of breakouts with an approximately E-W orientation (the expected S_3 azimuth) is relatively small. The results to date suggest that there is no strongly preferred orientation of the minimum horizontal stress in the region sampled. As discussed in more detail below, these data may indicate that both the minimum and maximum horizontal principal stresses (assumed to be S_3 and S_2 respectively) are approximately equal in magnitude.

Hydraulic fractures (the strike of which indicates the orientation of the maximum horizontal principal stress, S_2, in a normal faulting regime, Hubbert and Willis, 1957) have been investigated in five wells in the Wasatch front region (Figure 2). Three of the wells lie west of the Wasatch fault: two in the Raft River geothermal field (Keys, 1980), and the other in the Roosevelt Hot Springs field (Keys, 1979). In all three of these geothermal wells the observed hydraulic fractures were inadvertertently induced probably as result of overpressure during drilling (Keys, 1979, 1980). Such drilling-induced hydraulic fractures are not uncommon in normal faulting stress regimes (e.g. Nevada Test

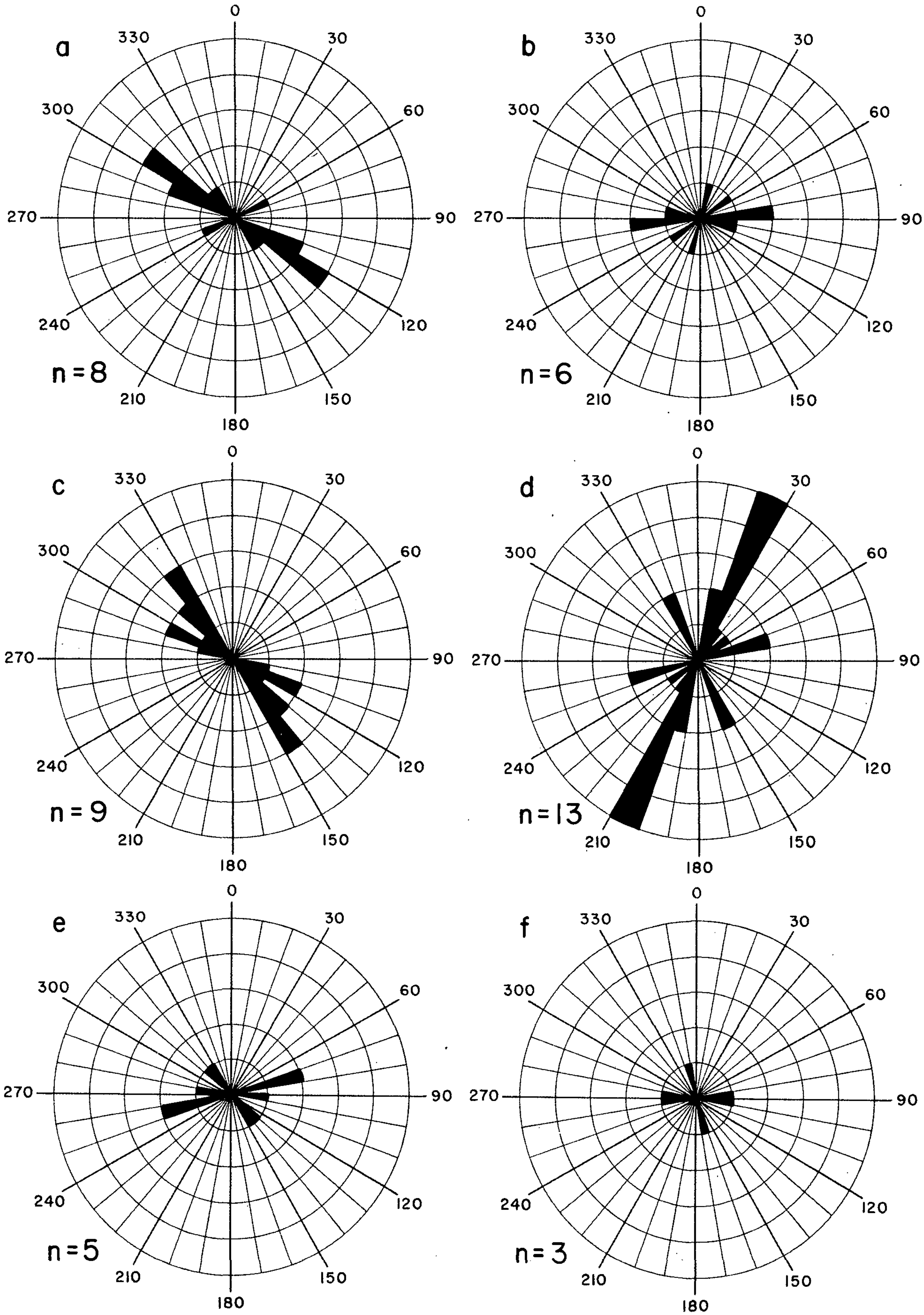


Figure 3. Rose diagrams of borehole elongation azimuths in the analyzed wells. a) Howard #1-a, b) State #2, c) USA #1-2 d) Henley #1-e) Monroe #13-7 f) Paxton #1.

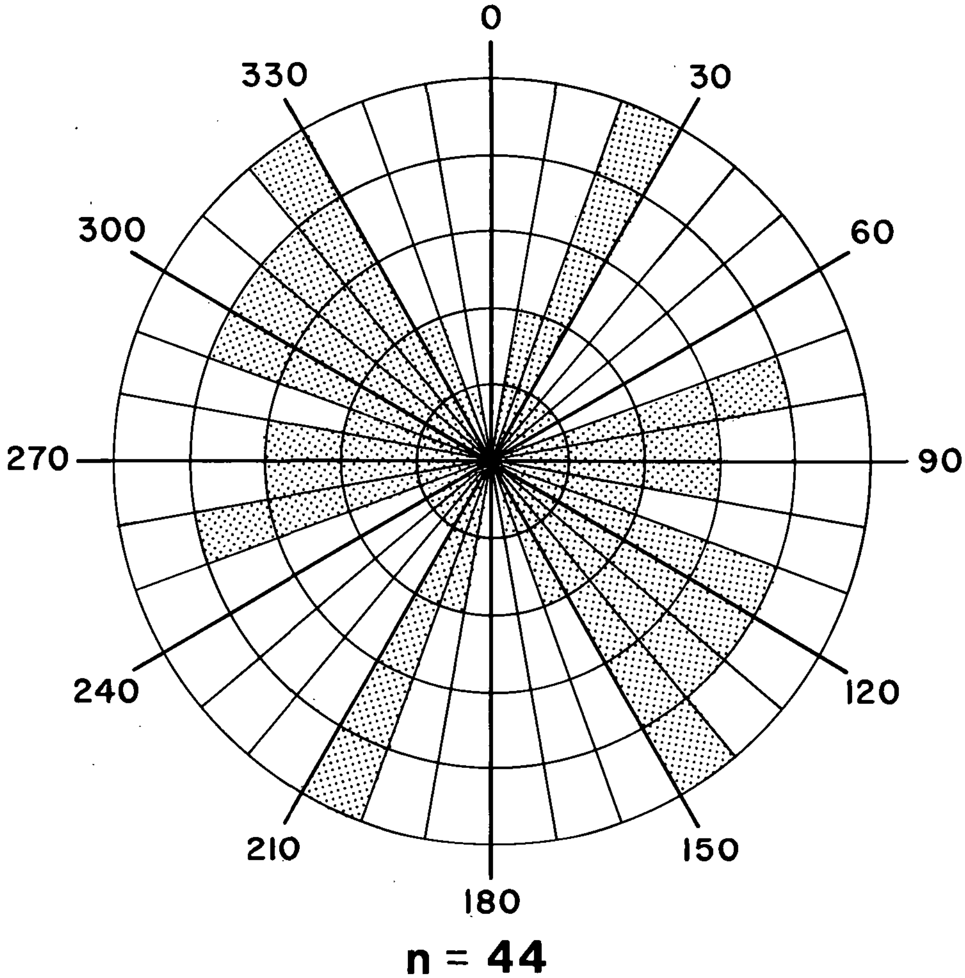


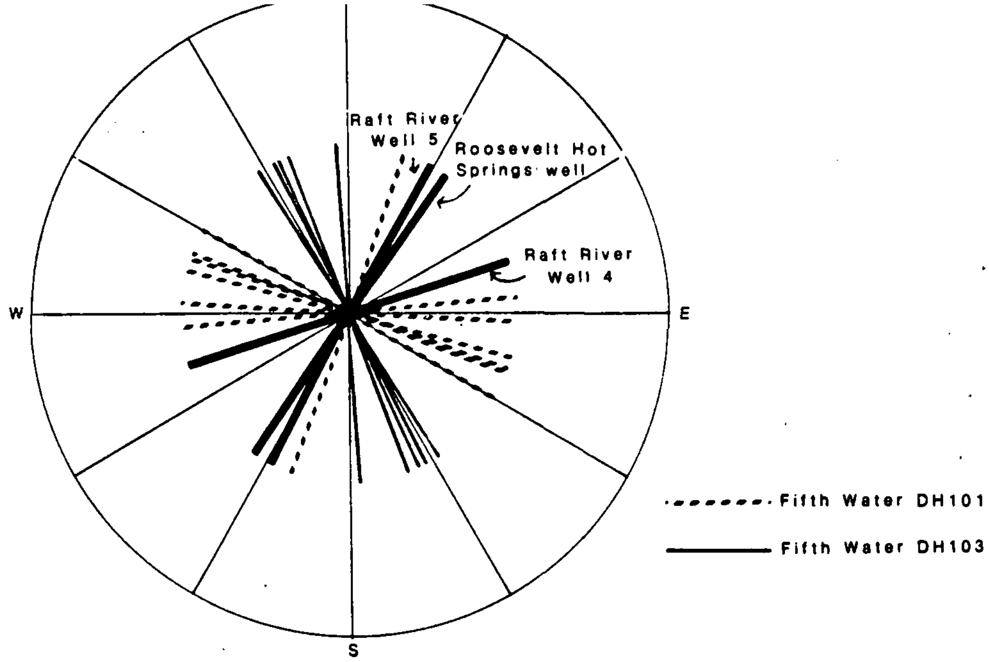
Figure 4. Composite rose diagram for all breakouts shown in Figure 3.

Site, Stock and others, 1983) and are indicative of the low magnitude of the minimum horizontal stress (which in normal faulting regimes corresponds to the minimum principal stress, S_3).

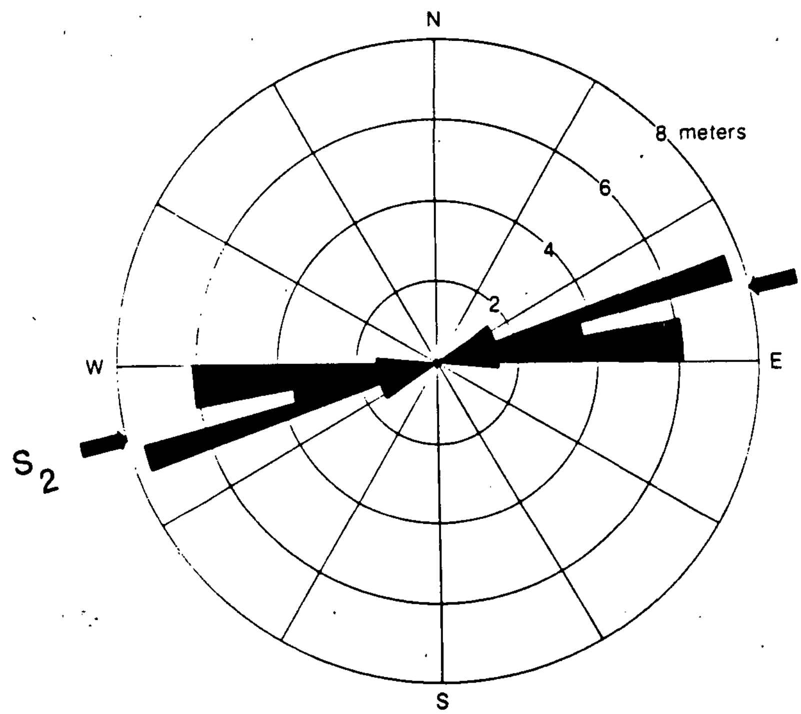
In Raft River Well 4 a hydraulic fracture was logged using a borehole televiewer from a depth of 1428 m to 1485 m with an average azimuth of N72°E, implying an S_3 azimuth of 162° (Table I, Figure 5a). In Raft River Well 5 (located approximately 500 m from Well 4) a hydraulic fracture was logged from a depth of 1391 m to 1434 m with an average azimuth of N29°E (Table I, Figure 5a). In the Roosevelt Hot Springs well the drilling-induced hydraulic fracture had an average azimuth of N35°E (Table I, Figure 5a).

Hydraulic fracturing tests were conducted in two wells southeast of Provo, Utah, approximately 20 km east of the Wasatch fault, in an area of young but small displacement normal faulting. The two wells, DH-103 and DH-101, are located within 500 m of one another. The wells were drilled by the U.S. Bureau of Reclamation in 1980-1981 as part of a feasibility study for the Fifth Water Powerplant site. Using a borehole televiewer, Zoback and others (1981) logged five new (induced by testing) hydraulic fractures in DH-103 at depths between 574 and 603 m with azimuths of 174°, 159°, 156°, 154°, and 148°, and a mean azimuth of 163° $\pm$ 15° (Figure 5a). In addition, numerous drilling induced hydraulic fractures were also logged. These fractures should also strike parallel to the azimuth of the maximum horizontal stress (S_2). They have a mean azimuth of about 80° (Figure 5b).

In DH-101, located only 500 m away, hydraulic fracturing tests were conducted at 9 depth intervals between 458 and 570 m. (Haimson, 1981). Hydraulic fracture orientations were obtained from 8 of these tests using



A) HYDRAULIC FRACTURE ORIENTATIONS
WASATCH FRONT REGION



B) 5TH WATER UTAH (DH103)
DRILLING INDUCED FRACTURES

Figure 5. a) Rose diagram of all hydraulic fracture orientations reported from wells in the Wasatch front region. b) Rose diagram of drilling induced hydraulic fractures in Fifth Water DH-103 (M. D. Zoback, written communication, 1984).

both impression packers and a borehole televiewer log. The mean azimuth of the fractures is $105^{o} \pm 15^{o}$ although one fracture is oriented 020° (Figure 5a).

Thus, the orientations of experimentally produced hydraulic fractures in closely spaced wells east of the Wasatch front region (Figure 5a) show a mean difference of about 60^{o}. In addition, drilling-induced hydraulic fractures in DH-103 (Figure 5b) have a preferred orientation somewhat intermediate between the two test-induced fracture orientations. The three hydraulic fractures from geothermal wells west of the Wasatch front also show inconsistent directions. These data, when considered with the borehole elongation analysis (see Table 1), seem to support the hypothesis that both horizontal principal stresses in the vicinity of the southern Wasatch fault are approximately equal in magnitude this implies that there is no strongly preferred orientation for the least principal stress, S_3.

Relative Magnitudes of the Principal Stresses, Ø

Information on the relative magnitudes of stresses comes from both deformation and hydraulic fracturing data. Since the value of the maximum horizontal stress (S_2 in a normal faulting regime) is poorly determined in hydraulic fracturing tests (Zoback and Healy, 1984), the Ø values determined by this method can be considered to be only approximate values.

The low Ø value determined by Angelier's fault slip inversion technique for the Holocene slickenside data along the Wasatch fault zone is not surprising since the observed slickensides have very steep rakes (56^{o} - 87^{o}, with 8 of the 9 angles greater than 73^{o}, Zoback, 1983). (The rake is the angle in the fault plane between horizontal and the slickensides, a 90^{0} angle is pure down-dip slip.) As illustrated in Figure 1, in a normal faulting regime with a low Ø value (Ø≈0) the expected slip direction is always down-dip, regardless of the strike of the fault. This is because of the very low shear stresses (difference between stresses) in the horizontal plane. Thus, the tendency toward predominately down-dip slip on the observed fault planes whose strikes varied 85^{0} (between $N45^{0}W$ and $N40^{0}E$) is, as the analysis concluded, indicative of a very low Ø value, approximately equal to zero.

In fact, the earthquake focal mechanism data show a similar pattern. All Wasatch front mechanisms north of $39.5^{0}N$ are predominantly normal dip-slip events showing only small components of strike slip-motion (Arabasz and others, 1980). Computed rakes on all possible nodal planes ranged from 53^{0} to 90^{0}, with one low value of 25^{0}.

The wide range in azimuth of the hydraulic fractures (Figure 5a), as discussed above, is also consistent with a nearly invariant horizontal stress field, i.e. a radial stress field in which the horizontal stresses are equal in all directions. The lack of well-defined, preferred borehole elongation direction (Figure 3) is consistent with such a state of stress. Thus, all the data considered together suggest a Ø value of approximately zero. The preference for active deformation to occur on generally N-S striking planes probably reflects the strong influence of pre-existing zones of weakness.

Absolute Magnitudes of the Principal Stresses

Zoback and Healy (1984) have recently reviewed subsurface in-situ stress measurements made in areas of active faulting. The measurements indicate that the magnitude of principal stress differences in unfaulted regions of the shallow crust (upper few kilometers) is similar to the predicted frictional strength of the active faults using laboratory-derived coefficients of friction between 0.6 and 1.0. The general frictional sliding law (equation 2) reduces to the following relationship between principal stresses (S_1 and S_3), pore pressure (P), and the coefficient of friction (μ) for optimally-oriented fault-planes (planes in which S_2, the intermediate stress, is in the plane of the fault):

$$(3) \qquad \frac{S_1 - P}{S_3 - P} = [(\mu^2 + 1)^{1/2} + \mu]^2$$

In a normal faulting regime, $S_1 = S_v$ (weight of the overburden), S_3 = minimum horizontal stress (the magnitude of which is obtained directly by hydraulic fracturing tests).

In each of four examples of stress measurements in areas of normal faulting (including the Fifth Water, Utah and Nevada Test Site) Zoback and Healy (1984) show that the magnitude of S_3 has approximately the value (given by equation (3) with μ ranging between 0.6 and 1.0) at which normal faulting would be expected to occur on optimally-oriented planes. Figure 6 shows measured values of the minimum horizontal stress values (S_3) as a function of depth for the two USBR wells southeast of Provo together with the range in values for frictional strength at which normal faulting is expected for the pore pressure shown. Also shown in Figure 6 is measurement of the minimum horizontal stress determined from an "acid-breakdown hydrofrac" at 5070 m depth in the Chevron USA #1 Chriss Canyon well, located less than 10 km east of the southern Wasatch fault

(Arabasz, 1984--see Figure 2 for location). As noted by Arabasz the measured value of S_3 is also consistent with the range predicted by frictional strength values, hydrostatic pore pressure, and a reasonable estimate of S_v.

The available data on stress magnitudes thus indicates that stress differences (the difference between S_1 and S_3) are quite large in areas of active normal faulting in general and in the Wasatch front region in particular. The stress differences appear limited by critical values predicted from frictional strength of pre-existing faults.

Discussion

It can be argued that some of the results described here represent anomalies or special cases which may not be representative of the overall state of stress along the Wasatch front region. In particular, the seemingly contradictory results of hydraulic fracturing tests in the two wells in the Fifth Water Ridge area east of the Wasatch fault are subject to question. Tensile strength tests performed by the U.S. Geological Survey on core samples from DH 103 indicated a pronounced azimuthally-dependent strength anisotropy, with strength variations of about 50 percent. However, tensile strength tests done by the Bureau of Reclamation on core from the same depth interval indicated no strength anisotropy at all. Nonetheless, the significant result of all hydraulic fracturing tests in the Fifth Water Ridge site is that the measured magnitude of S_3 (regardless of its orientation) was consistently near the critical value for frictional sliding on pre-existing fault planes (see Figure 6). Continuous core and pre-testing televiewer logs were available for both holes, assuring that the intervals selected for

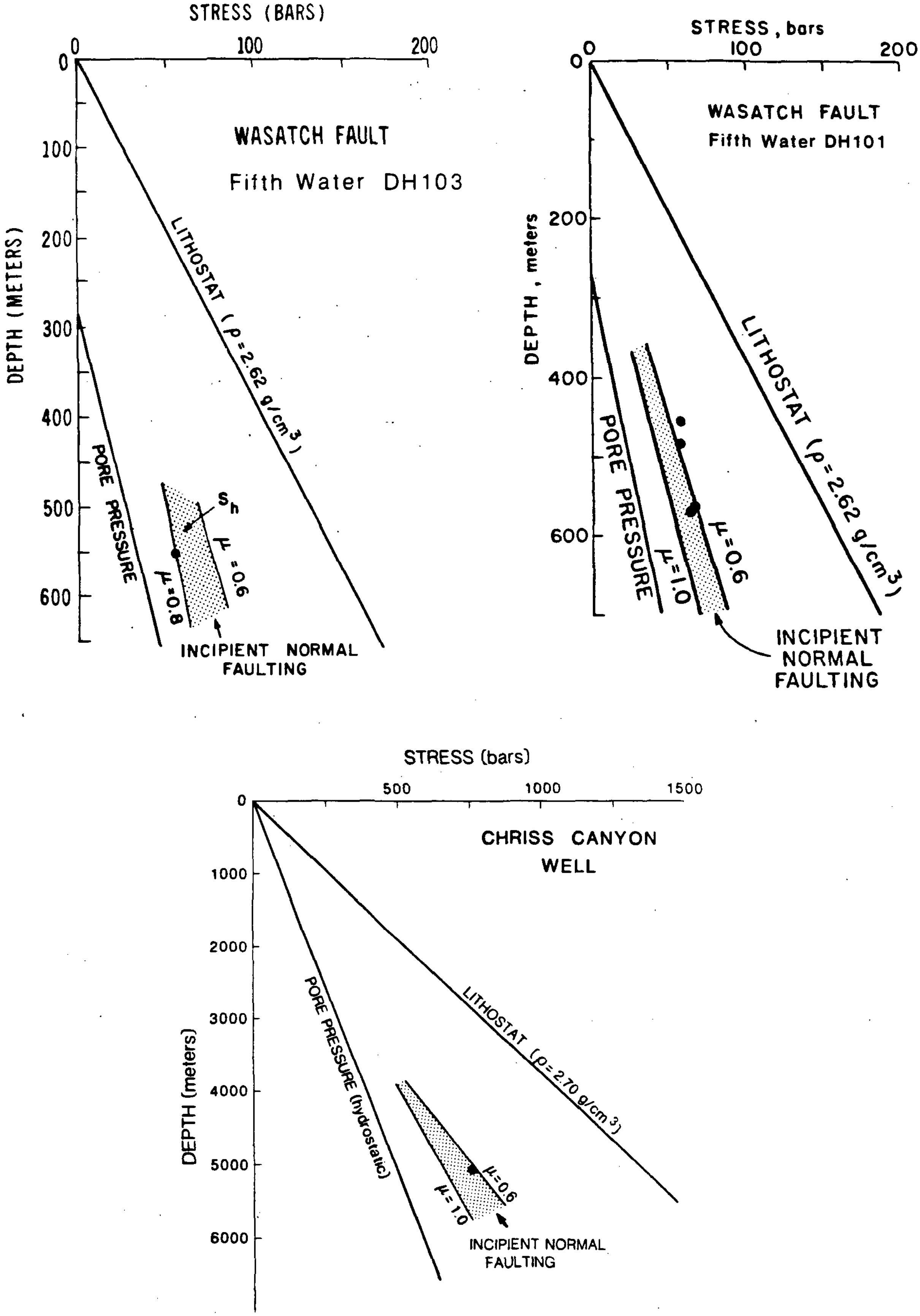


Figure 6. Minimum principal stress values measured in three wells in the Wasatch front region (plotted as dots). Also shown are the variations with depth of 1) the estimated magnitudes of the vertical principal stress (lithostat), 2) the pore pressure, and 3) the expected range for S_3 for active normal faulting based on equation 3 (patterned areas).

hydraulic fracturing contained no pre-existing fractures or faults. The wide azimuthal variation in inferred orientation for S_3 is consistent with a nearly radially invariant horizontal stress field, the magnitude of which is everywhere near the critical value.

The validity of the hydraulic fracturing results in the geothermal areas may be questioned on the grounds that typically these areas are structurally quite complex. Furthermore, both the Raft River and Roosevelt geothermal areas are located a fair distance away from the Wasatch fault zone proper, and quite possibly in a different tectonic environment. The results from these areas are included more for completeness and supplementary data, and are probably not directly applicable to the Washatch front region.

Finally, detailed microearthquake focal mechanism studies from the Sevier Valley area in the Basin and Range-Colorado Plateau transition region in central Utah between 38°N and 39°N indicate an overwhelming predominance of strike-slip mechanisms at all focal depths (Julander and Arabasz, 1982 and Julander, 1983). These focal mechanisms are supported by fault-slip studies in the Sevier Valley area which show that whereas normal faults are common, strike-slip and oblique slip faults with a wide range of sizes and orientations are equally common (Anderson and Barnhard, 1984). Both the focal mechanisms and the fault slip data suggest an approximately E-W orientation for S_3, and a $\emptyset$ value close to 1.0 for central Utah. Thus, the proposed normal faulting stress regime characterized by low $\emptyset$ values ($\emptyset \simeq 0$) for the Wasatch front region in northern Utah probably has a southern boundary somewhere near 39°N. Focal mechanisms for swarm seismicity believed induced by the acid breakdown hydrofracture test in the Chriss Canyon well just east of the southern terminus of the Wasatch fault (well j; Figure 2) suggest oblique normal faulting, implying a strike-slip component of the motion. Thus, the transition between the two different stress states ($\phi \simeq 0$ to the north and $\phi \simeq 1$ to the south) may be occurring in the area near the southern end of the Wasatch fault.

Despite possible problems and complexities noted above, the available stress data for the Wasatch front region are consistent with a normal faulting stress regime characterized by nearly radial horizontal stress field ($\phi \simeq 0$) the magnitude of which is close to the critical value for slip on optimally oriented pre-existing normal faults. Transition to the a compressive stress regime with S_1 oriented N-S to NNE-WSW in the Colorado Plateau interior (Zoback and Zoback, 1980) requires that the magnitude of both horizontal stresses be increased to exceed the lithostat, with the approximately N-S horizontal stress being increased slightly more that tne E-W stress. In the Wasatch front region the available data suggest that this transition must lie well east of the Wasatch fault.

Concluding Remarks

Available data on the in-situ stress field along the Wasatch fault indicate high stress differences between the maximum principal stress, S_1, (assumed vertical) and the minimum horizontal stress, S_3. The data also indicate that both horizontal stresses are (S_2 and S_3) approximately equal in magnitude ($\phi \simeq 0$) and that there is no strongly preferred orientation for the minimum horizontal stress other than that dictated by the generally N-S normal faults which are currently active.

The implications of this conclusion, if correct, are far-reaching. Since faulting is driven by the difference between the maximum and minimum principal stress ($S_1 - S_3$) and if $\phi \approx 0$ in the Wasatch front region, then normal faults of a wide variety of azimuths may be potentially active. In addition, following a major stress release event (large earthquake) it is possible that the previous intermediate stress value, S_2, might become the new minimum stress; i.e., even the small stress drops of earthquakes (typically 30-100 bars) may be enough to cause an exchange in the relative magnitude of the two horizontal stresses. Temporal variations of the horizontal stress field (magnitude and/or orientation) thus may be strongly influenced by the earthquake cycle itself. In addition, the near equality of the horizontal stresses may also help understand the complicated recent geodetic strain data along the Wasatch which yield two nearly orthogonal directions of extensional strain (Prescott and others, 1979; Snay and others, 1984).

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EARTHQUAKE BEHAVIOR IN THE WASATCH FRONT AREA: ASSOCIATION WITH GEOLOGIC STRUCTURE, SPACE-TIME OCCURRENCE, AND STRESS STATE

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INTRODUCTION

The potential in Utah for a large disastrous earthquake--notably along the Wasatch fault--has been recognized and documented for more than a century. Geological observations, the record of earthquake activity since 1850, and modern methods of probabilistic analysis firmly establish a significant level of earthquake risk. This risk relates not only to the occurrence of a large (magnitude 6-1/2 to 7-3/4) surface-faulting earthquake but also to cumulative exposure to moderate-size (magnitude 5 to 6-1/2) earthquakes, perhaps below the threshold for surface rupture. Distinction between these two threats is useful because they appear to require attention to separate aspects of the tectonic framework of the Wasatch Front area--and different, albeit complementary, research strategies.

The purpose of this invited contribution is to stimulate discussion of specific risk-related issues raised by organizers of this workshop. Some of these issues amenable to a seismological perspective include: historical seismicity versus tectonics, seismic cycle, characteristic earthquakes, seismic gaps, and mechanics of the Wasatch fault zone. For convenience, these issues will be discussed within the context of three general topics: (1) the association of seismicity with geological structure, (2) space-time patterns of earthquake occurrence, and (3) stress state. Because the Wasatch fault itself during historical time has had no large earthquakes and few (perhaps no) moderate-size earthquakes, consideration of earthquake experience within a broader region is inescapable.

ASSOCIATION OF SEISMICITY WITH GEOLOGICAL STRUCTURE

A fundamental obstacle for understanding fault behavior and earthquake generation in the Utah region is the problematic correlation of diffuse seismicity with mapped Cenozoic faulting (e.g., Smith, 1978; Arabasz and others, 1980; Arabasz and Smith, 1981; McKee and Arabasz, 1982). Problems include: (1) uncertain subsurface structure, which typically is more complex along the main seismic belt than apparent from the surface geology; (2) observations of discordance between surface fault patterns and seismic fault slip at depth (Arabasz and others, 1981; Zoback, 1983); (3) a paucity of historic surface faulting; and (4) inadequate focal-depth resolution from regional seismic monitoring (discussed later). Investigations of diffuse seismicity should also consider the possibility of depth-varying stress orientation (for which there is no good evidence yet in the Intermountain area), and variations in seismicity patterns with earthquake size or stress level (see McKee and Arabasz, 1982).

The characterization of subsurface structure will not be pursued here. See Smith and Bruhn (1984) for a summary of seismic-reflection data that indicate the widespread presence of low-angle and downward-flattening faults in the subsurface, and an intimate relationship between pre-Neogene thrustbelt structure and young normal faults, along the eastern Basin and Range margin. Seismological evidence to date indicates that, at least for small to moderate earthquakes, seismic slip in this region predominates on fault segments with moderate (>30°) to high-angle dip (Arabasz, 1983; Zoback, 1983).

There has been only one instance of historic surface faulting in the Utah region--the 0.5-m vertical displacement associated with the M6.6 Hansel Valley earthquake of 1934. The occurrence of seven other historical earthquakes of magnitude $6.0 \leq M_L < 6.6$ without surface rupture (see Arabasz and others, 1979) suggests a relatively high threshold for such faulting in the region. Bucknam and others (1980), summarize data on documented surface faulting in the Basin and Range province and note that all historic earthquakes in the Great Basin of $M_L 6.3$ or greater (7 earthquakes) have produced surface rupture. The two smallest earthquakes in their tabulation, M_L 5.6 and 6.3, had maximum displacements of 0.2 m and 0.1 m, respectively; earthquakes of $M_L 6.8$ or less (5 earthquakes) all had a maximum displacement less than one meter.

Rigorous efforts were not made to search for evidence of surface faulting immediately following many of Utah's larger historical earthquakes, say $M_L \geq 5$, so the threshold for small surface displacements up to a few tenths of a meter is debatable. Moreover, the minimum magnitude for surface rupture depends on variable parameters of an earthquake source, including focal depth, fault geometry, stress drop, seismic moment, rupture-propagation dynamics, and the like. No evidence was found for tectonic surface faulting accompanying the M_L 6.0 Pocatello Valley earthquake in 1975, but observations were made of non-tectonic surface cracking in frozen snow cover in the alluviated valley, and up to 13 cm of localized subsidence in the valley may have been coseismic (see Arabasz and others, 1981, p. 819f).

Given the relatively high threshold of surface faulting and observations noted earlier of discordance between surface fault patterns and seismic slip at depth, one can argue that--with the sole exception of the 1934 Hansel Valley earthquake--no other of Utah's 15 historical earthquakes of M_L 5.5 or greater (Arabasz and others, 1979, p. 9) can be confidently associated with a mapped surface fault. Further, our present incomplete understanding of the association of seismicity with geological structure in the Utah region allows the following assertion. Within the domain of Utah's main seismic belt, future seismicity below the threshold of surface faulting (M_L approx. 6 to 6-1/2) cannot be confidently precluded by knowledge of the surface geology alone. Where subsurface structure is complex, moderate size earthquakes may occur on "blind" subsurface structures that have no direct surface expression.

Crustal structure along the eastern Great Basin is now known to involve vertically stacked plates separated by low-angle detachments resulting from relict pre-Neogene thrustbelt structure and/or Neogene extension (Allmendinger and others, 1983; Smith and Bruhn, 1984; Standlee, 1983). On the basis of special earthquake studies in the southern Wasatch Front area, neighboring parts of central Utah, and southeastern Idaho, the following working hypothesis is offered to explain observations of diffuse background seismicity. Background seismicity is fundamentally controlled by variable mechanical behavior and internal structure of individual horizontal plates within the seismogenic upper crust. Diffuse epicentral patterns result from the superposition of seismicity occurring within individual plates, and also perhaps from favorable conditions for block-interior rather than block-boundary microseismic slip.

To illustrate this hypothesis, Figure 1 summarizes evidence for a spatially discontinuous distribution of seismicity with depth, above and below about 5-6 km below datum, in the vicinity of the Sevier Valley near Richfield, Utah. Aftershock foci of a magnitude 4.0 earthquake on the eastern side of the valley (lower right, Figure 1) abruptly terminate at this level; foci of background earthquakes along the western side of the valley (lower left, Figure 1) decrease markedly in frequency below this level.

A schematic diagram in the upper part of Figure 1 shows that the depth-discontinuities in seismicity approximately coincide with an identified jump in P-wave velocity. Nearby drill-hole data, local geological information, and evidence from both COCORP (Allmendinger et al., 1983) and industry seismic reflection data (Frank Royse, Chevron, U.S.A., personal communication, 1983) suggest that the seismicity discontinuities coincide with a regional near-horizontal detachment fault at that level. One outstanding implication is the possibility of decoupling between surface faulting (and shallow seismicity) and deeper extension (e.g., see Cape et al., 1983). Because the Richfield area has been the site of some of the most significant magnitude 6 to 6-1/2 earthquakes in the Utah region, the critical question arises whether such strain release was related to very shallow or deeper extension.

Results of a special field study of earthquake swarm activity ($M \leq 4.7$) near Soda Springs, Idaho, in October 1982 by Richins et al. (1983) also

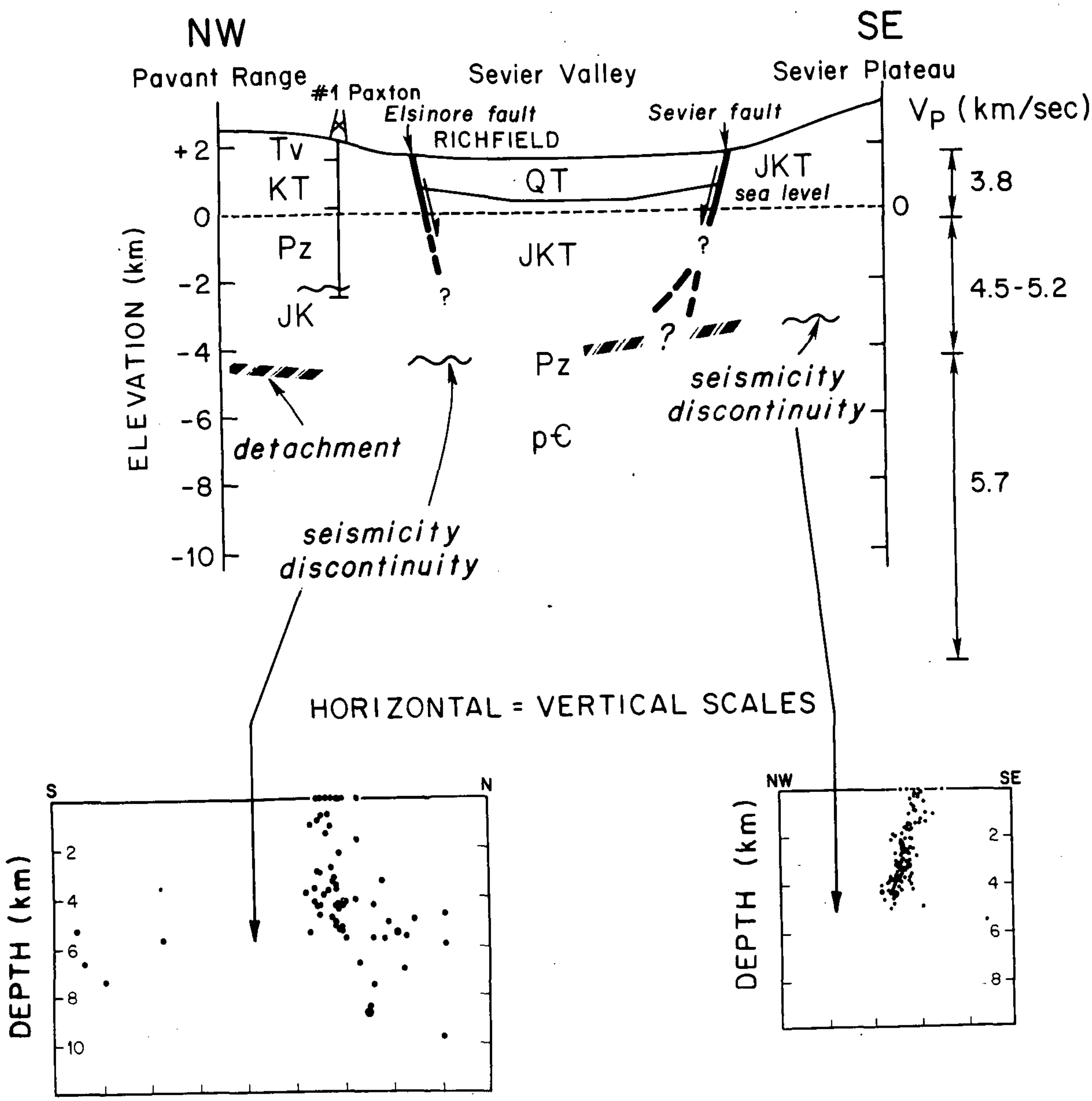


Figure 1. Results from detailed studies near Richfield, Utah (Julander and Arabasz, 1982; Julander, 1983, Arabasz, 1983). Spatially discontinuous seismicity with depth appears to reflect local structural control by a low-angle detachment, rather than a brittle-ductile transition (see text for discussion). Local P-wave velocity structure determined from nearby quarry blasts as refraction sources and by analysis of local earthquake data for multilayering using both the minimum-apparent-velocity technique and a simultaneous velocity-hypocenter inversion technique.

suggest the influence of a low-angle structural discontinuity upon seismic deformation within the upper crust. Comparison of accurately located earthquake foci from that study (Figure 2) with subsurface seismic reflection data from that same area (Dixon, 1982) indicate (1) that seismicity is not simply identifiable with late Cenozoic faulting (the earthquake foci define a NW-trending high-angle structure within and not simply bounding a major range block), and (2) that an apparent discontinuity in the frequency distribution of earthquakes with depth coincides with the pre-Cenozoic Meade thrust fault. Abundant seismicity above 7 km in Figure 2 occurs within the Meade thrust plate; subjacent foci lie within the Absaroka thrust plate. Focal mechanisms indicate a predominance of strike-slip faulting on NW-trending steeply-dipping fault segments--both above and below the near-horizontal thrust fault. There is some mixing of normal-faulting mechanisms in spatial compartment 3, but no indication of seismic slip on a low-angle plane.

One important point of these examples is that precise hypocenters, adequately concentrated seismicity, and abundant single-event focal mechanisms are required to unravel the association of seismicity with structure. Our fixed-network station spacing is simply inadequate for the critical resolution achievable with supplementary short-term efforts with portable seismographs. A second point is that precisely resolving the focal depth of background seismicity may be crucial for effective surveillance in the ISB. Because large earthquakes expectedly nucleate at the base of the seismogenic layer (Sibson, 1982; Das and Scholz, 1983), at about 10-15 km in the Utah region (Smith and Bruhn, 1984), the pattern of background seismicity at this depth may in some cases be masked or blurred by greater flux of small to moderate-size earthquakes within an overlying plate. Such an hypothesis requires

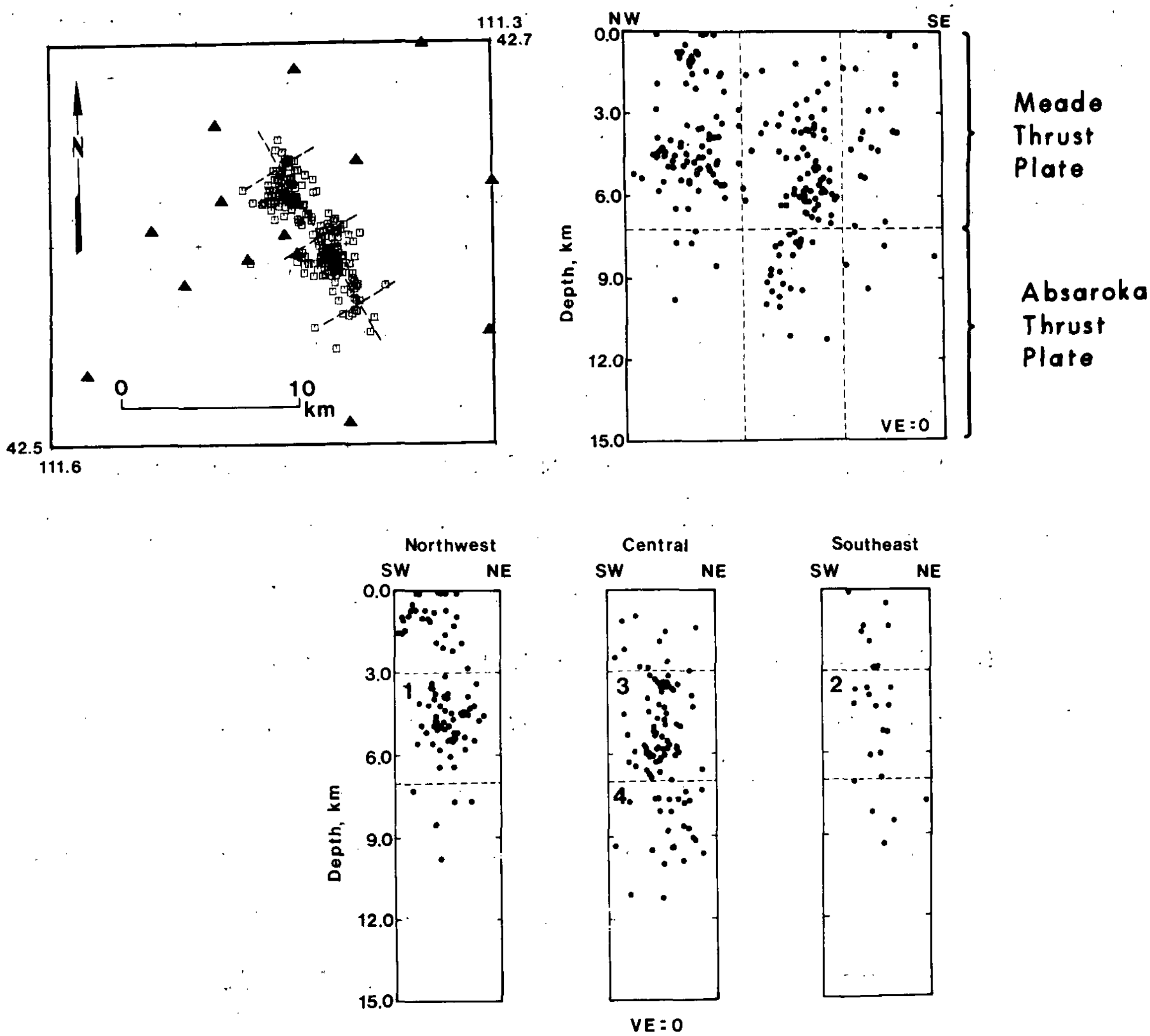


Figure 2. Epicenter map (upper left) and cross-sectional views of earthquake foci from special study of an earthquake swarm sequence (M_L <4.7) near Soda Springs, Idaho, October 1982 (adapted from Richins and others, 1983). Apparent discontinuity in the frequency distribution of earthquakes with depth coincides with the pre-Neogene Meade thrust fault.

"linkage" or some rupture pathway between the deep nucleation points of large earthquakes and existing surface fault scarps.

Figure 3 schematically shows some aspects of the working hypothesis proposed here as relating diffuse seismicity to vertically stacked plates in the upper crust. These aspects (by no means exhaustive) include: (a) local predominance of background microseismicity within a lower plate, such as at 7-12 km depth in Goshen Valley, southwest of Provo, Utah (McKee and Arabasz, 1982); (b) nucleation of a large normal-faulting earthquake near the base of the seismogenic layer, on an old thrust ramp, and with linkage or an established rupture pathway to a major surface fault; (c) occurrence of a moderate-size earthquake within a lower plate--manifesting structural discordance with surficial geology, and with surface rupture inhibited by no established linkage to a shallow structure; (d) occurrence of a moderate-size earthquake and aftershocks on a secondary structure where an underlying detachment restricts deformation to the upper plate; (e) diffuse block-interior microseismicity predominating within an upper plate--perhaps responding to extension enhanced by gravitational backsliding on an underlying detachment; and (f) diffuse block-interior microseismicity within a lower plate where frequency of occurrence is markedly lower than in the overlying plate. In the case of location (b), note that focal-depth resolution would be critical to discriminate background earthquakes associated with the deeper nucleation zone from background seismicity associated with an overlying shallow structure. This situation may be analogous to that in the western Salt Lake Valley.

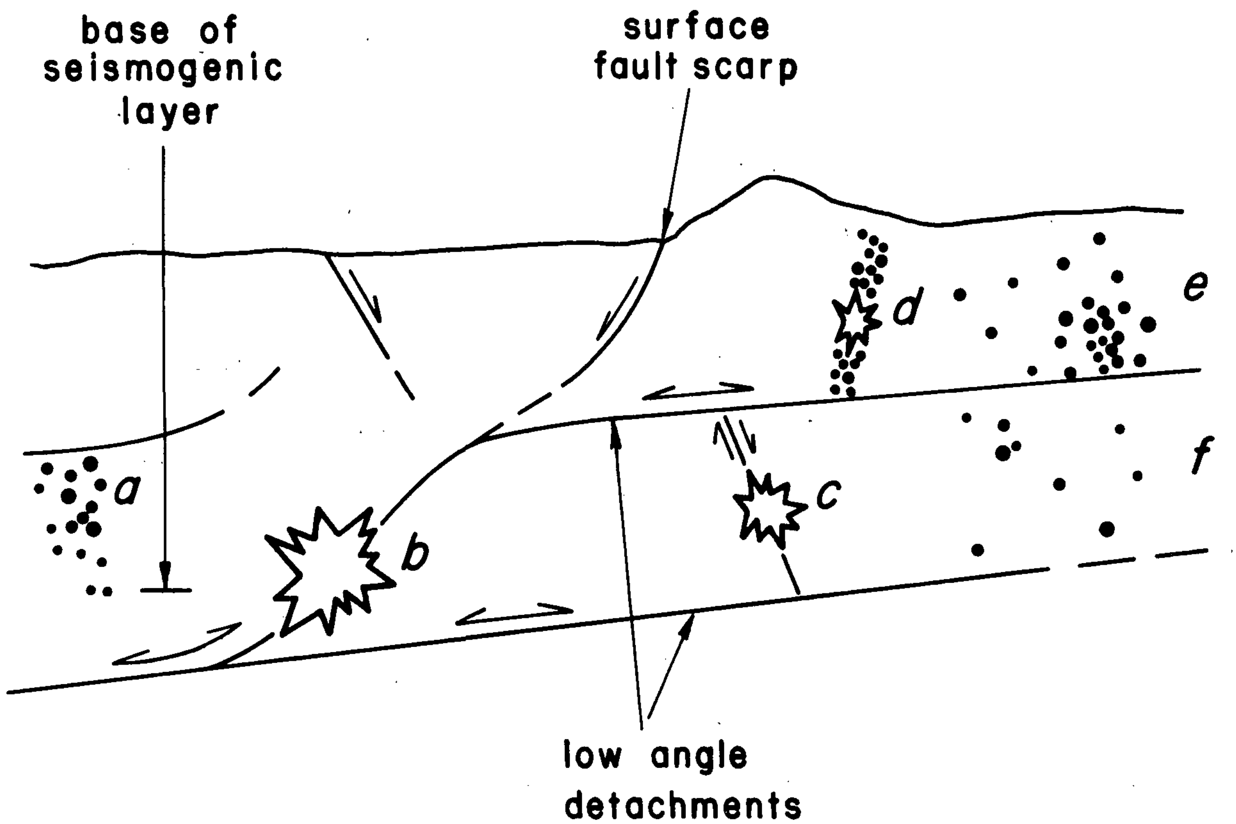


Figure 3. Schematic geologic cross-section of the upper crust illustrating complex association of seismicity with geological structure in the Intermountain seismic belt. Starbursts indicate foci of moderate-to-large earthquakes; small circles, microseismicity; lines in subsurface, faults. Arrows indicate sense of slip on faults; two-directional arrows, extensional backsliding on pre-existing low-angle faults possibly formed as thrust faults. Letters identify examples referred to in text. Base of seismogenic layer is approximately at 10-15 km depth.

SPACE-TIME PATTERNS OF EARTHQUAKE OCCURRENCE

Observations have earlier been published regarding space-time patterns of earthquake behavior in the Utah region. These include discussion of persistent microseismicity gaps along the Wasatch fault zone (Arabasz and others, 1980), and extended discussion of a systematic examination of the Utah earthquake record for foreshock occurrence, precursory quiescence and clustering, migration of mainshocks, and seismicity gaps (Arabasz and Smith, 1981; see also Griscom, 1980). The intention here is to provide an up-dated perspective on seismicity gaps associated with the Wasatch fault zone on a local and regional basis. The same data allow comment on characteristic earthquakes and seismic cycle.

Figure 4, reproduced from Arabasz and others (1980), indicates two elliptical zones of anomalously low seismicity along the Wasatch fault that have been described as seismicity gaps. It should be emphasized that the boundaries of these zones, located to the north and south of Salt Lake City, were based directly on observations of Smith (1974) of pre-1974 seismicity--not on the post-1974 seismicity shown in Figure 4. Nevertheless, the zones demarcate a remarkable paucity of microseismicity within the broadly active earthquake belt of the Wasatch Front. The 3.75-yr period of Figure 4 represents the initial period of modern instrumental monitoring Figure 5 is an updated 5.5-yr sample of seismicity of the Wasatch Front area subsequent to that of Figure 4. Comparison of the two figures suggests a basically stationary pattern of background seismicity during the two time samples. In terms of the seismicity gaps, Figure 5 shows a persistent paucity of earthquake epicenters in the northern zone. In the southern zone, however, an earthquake of

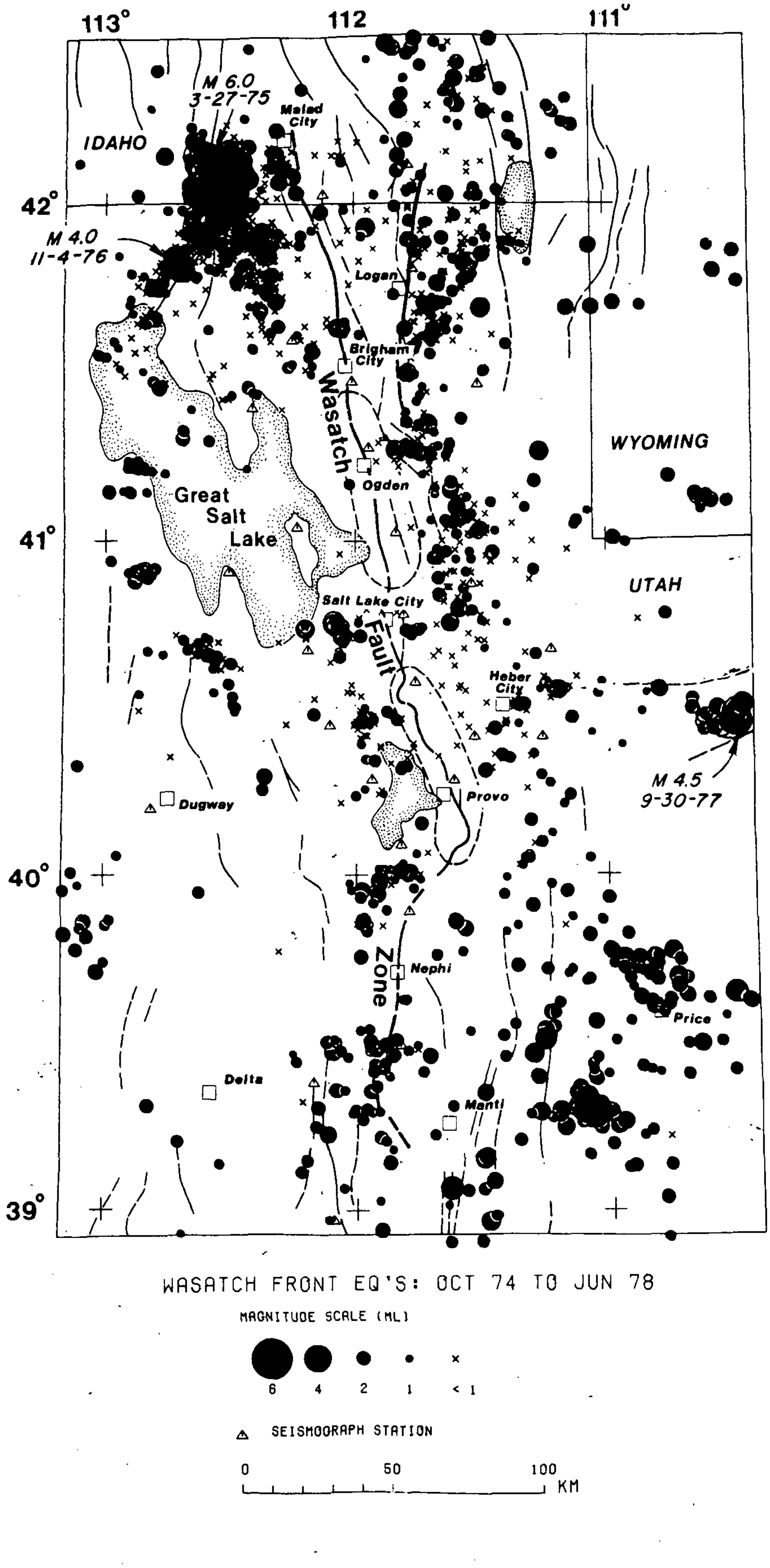


Figure 4. Epicenter map of the Wasatch Front area for October 1974 through June 1978 based on seismic monitoring by the University of Utah (reproduced from Arabasz and others, 1980). Dashed elliptical areas outline seismicity gaps defined on basis of pre-1974 seismicity and discussed in text.

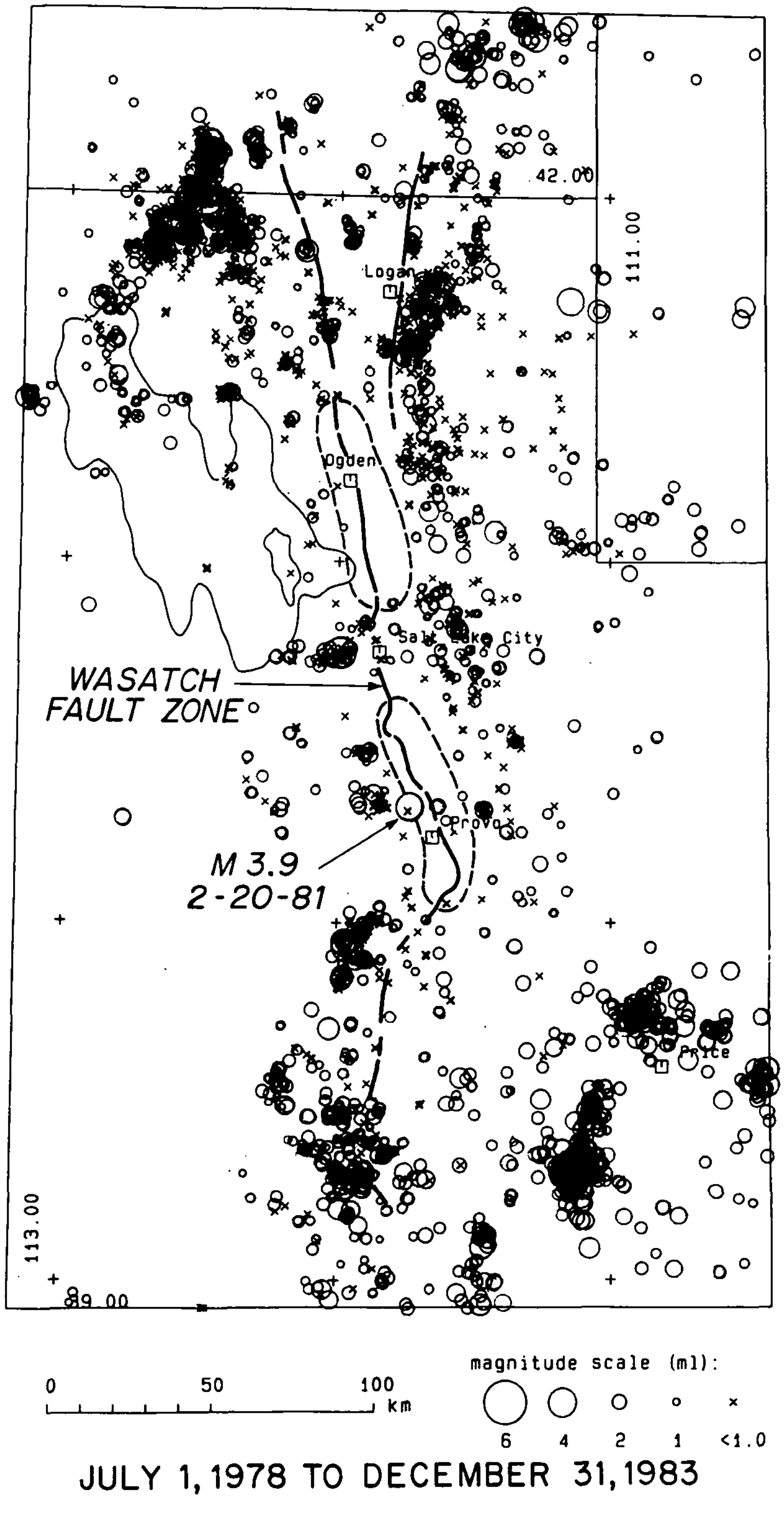


Figure 5. Updated epicenter map of the Wasatch Front area for a 5.5-yr period subsequent to that in Figure 4. Dashed elliptical areas as in Figure 4 for comparison.

magnitude 3.9 occurred on February 20, 1981, near the town of Orem, northwest of Provo. A distinctive aspect of this earthquake was the relative absence of aftershocks compared to sequences associated with other comparable mainshocks in the region. Only a single microaftershock was located by the local network.

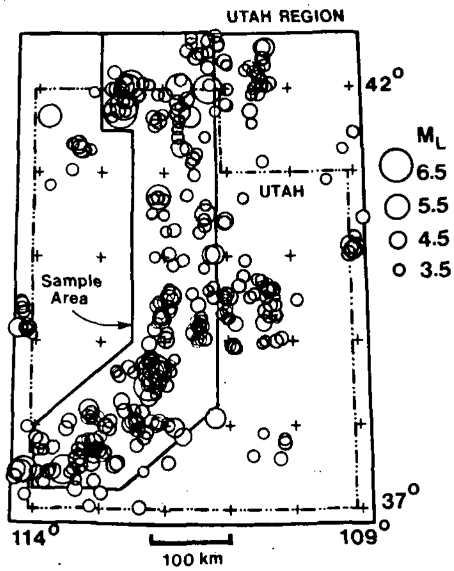
Arabasz and others (1980) discuss the depicted seismicity gaps along the Wasatch fault, including their initiation and considerable uncertainty in relating them to sectional behavior of the fault. Indeed, one need only recall problems raised in the preceding section. It is apparent, however, that specific features of small-earthquake occurrence in the vicinity of the Wasatch fault are open to investigation. These notably include (1) epicentral clustering along the fault trace north of Brigham City, (2) episodic earthquake activity west of the fault beneath the Salt Lake Valley and beneath Goshen Valley southwest of Provo, and (3) diffusely scattered seismicity in the vicinity of the southernmost Wasatch fault (see Pechmann and Thorbjarnardottir, this volume; McKee and Arabasz, 1982; Arabasz, 1984, regarding relevant special studies).

There is minimal microseismicity along the 20- to 30-km-long segment of the Wasatch fault north of Nephi, possibly associated with the youngest (<300 yr?) surface rupture anywhere on the Wasatch fault (Schwartz and Coppersmith, 1984). Relatively intense but dispersed seismicity to the south belies simple correlation with the southernmost Wasatch fault, which markedly changes character south of Nephi. Preliminary results suggest predominant background seismicity shallower than about 7 km within Jurassic and younger sedimentary rocks involved in complex structure (see Standlee, 1983).

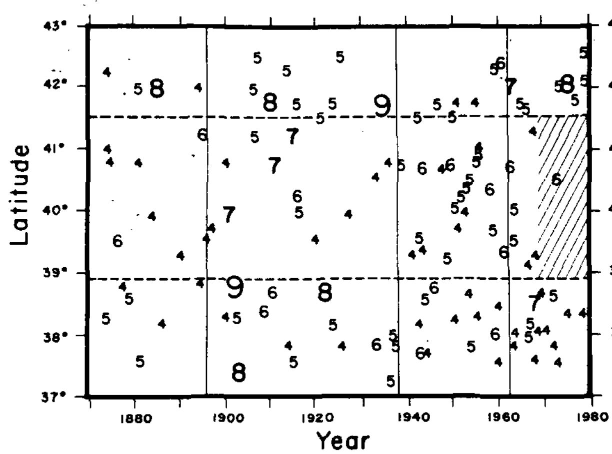
As argued by Arabasz and Smith (1981), the microseismicity gaps along the Wasatch fault north and south of Salt Lake City are not necessarily indicative of a late (i.e., pre-earthquake) stage of a seismic cycle. Uncertainties include the timing of the last surface-faulting event and the variation of interevent times at sites within the gaps. They observed, however, that the microseismicity gaps are encompassed by a more extensive regional zone of anomalous seismicity for earthquakes of M_L3.5 or greater. Those observations will next be updated and examined.

Figure 6, reproduced from Arabasz and Smith (1981), summarizes the observation of a 300 km by 100 km N-S trending seismicity gap ($M_L \geq 3.5$) along the main axis of the Intermountain seismic belt between 38.9°N and 41.5N latitude. (Only independent mainshocks are considered.) This spatial compartment, hereafter referred to as the Wasatch Front (WF) compartment, encompasses 80 percent of the Wasatch fault zone. No mainshock larger than Modified Mercalli intensity VII, or about magnitude 5-1/2, has occurred in this area since 1915. Despite background microseismicity (e.g., Figure 4), the hachured space-time compartment in Figure 6 shows that only one mainshock of M_L3.5 or greater occurred from 1968 through March 1980. Figure 7 gives an updated view of earthquakes within the WF compartment above magnitude thresholds of 2.5 and 3.5.

As shown in Figure 7b, four independent mainshocks of M_L3.5 or greater occurred in the WF compartment during 1980-1983. (A fifth shock near its southeast extremity is in an area of known mining-related seismicity and is justifiably excluded.) The largest event had a magnitude of 4.4 and was investigated by McKee and Arabasz (1982). The next largest event of magnitude 4.3



Earthquakes ($M_L \geq 3.5$) in the Utah region, 1850-1979. Pre-instrumental shocks have Modified Mercalli epicentral intensities of IV or greater.



Space-time plot of earthquakes, in terms of Modified Mercalli epicentral intensity ($I_o \geq 4$), within the sample area of Figure 3 as a function of latitude. Vertical lines are time markers for sample completeness: $I_o \geq 7$ since 1896 and $I_o \geq 6$ since 1938; shocks of $I_o \geq 5$ are complete since 1950, and those of $I_o \geq 4$ or $M_L \geq 3.5$ since 1962 when instrumental monitoring began. Hachured area and dashed lines outline space-time compartments discussed in text.

Figure 6. Epicenter map (above) and space-time plot (below) of earthquake activity in the Utah region (reproduced from Arabasz and Smith, 1981). The hachured space-time compartment in the lower figure indicates a seismicity gap identified by Arabasz and Smith (1981) and discussed in text here.

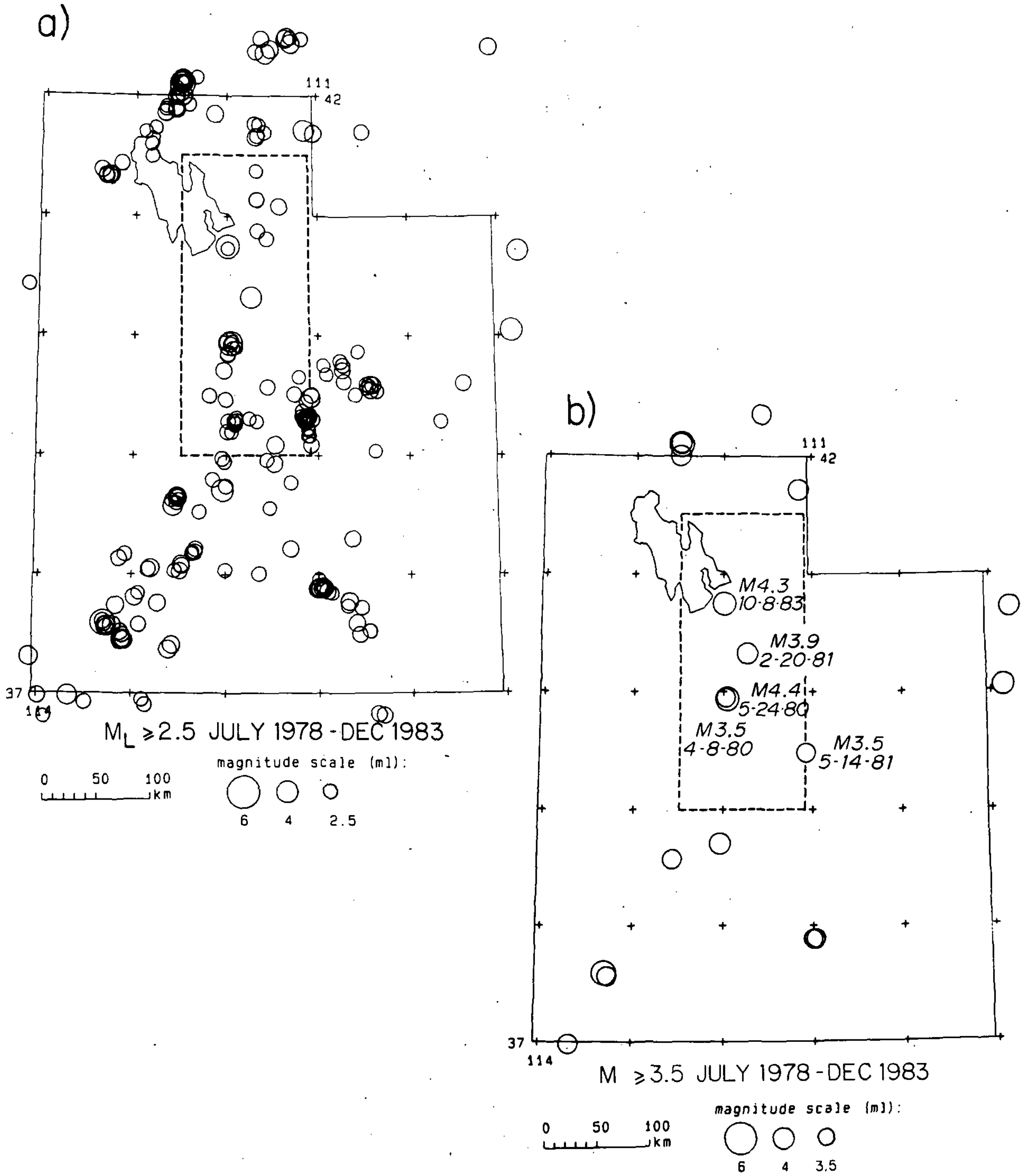


Figure 7. Epicenter maps of the Utah region, July 1978-December 1983, based on seismic monitoring by the University of Utah, for all shocks greater than or equal to (a) magnitude 2.5 and (b) magnitude 3.5. The dashed rectangles correspond to the spatial compartment of the seismicity gap defined in Figure 6. Sizes and dates of occurrence are specially indicated for the larger earthquakes in that compartment since July 1978.

is the subject of a companion report by Pechmann and Thorbjarnardottir (this volume). Epicentral distributions in both Figures 7a and 7b suggest random occurrence throughout the main seismic belt during the 5.5-yr sample period. The WF compartment does not appear to be anomalously quiet in either sample. Inspection of Figure 7a, however, shows that seismic flux is relatively low within the part of the WF compartment north of 40^{o}N lat.--similar to the relative flux seen in the epicenter map of Figure 6 for a 130-yr period.

In view of its location within the densest part of the University of Utah's seismic network, it is noteworthy that the northern part of the WF compartment exhibits minimal clustering compared to neighboring areas (Figure 7a). The possibility that some source zones in this area may exhibit suppressed aftershock behavior--perhaps indicative of high stress (Sanders and Kanamori, 1984)--is the subject of current investigation.

With updated information in hand, the earthquake record of the WF compartment was re-examined using two approaches. First, a homogeneous space-time sample with a reasonable number of events was established by considering all independent earthquakes (aftershocks excluded) of Modified Mercalli epicentral intensity (I_o) V or greater, or M_L4.3 or greater, complete since 1950 (see Arabasz and others, 1980 regarding thresholds of completeness and equivalence between I_o and M_L). The instrumental record begins in 1962 with confidence in completeness at least for M_L3.5 and greater.

The cumulative distribution for the selected sample of events is shown in the lower part of Figure 8a. For comparison, the cumulative distribution for all earthquakes of I_o IV or greater since 1950 and M_L3.5 or greater since 1962 is also shown. The latter sample, however, cannot simply be demonstrated to be

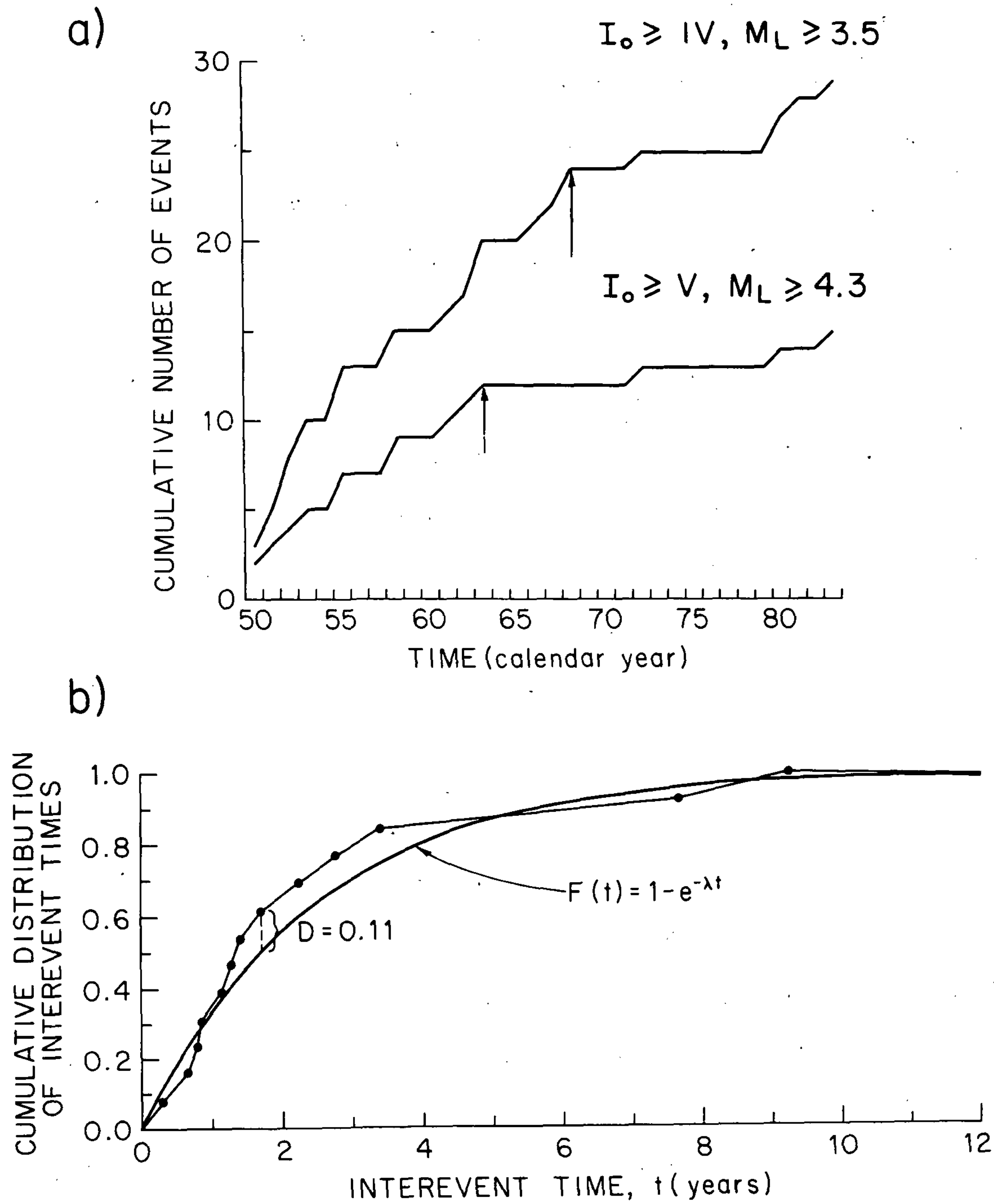


Figure 8. (a) Cumulative seismicity, January 1950-December 1983, within the Wasatch Front spatial compartment outlined in Figures 6 and 7. I_o and M_L specify, respectively, the sample thresholds of Modified Mercalli epicentral intensity for shocks prior to July 1962, and the local Richter magnitude for shocks after that date. Vertical arrows indicate changes in rate of occurrence. (b) Kolmogorov-Smirnov test of the cumulative distribution of interevent times associated with the sample for $I_o \geq V$, $M_L \geq 4.3$, indicated in (a) above. The maximum absolute difference $\underline{D}$ between the observed distribution and the continuous distribution, $\underline{F}(\underline{t})$, predicted for a Poisson process is less than the critical value required to reject, at the 95 percent confidence level, the hypothesis that the observed distribution is non-Poisson.

homogeneous. One reason for plotting it is that the change in rate for the former sample lies suspiciously close to the juncture between the non-instrumental and instrumental earthquake catalogs. In either case, there appears to be a significant decrease in rate of seismicity during the 1960's. Changes in rates are apparent in 1963 for $M_L \geq 4.3$ and in 1968 for $M_L \geq 3.5$. The significance of differences in the mean rates before and after these two respective points was tested using the normal deviate (z) test (e.g., Habermann, 1981). In both cases, the compared sample means can be considered different with 99 percent confidence.

A second approach that was taken was to look critically at the worst-case sample for $M_L \geq 4.3$, which includes interevent times as long as 7.7 and 9.2 years, to test whether the associated time sequence of events was non-random. Assuming the mean rate of occurrence from the 34-year sample for the WF compartment, application of the Kolmogorov-Smirnov test, shown in Figure 8b, indicates that we cannot reject at the 95-percent confidence level the hypothesis that the observed distribution is non-Poisson. Neither can the sample for $M_L \geq 3.5$ similarly be shown to be non-Poisson. In other words, the occurrence of only a single shock of M_L 3.5 or greater during the 1968-1980 period, as shown in the hachured space-time compartment of Figure 6, can be argued to have been due to a random Poisson process. Arabasz and Smith (1981) argued that the anomaly was non-Poisson by considering the average rate of occurrence throughout the main seismic belt in Utah. The critical issue is whether the WF compartment has a long-term rate of flux for small to moderate-size earthquakes that is different--and lower--than that for neighboring parts of the seismic belt.

The issue of characteristic earthquake occurrence on the Wasatch fault is worth examining in the context of flux of moderate-size earthquakes. Schwartz and Coppersmith (1984) use the paucity of moderate-size earthquakes in the historical record to support the idea that the Wasatch fault tends to generate essentially same-size or characteristic large earthquakes. We can use the average recurrence interval of 444 years estimated by them for surface-faulting earthquakes on the Wasatch fault and compare it with the historical record. During the last 100 years, the number of moderate-to-large earthquakes ($M \geq 5.5$) that can be associated with the Wasatch fault is 0 to 2 (Arabasz and others, 1980).

Assuming (1) a Poisson process, (2) that surface-faulting earthquakes of magnitude 6-3/4 or greater occur once every 444 years on the Wasatch fault, and (3) that the minimum number of observations is 18--the number of probable surface-faulting events upon which the recurrence interval of 444 years was based, we can compute the probability of having no earthquakes of M_L5.5 or greater on the Wasatch fault during the last 100 years (see, for example, Benjamin and Cornell, 1970). For a low b-value of 0.5, the lowest published value for a historical catalog in the Intermountain seismic belt (see Arabasz and others, 1980), 0.95 events per century of M5.5 or greater would be expected, and with 95 percent confidence the probability of having no such earthquakes in 100 years would be 0.50. Alternatively, for a b-value of 1.0, 4.01 events per century of M_L 5.5 or greater would be expected and the corresponding probability of no such earthquake would be 0.06. Assignment of two historical moderate-size earthquakes to the Wasatch fault alters the argument considerably. In sum, implications of the historical record for the characteristic earthquake hypothesis should be considered with care.

It is arguable whether space-time patterns of earthquake occurrence in the Wasatch Front area can be used as indicative of stage within a seismic cycle. Relatively low seismic flux, compared to active plate boundaries, and the absence of a complete seismic cycle in the historic record diminish our statistical and scientific confidence. Temporal decreases in seismicity ambiguously characterize both the early post-aftershock stage and the late pre-mainshock stage of a seismic cycle (e.g., Ellsworth and others, 1981). Nevertheless, the microseismicity gaps along the Wasatch fault and the seemingly anomalous behavior of the broader Wasatch Front spatial compartment deserve serious attention. They provide investigative targets for geodetic monitoring and for studies of the characteristics of small earthquakes to test for indications of potential for moderate-to-large earthquakes.

STRESS STATE

The focus of this final section is a summary of results presented by Arabasz (1984) from a case study of "Swarm seismicity and deep hydraulic fracturing within 10 km of the southern Wasatch fault." The information allows inductive reasoning about the orientation and magnitude of principal stresses in the vicinity of the Wasatch fault--directly relevant to understanding its mechanical behavior.

In June-July 1982 during the course of a 7-week microearthquake field experiment in the vicinity of the southern Wasatch fault, two earthquake swarms ($M_L \leq 2.1$) were recorded originating within a few kilometers of a deep exploration well (Chevron U.S.A. #1 Chriss Canyon, TD 5,344 m), coincidentally located within a temporary 10-station network. The well penetrates a section of Jurassic and younger sedimentary rocks (Standlee, 1983). On April 16, 1982, an "acid-breakdown hydrofrac" had been made in the wellbore at a depth of 5,070 m. A causal connection between the observed swarm seismicity and pore-pressure changes due to the deep fluid injection 2 to 3 months earlier is suggested by: (1) hypocentral clustering in the vicinity of the wellbore, (2) distance-delay times consistent with fluid diffusion, (3) significant timing of the swarm seismicity compared to the record of continuous monitoring by the University of Utah's permanent seismic network (3 stations within 25 km), and (4) near-critical stress differences for frictional sliding inferred from the hydrofrac results.

On the basis of the instantaneous shut-in pressure measured for the hydrofrac and corrected for depth, an in situ minimum horizontal compressive stress S_h of approximately 750 bars (75 MPa) is estimated at the hydrofrac depth of 5,070 m. Figure 9a shows the value of S_h in stress-depth space together with the lithostat (assumed to correspond to the maximum vertical stress S_v), the hydrostat, and the domain of S_h associated with a critical maximum stress difference appropriate for incipient frictional sliding on a pre-existing fault (e.g., Zoback and others, 1978). Also shown in Figure 9a are a range of values for S_h determined by Zoback (1981) from hydrofrac tests in a shallow well about 90 km to the north, and the average gradient for S_h determined by McGarr and Gay (1978) for sedimentary basins in the U.S. The maximum horizontal compressive stress S_H is inferred to lie midway or more between the values of S_h and S_v (discussed below).

Figure 9b shows a Mohr-circle stress plane in which S_v and S_h from the deep hydrofrac are assumed to represent extremal principal stresses--following the usual assumption that one of the principal stresses is vertical (e.g.,

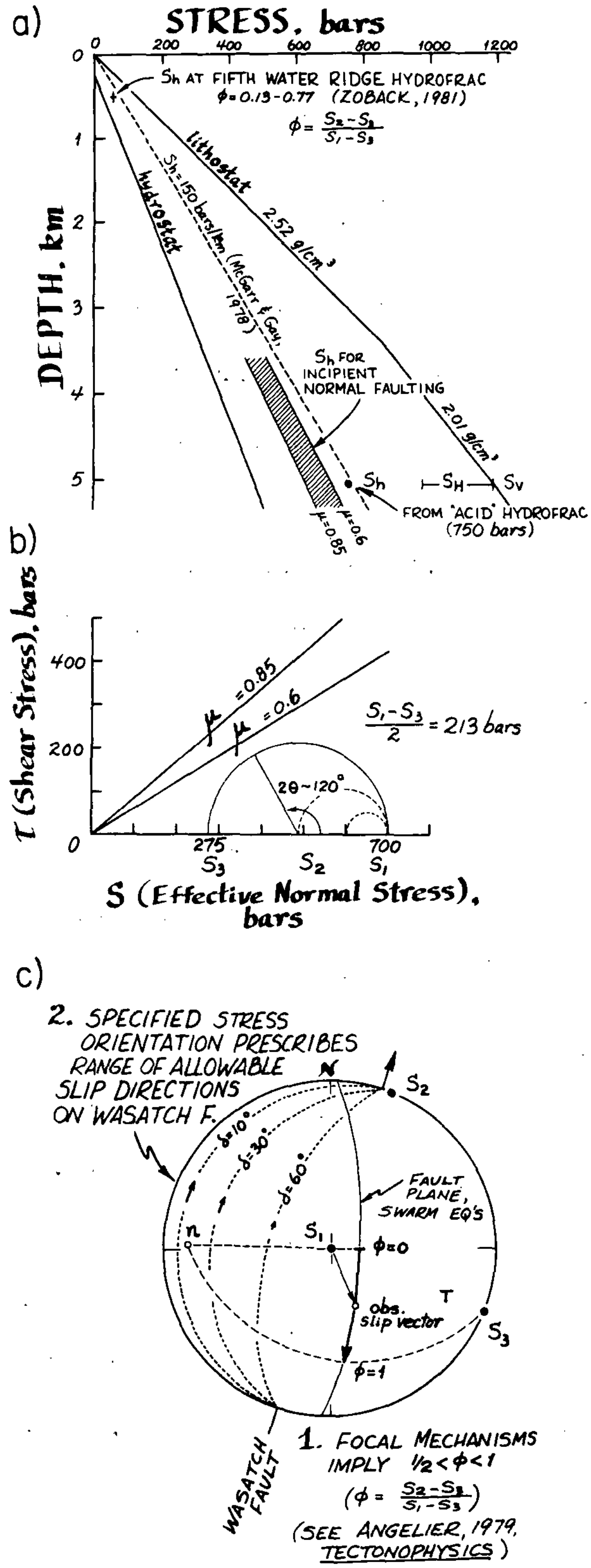


Figure 9. Results presented by Arabasz (1984) relating to inferences of stress state in the vicinity of the southern Wasatch fault. These include: (a) the location in stress-depth space of a value of minimum horizontal compressive stress S_h of 750 bars (75 MPa) determined at a depth of 5.1 km from an "acid-breakdown hydrofrac"; (b) a Mohr-circle diagram relating the estimated stress state at 5.1 km depth from (a) to criteria for frictional failure on a pre-existing plane of weakness; and (c) key observations, presented in stereographic projection, that allow inferences of the orientation and relative magnitude of principal stresses from small earthquakes inferred to have been induced by the deep hydrofrac. See text for complete explanation.

Zoback and Zoback, 1980, p. 6113) and given normal-faulting mechanisms for nearby seismicity. Accounting for hydrostatic pore pressure, maximum deviatoric stress is 213 bars. Options for failure to "drive" the Mohr circle into a failure envelope for frictional sliding on a pre-existing fault (following Byerlee's law) include: (1) decreasing the mean stress (i.e., increasing pore pressure) by about 70 bars, (2) decreasing S_h by about 50 bars, or (3) decreasing the coefficient of static friction to about 0.5. There are obvious uncertainties in the various parameters, but if the observed earthquake activity was indeed causally related to the fluid injection, then the maximum and minimum principal stresses have probably been reasonably estimated to within tens of bars.

Figure 9c illustrates additional information on stress state near the southern Wasatch fault that can be inferred from the observed swarm earthquakes. Corresponding focal mechanisms based on both P-wave polarities and SV/P amplitude inversion indicate: normal faulting, a consistent northerly-trending nodal plane dipping steeply (72^o-86^o)E, and near-horizontal T-axes trending WNW-ESE. Assuming that one of the principal stresses is vertical, S_v then corresponds to S_1 the maximum principal stress, and the direction of S_3 the minimum principal stress will be in the horizontal plane and its azimuth should be estimated by the average direction of T-axes from the focal mechanisms. The intermediate principal stress S_2 will also be horizontal and orthogonal to S_3.

Angelier (1979) describes constraints on the geometric range of allowable slip on a pre-existing fault if the orientation of principal stresses is known. Further, the slip direction on a pre-existing fault is uniquely determined if the relative magnitude of the principal stresses is also prescribed. Information in the lower-right part of Figure 9c illustrates the range of allowable slip on the fault plane plotted as a continuous line. Further, whether one selects the northerly nodal plane or its auxiliary plane, the focal mechanisms imply a value of 0.5 to 1.0 for the parameter ϕ , defined in Figure 9c, for the specified stress orientation. Note that the parameter ϕ describes on a scale of 0 to 1 where S_2 lies between S_3 and S_1 and defines the shape of the stress ellipsoid. The southern Wasatch fault lies within the Basin and Range-Colorado Plateau transition where eastward interchange of S_H with S_V is demonstrated by abundant strike-slip focal mechanisms in the Sevier Valley area (Arabasz, 1983; Julander, 1983).

A final point illustrated in the upper-left part of Figure 9c is that the specified stress orientation prescribes the range of allowable slip directions on the southern Wasatch fault. For the three planes aligned with the strike direction of the Wasatch fault west of the Chriss Canyon well and with arbitrary dips of 60°, 30°, and 10°, allowable slip is constrained to be nearly purely dip slip. Given the specified stress state, faults oriented NNE perpendicular to S_3 and with 60° dip should have optimal susceptibility to slip. Fault slip triggered by the pore-fluid diffusion did not occur on optimally oriented faults within the southern Wasatch fault stress field. There would appear to be variations in strength and/or pore pressure of the order of tens of bars between, say, the optimally oriented upper part of the Wasatch fault and less favorably oriented block-interior faults that accommodated the swarm seismicity.

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INVESTIGATIONS OF AN M_L 4.3 EARTHQUAKE IN THE WESTERN SALT LAKE VALLEY USING DIGITAL SEISMIC DATA

by

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INTRODUCTION

Earthquakes in the Utah region have been recorded digitally by the University of Utah seismic network since January 1981. To date, digital seismograms from more than 2000 earthquakes have been archived on magnetic tape. Together with colleagues at the University of Utah, we have begun to systematically test and apply techniques for extracting information on source properties of small earthquakes from these data. Our goal is to try to obtain a better understanding of how these earthquakes are related to geologic structure and to cycles of strain accumulation and release on major faults along the Wasatch Front. To illustrate the type of research we are pursuing, we present here a study of an M_L 4.3 earthquake that occurred approximately 10 km west of downtown Salt Lake City, Utah, at 11:57 GMT on October 8, 1983 (Figure 1). This earthquake occurred within a region of the western Salt Lake Valley that has been characterized by persistent seismicity since at least 1962, when instru-

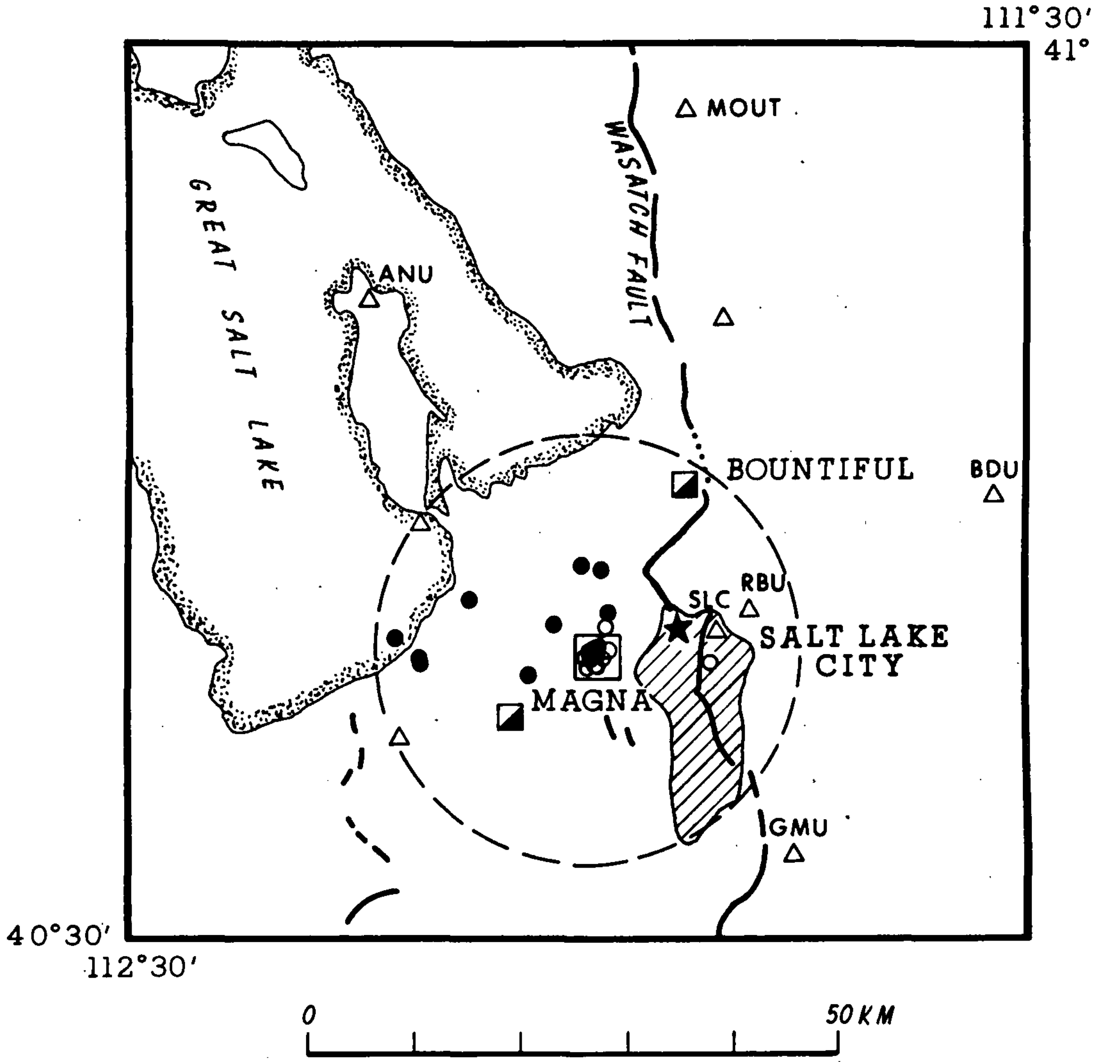


Figure 1. Map showing epicenter of the M_L 4.3 earthquake at 11:57 on October 8, 1983 (solid octagon within aftershock cluster) and relocated epicenters of all events within a 20 km radius of this earthquake during the period January 1981 up until the time of this earthquake (solid circles) and from immediately after the earthquake through November 1983 (open circles). The box encloses the aftershocks selected for waveform analysis. The large dashed circle is the area within which relocations were done. Triangles are seismic stations and squares are cities.

mental location of Utah earthquakes was begun at the University of Utah (Arabasz et al., 1980). Past activity in this region has included an M_L 5.2 earthquake located approximately 8 km northwest of Magna, Utah, on September 5, 1962, and an earthquake swarm several kilometers north and northwest of Magna during February and March of 1978 (largest event M_L 3.2) (Arabasz, et al., 1979; Cook, 1979). Earthquakes in this region are of particular interest because of their proximity to Salt Lake City and the possibility of an association with the Wasatch fault which dips westward beneath the Salt Lake Valley (Figure 1).

MAINSHOCK LOCATION AND FOCAL MECHANISM

The M_L 4.3 mainshock on October 8, 1983 was located using the computer program HYPOINVERSE (Klein, 1978) and the velocity model in Table 1. This velocity model is from a refraction line extending southward from the Bingham Canyon copper mine 35 km southwest of Salt Lake City (Keller et al., 1975). A 7.9 km/sec half space at 42 km depth has been added in order to fit observed travel time data from earthquakes at distances greater than about 250 km (J.C. Pechmann, unpublished data, 1984).

The constraint of the arrival time data on the source depth was carefully examined. For our initial location, we used stations out to a distance of 300 km. Figure 2 (top) demonstrates that the velocity model fits the observed travel-time data from the earthquake very well even at large distances. The hypocentral depth obtained, 4 km, is constrained

Table 1. Wasatch Front Velocity Model (Modified from Keller et al., 1975)

P-Wave Velocity of Layer	Depth Below Datum (1500 m) of Top of Layer
3.4 km/sec	0.0 km
5.9	1.4
6.4	15.5
7.5	25.4
7.9	42.0

Table 2. $\tau_{1/2}$ Measurements

Station	Delta (km)	Azimuth (deg)	Minimum $\tau_{1/2}$ (sec)	Mainshock $\tau_{1/2}$ (sec)	Corrected $\tau_{1/2}$ (sec)
GMU	27.2	134	0.06	0.26	0.20
CWU	34.8	196	0.05	0.25	0.20
JLU	48.5	109	0.10	0.35	0.25
MOUT	51.0	10	0.04	0.22	0.18

Table 3. Calculation of Fault Radius for Mainshock

	Fault Plane 1 (Strike 161°, Dip 16°W)		Fault Plane 2 (Strike 348°, Dip 74°E)	
Station	θ (deg)	r (meters)	θ (deg)	r (meters)
GMU	88	1319	55	1101
CWU	77	1282	65	1191
JLU	80	1623	34	1098
MOUT	85	1182	68	1099
average fault radius:		1352		1123

Table 4. Relocated Epicenters in the Magna Study Area

Date	Time	Latitude N	Longitude W	Magnitude	
Feb. 06, 1981	0102 47.75	40° 48.60'	111° 58.42'	1.0	
Mar. 08, 1982	1023 04.97	40° 45.90'	112° 1.67'	0.8	
Apr. 18, 1982	1215 26.36	40° 44.89'	111° 58.37'	1.5	
May 21, 1982	2001 31.38	40° 48.82'	111° 59.68'	1.1	
Nov. 18, 1982	2116 08.29	40° 47.05'	112° 7.27'	1.2	
Dec. 26, 1982	0947 10.14	40° 43.29'	112° 3.45'	0.8	
Jan. 09, 1983	1331 05.23	40° 43.73'	112° 10.40'	0.7	
Apr. 02, 1983	2323 22.69	40° 45.18'	112° 12.22'	0.8	
Apr. 13, 1983	0551 52.42	40° 44.07'	112° 10.55'	1.8	
Apr. 24, 1983	1833 14.32	40° 46.36'	111° 58.06'	1.0	
Oct. 08, 1983	1157 53.66	40° 44.36'	111° 58.91'	4.3	#
Oct. 08, 1983	1215 46.64	40° 44.46'	111° 58.79'	0.5	+
Oct. 08, 1983	1321 53.46	40° 43.77'	111° 59.50'	0.4	+
Oct. 11, 1983	1023 01.46	40° 44.31'	111° 59.13'	0.9	+
Oct. 11, 1983	1101 58.05	40° 44.03'	111° 59.24'	2.5	+
Oct. 16, 1983	0215 11.99	40° 44.49'	111° 59.14'	1.7	+
Oct. 16, 1983	0540 52.03	40° 44.17'	111° 58.77'	0.6	+
Oct. 16, 1983	0630 43.65	40° 44.27'	111° 58.41'	0.8	+
Oct. 22, 1983	1317 16.26	40° 43.86'	111° 58.96'	0.9	+
Nov. 04, 1983	2243 33.80	40° 44.55'	111° 57.92'	1.0	+
Nov. 05, 1983	0817 51.44	40° 45.80'	111° 58.19'	1.0	
Nov. 17, 1983	1955 06.13	40° 43.55'	111° 51.05'	0.8	
Nov. 20, 1983	0957 36.64	40° 44.20'	111° 59.58'	1.0	+

Mainshock

\+ Events in box in Figure 1 (aftershock cluster)

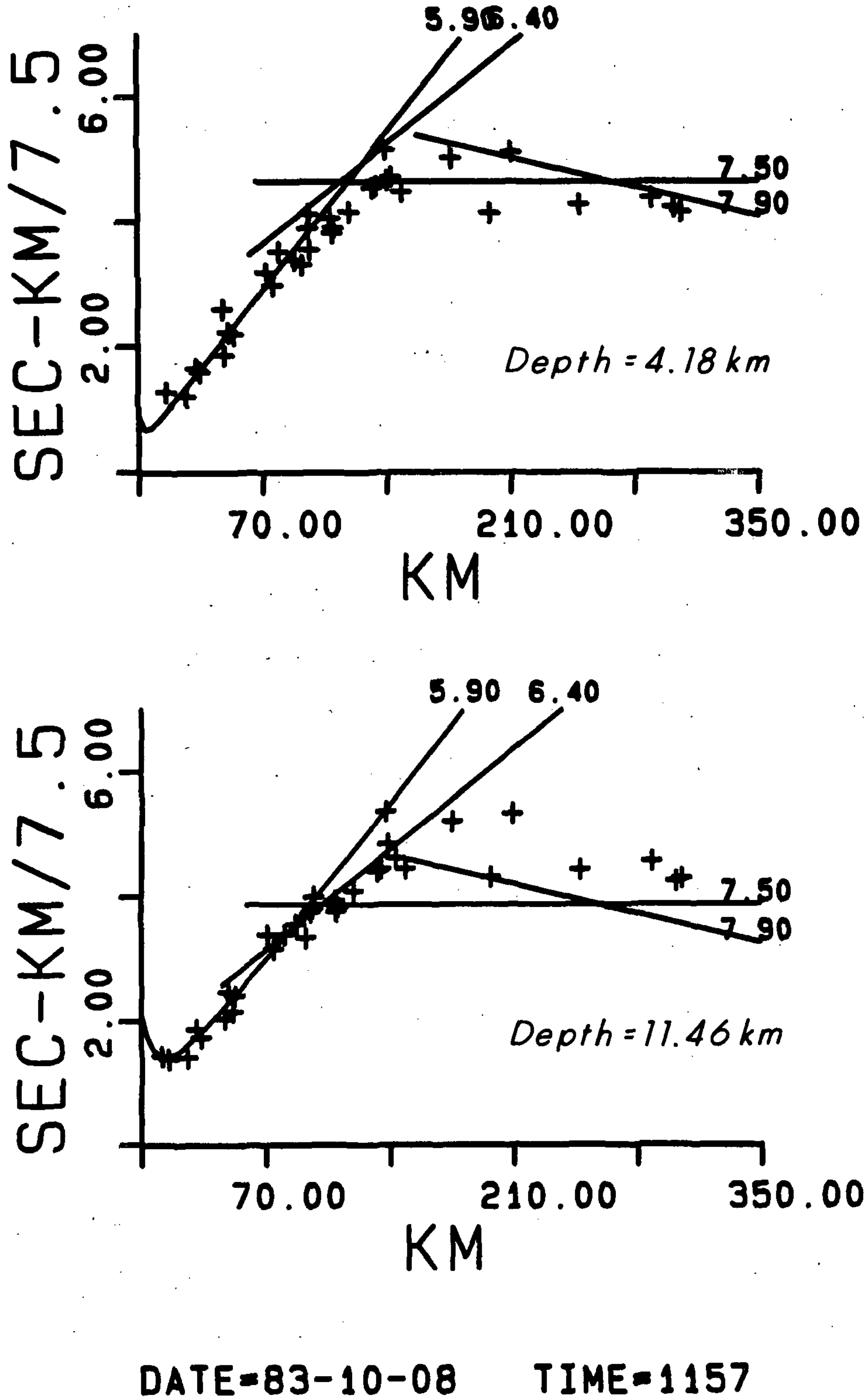


Figure 2. Reduced travel-time plots for the mainshock for two different hypocentral determinations (see text). Solid lines show travel times calculated from the velocity model in Table 1.

primarily by the well-defined 'P_n' crossover at a distance of 120-130 km from the source, where the velocity of the first arrivals changes from 5.9 km/sec to about 7.5 km/sec. The accuracy of this depth determination depends on the accuracy of the velocity model, in particular the crustal thickness. A crustal thickness of 28 km and a P_n velocity of 7.6 km/sec was obtained by Braile et al. (1974) from a refraction line extending northeastward from the Bingham Canyon mine. If the depth of the moho is changed from 25.4 km to 28 km in the velocity model in Table 1 the earthquake locates at a depth of 8 km. If stations beyond the P_n crossover distance are not used in the location, a hypocentral depth of 11 km is obtained. In this case the depth control comes from the arrival time at the closest station, RBU, which is 15 km from the epicenter. If a less reliable P-wave arrival time from the Wood-Anderson instrument at SLC, 12 km from the epicenter, is added to the data set the depth of 11 km remains unchanged (Figure 2, bottom). However, because even the closest stations are more than one focal depth away from the epicenter the arrival times at these stations do not provide a strong constraint on focal depth. We conclude that the depth of the M_L 4.3 mainshock probably lies between 4 and 11 km, but it is not possible to constrain the depth any more accurately than this with the data at hand.

The focal mechanism obtained for the mainshock is shown in Figure 3. The two sets of nodal planes illustrate the range of possible solutions. The takeoff angles used for this mechanism are for a source depth of 4.2 km. Despite the uncertainty in focal depth we are confident that these takeoff angles are realistic because of the excellent

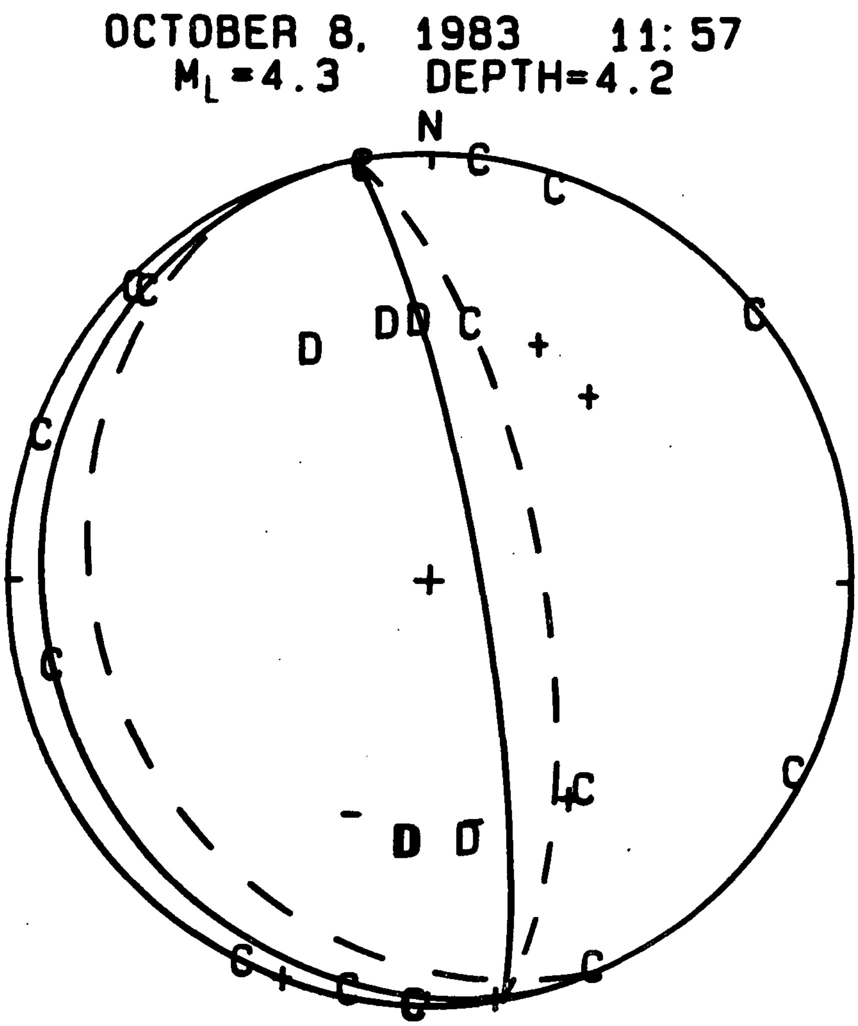


Figure 3. Lower hemisphere P-wave fault plane solution. C's and D's indicate compressions and dilatations, respectively. Pluses and minuses indicate less certain compressional and dilatational first-motion readings.

agreement between the travel time data and the model (Figure 2). If a focal depth of 8 km and a crustal thickness of 28 km are used to compute the takeoff angles the mechanism obtained is virtually identical to the one shown by the dashed nodal planes in Figure 3. Note that both nodal planes are very well constrained by the data.

The mechanism of Figure 3 indicates normal faulting on a north-northwest-striking fault that dips either 68°-80° east or 10°-22° west. Our knowledge of the subsurface geology is insufficient to choose between these two possibilities. If the westward-dipping plane is the fault plane and if the Wasatch fault beneath the Salt Lake Valley is listric, then the possibility that this earthquake occurred along the Wasatch fault cannot be ruled out. However, there are undoubtedly other faults in this region along which the earthquake could have occurred.

First motion data from the largest aftershock, an M_L 2.5 event that occurred three days after the mainshock, indicates predominantly normal faulting on northerly striking nodal planes. Unfortunately, the dips of these planes are not constrained by the available data.

ESTIMATION OF SOURCE RADIUS AND STRESS DROP

The method of Frankel and Kanamori (1983) was used to estimate the source radius of the M_L 4.3 mainshock. This technique involves measurement at nearby stations of a parameter designated $\tau_{1/2}$, the time between the P-wave onset and the first zero crossing. $\tau_{1/2}$ was measured at four stations for the mainshock and ten aftershocks. The results are shown in Figure 4, where $\tau_{1/2}$ is plotted as a function of magnitude. At each station, $\tau_{1/2}$ was found to remain nearly constant with decreasing magnitude for aftershocks less than about magnitude 2, as was found by Frankel and Kanamori (1983), O'Neill (1984), and O'Neill and Healy (1973) for earthquakes in California. This is interpreted to signify that the waveforms of the events smaller than magnitude 2 represent the combined impulse response of the path between the source and receiver and the instrument itself. When the values of $\tau_{1/2}$ for the smallest aftershocks are subtracted from those measured for the mainshock at each station (in effect deconvolved), the corrected values of $\tau_{1/2}$ show excellent agreement from one station to another (Table 2). These corrected values of $\tau_{1/2}$ are estimates of the half-duration of the source time function for the mainshock (see Frankel and Kanamori, 1983).

The mainshock seismograms from which $\tau_{1/2}$ measurements were taken are shown in Figure 5, together with representative $M_L<2$ aftershock seismograms from each station. It can be clearly seen from these data that the initial pulse widths for the aftershocks are nearly the same at any given station and that the initial pulse widths for the mainshock are larger than those for the aftershocks, reflecting the longer duration of the source. Despite the complexity in the initial waveforms at stations GMU and JLU, which is not accounted for in the simple model we are using, the corrected $\tau_{1/2}$ measurements from these stations agree very well with the measurements from the other two (Table 2).

The corrected $\tau_{1/2}$ measurements are converted to estimates of

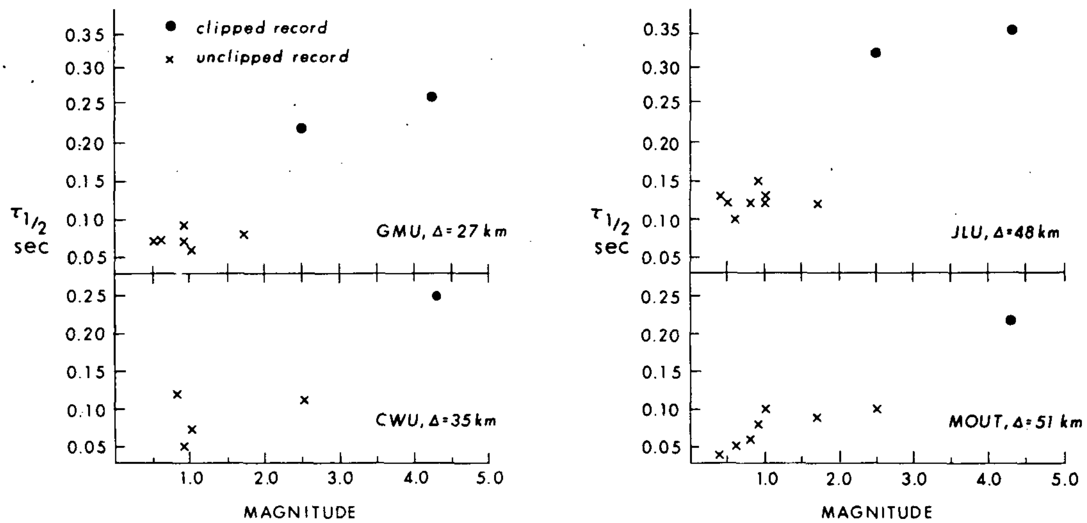


Figure 4. Initial pulse width, $\tau_{1/2}$, plotted vs. magnitude for the mainshock and ten aftershocks for stations GMU, CWU, JLU, and MOUT. Δ is epicentral distance. Crosses indicate unclipped records and dots clipped records. Note how $\tau_{1/2}$ becomes nearly constant for earthquakes below about magnitude 2.0.

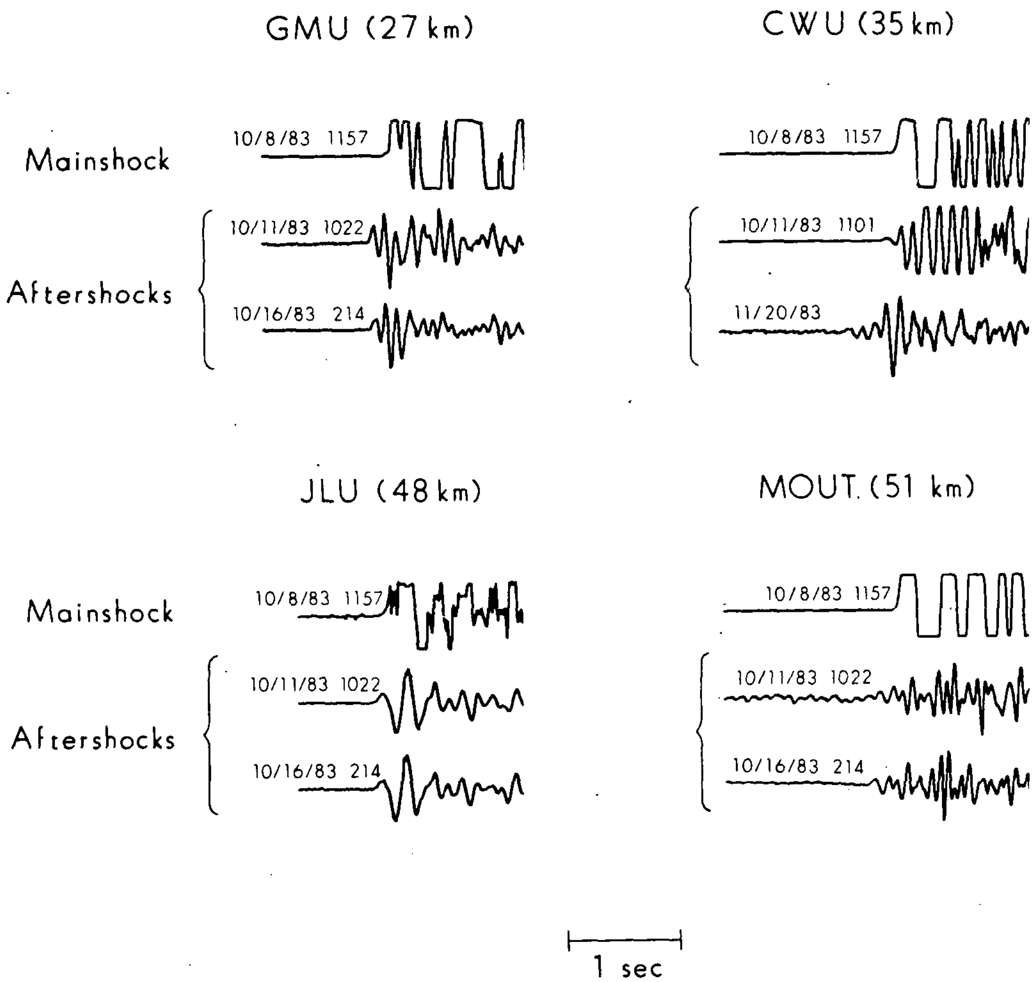


Figure 5. Waveforms of the M_L = 4.3 mainshock and two aftershocks for each of the stations GMU, CWU, JLU, and MOUT. $\tau_{1/2}$ is the time between the P-wave onset and the first zero crossing.

source radius r using

$$r = \tau_{1/2}\, v/(1-(v/c)\sin\theta)$$

where c is the P-wave velocity, v is the rupture velocity, and θ denotes the angle between the normal to the fault plane and the outgoing seismic ray (Sato and Hirasawa, 1975). We use 5.9 km/sec for c (Table 1) and assume that the rupture velocity v is 0.9 times the corresponding shear wave velocity of 3.5 km/sec (Keller et al., 1975). Values for θ are calculated for all four stations from the takeoff angles used for the mainshock focal mechanism and a set of fault planes intermediate between the solid and dashed solutions shown in Figure 3. θ and r were calculated for both possible fault planes (Table 3). The average value obtained for r is either 1.4 km or 1.1 km, depending on which plane is chosen as the fault plane. Assuming a circular fault, the estimated fault area is 3.8-6.2 km^2. This is comparable to the area of the aftershock zone determined from the epicenters in Figure 1 (4.5 km^2) but larger than the area of the aftershock zone deduced from cross correlation of wave forms ($\sim$0.5 km^2; see next section and Figure 10).

We estimate the moment for this earthquake from the Wood-Anderson magnitude and a moment-magnitude relation for Utah earthquakes determined by Doser and Smith (1982):

$$\log M_o = 1.1\, M_L + 18.4$$

The moment obtained is about 1.3×10^{23} dyne-cm. The stress drop $\Delta\sigma$ can be calculated from this moment and the fault radius determined above using the solution for a circular crack in an elastic medium determined by Eshelby (1957) and Keilis-Borok (1959):

$$\Delta\sigma = (7/16)\ M_o/r^3$$

The calculated stress drops are 21 and 43 bars, depending on whether 1.4 km or 1.1 km is used for the source radius. These are typical stress drop values for earthquakes, neither unusually high nor unusually low. However, since the moment was not determined directly for this earthquake and since all stress drop estimates are model-dependent, caution must be used in comparing this stress drop with those reported in the literature for other earthquakes.

REGIONAL SEISMICITY DURING 1981-83 FROM MASTER-EVENT RELOCATIONS AND WAVEFORM ANALYSIS

All earthquakes with preliminary locations within 20 km of the mainshock during the time period January 1981 through November 1983 were relocated relative to the mainshock using the master event technique of Johnson and Hadley (1976) with the computer program HYPOINVERSE. The results (Figure 1) show a clustering of aftershock activity surrounding the mainshock epicenter (box, Figure 1), but otherwise the seismicity within the study area is diffuse. No obvious precursory seismic activity was observed within the study area during the time period examined. (Some seismic events during 1981-1983 that are clustered near the surface trace of the Wasatch fault between Salt Lake City and Bountiful have been identified as quarry blasts during this study but are listed as earthquakes in the University of Utah catalog (Richins et al., 1984).)

Waveforms for the earthquakes in the aftershock cluster (Table 4) were examined at several stations. Figures 6 and 7 show the seismograms recorded at two typical stations, MOUT and RBU (Figure 1). Groups of earthquakes with similar waveforms can be identified within the aftershock sequence. This waveform similarity suggests similar hypocenters and focal mechanisms for these events.

To analyze the similarity of events within the aftershock cluster the seismograms were cross correlated following the procedure of Pechmann and Kanamori (1982). The normalized cross-correlation function $c_{xy}(m)$ for two real time series x and y of length N is given by:

$$c_{xy}(m) = \frac{\frac{1}{N-|m|} \sum_n x(n)y(n+m) - \overline{x(n)}\ \overline{y(n+m)}}{\sqrt{\overline{x^2(n)} - \overline{x(n)}^2}\sqrt{\overline{y^2(n+m)} - \overline{y(n+m)}^2}}$$

where the bar indicates the mean

$$\overline{x(n)} = \frac{1}{N-|m|} \sum_n x(n)$$

and the summation is from n=0 to n=N-m-1 for $m \geq 0$ and from $n=|m|$ to n=N-1 for $m<0$. For all cross-correlation calculations, a record length of 19.5 seconds was used. The sampling rate was 104.17 samples/sec except for the two events in January, 1981, for which the sampling rate was

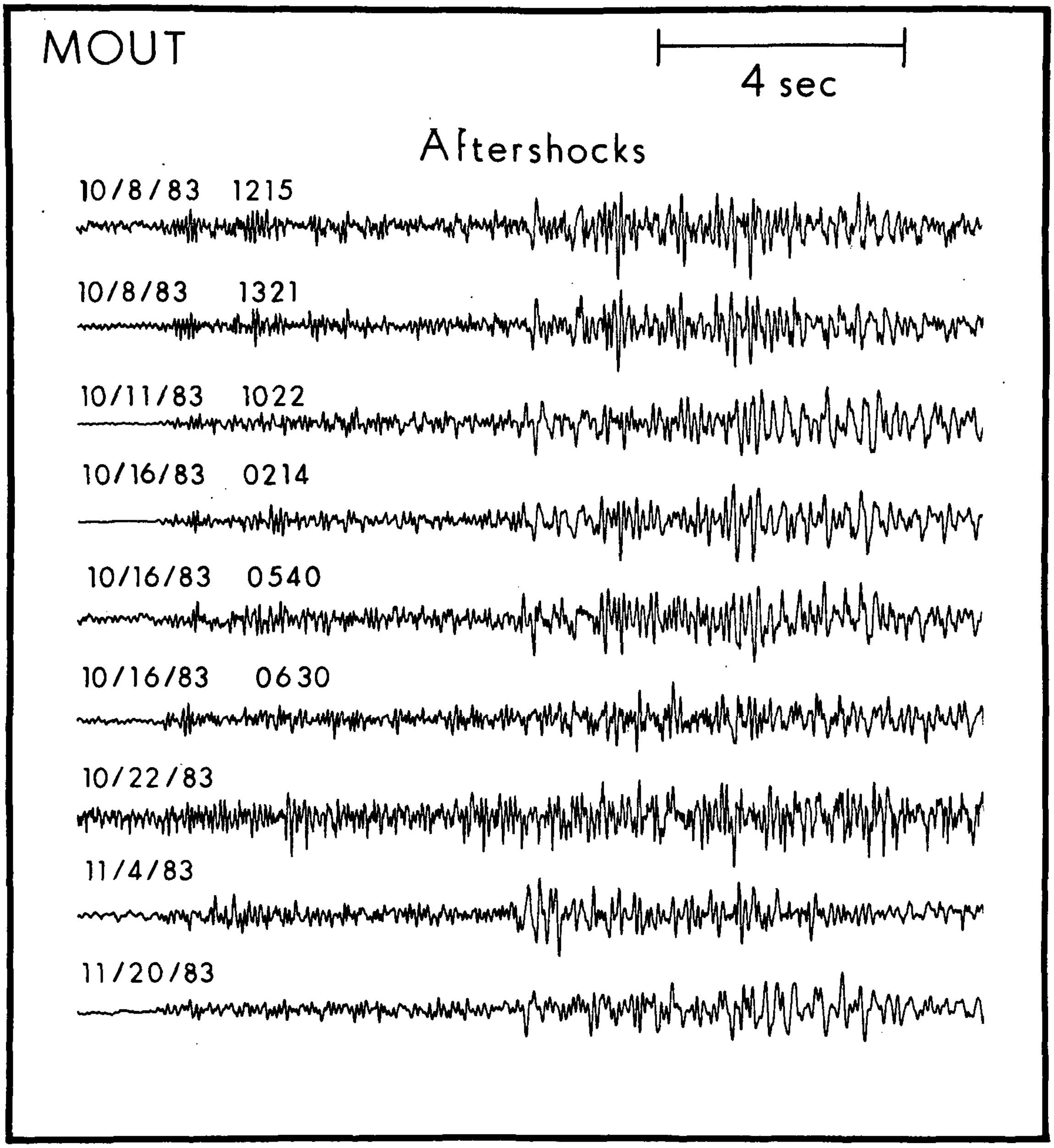


Figure 6. Vertical component seismograms recorded at station MOUT for aftershocks within 2 km of the mainshock epicenter (box, Figure 1). All seismograms are plotted with the same maximum amplitude. The record of the magnitude 2.5 aftershock is not shown because it was clipped at this station and all the other stations used for waveform analysis.

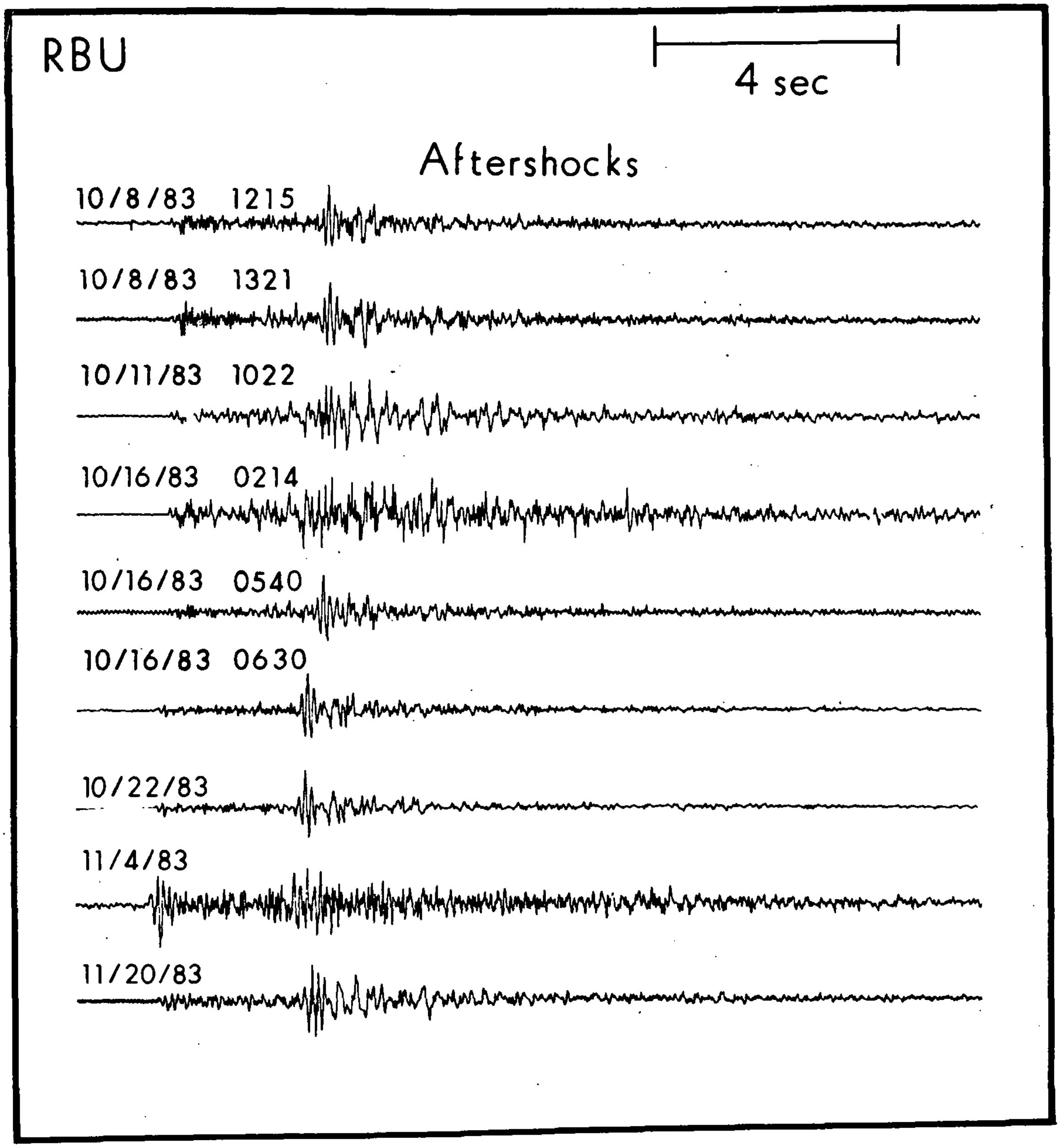


Figure 7. Same as Figure 6 for station RBU.

100.0 samples/sec. A linear interpolation was performed on the seismograms from these two events in order to increase their sampling rate to 104.17 samples/sec before doing the cross correlations. The maximum value of the cross correlation function $c_{xy}(m)$ was determined for all possible event pairs from seismograms recorded at stations ANU, BDU, MOUT, and RBU and then the results from all four stations were averaged. These stations were chosen because they provided good recordings of most of the aftershocks. The mean of the maximum cross-correlations was also calculated for the seismograms after they had been bandpass filtered in the passbands 2-4, 4-8 and 8-16 Hz with third-order recursive Butterworth filters. This was done to help quantify the constraint that the similarity between waveforms places on the maximum distance between the hypocenters.

The results of the cross-correlation calculations are plotted in Figure 8. The radius of each circle is proportional to the correlation values for the corresponding event pair. The open circles indicate pairs of events with a mean peak correlation of 0.6 or greater, which for the purposes of this discussion we will define as "well correlated". Figure 8 shows that our conclusions about waveform similarity based on visual inspection of the seismograms are essentially correct. To demonstrate more clearly how the events form smaller clusters within the main aftershock cluster, the order of events was rearranged to put similar events next to each other, as shown in Figure 9. The rearrangement concentrates the larger circles (best correlated pairs of events) near the diagonal. Boxes are drawn around event groups that are considered "well

CROSS-CORRELATION MATRICES

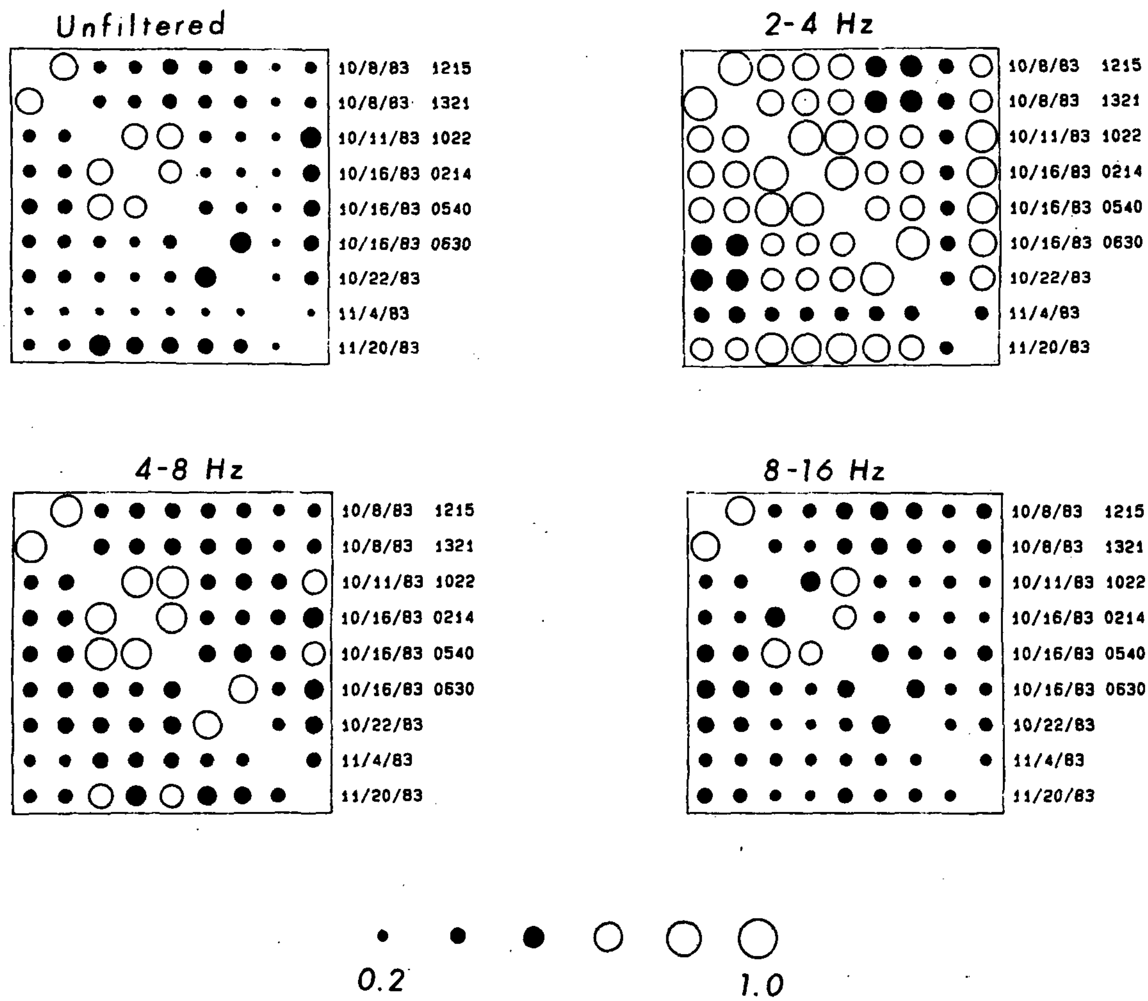


Figure 8. The mean of the maximum cross-correlations calculated for seismograms from stations ANU, BDU, MOUT, and RBU for all possible pairs of events in Figures 6 and 7. Each circle represents the mean peak correlation for the event pair corresponding to its position in the matrix. The radius of the circle is proportional to the correlation value. Circles representing values less than 0.6 are solid.

CROSS-CORRELATION MATRICES REARRANGED

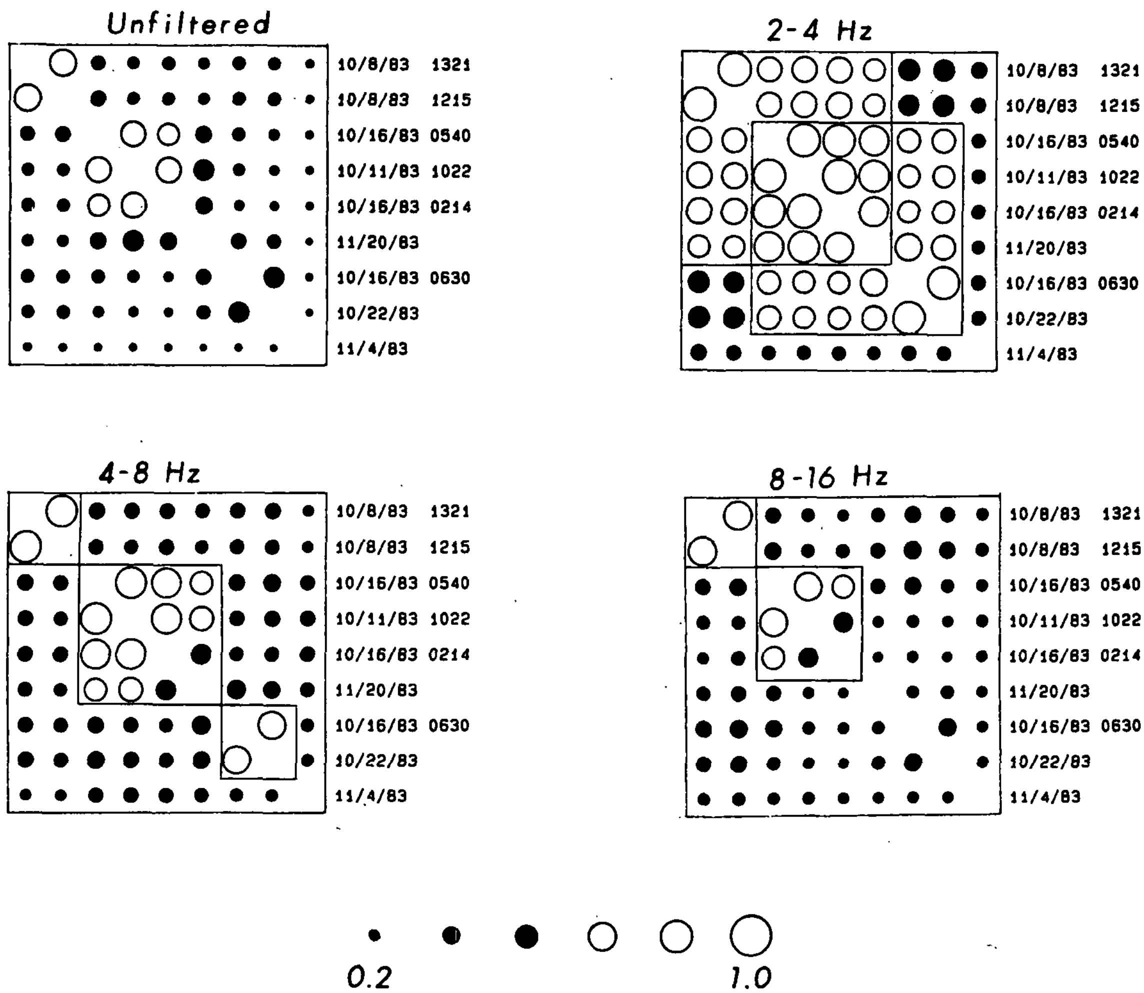
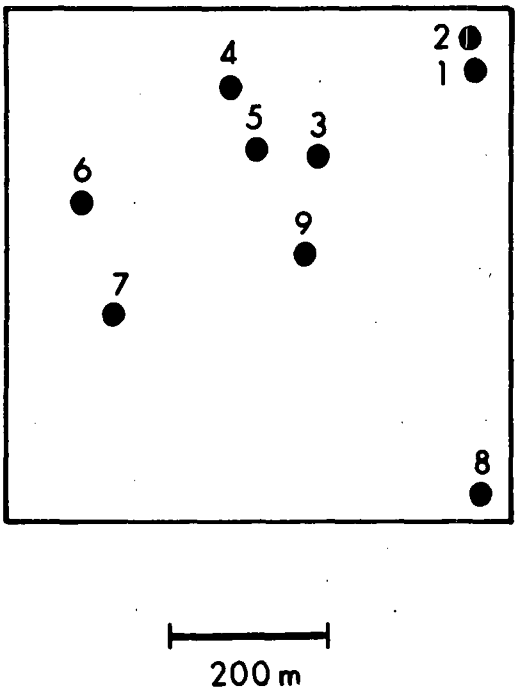


Figure 9. Same as Figure 8 except that the order of events has been rearranged to concentrate the large circles near the diagonal. Boxes show one way to divide the events into groups or clusters inside the main clusters.

correlated". Within the aftershocks there appear to be two overlapping groups of events for the 2-4 Hz bandpass filtered data, three separate groups for the 4-8 Hz passband, and two separate groups for the 8-16 Hz passband. The similarity of waveforms of the events within each group implies similar source mechanisms and hypocenters within about 1/4 of the shortest wavelength to which the similarity extends (Geller and Mueller, 1980; Thorbjarnardottir and Pechmann, unpublished data from quarry blasts, 1984). We can use this constraint to estimate the maximum separation between events. From Table 1 we have that the near-source P-wave velocity is about 5.9 km/sec. The near-source S-wave velocity is about 3.5 km/sec (Keller et al., 1975). Hence, for events that are well correlated at frequencies up to 16 Hz the maximum event separation should be 50-90 m. For events that are well correlated at frequencies up to 8 Hz the maximum event separation is 110-180 m and for frequencies up to 4 Hz the maximum separation is 220-370 m.

Figure 10 illustrates the interpretation we have made from these calculations of the relative distances between hypocenters within the aftershock cluster. For this interpretation, we used the values for the maximum event separation distances that were derived from the P-wave velocity (the larger of the two values given for each frequency band above). The details of the relative hypocentral distributions shown are certainly not unique, but the general patterns are reasonably well constrained. Some of the aftershocks cluster within small volumes of 200 meters or less such as aftershocks 1 and 2 and aftershocks 3, 4, and 5. These small clusters may represent local stress concentrations along



AFTERSHOCKS

1	10/8/83	1215
2	10/8/83	1321
3	10/11/83	1022
4	10/16/83	0214
5	10/16/83	0540
6	10/16/83	0630
7	10/22/83	
8	11/4/83	
9	11/20/83	

Figure 10. Two-dimensional schematic representation of relative hypocentral locations determined from cross correlation of filtered seismograms.

fault asperities (see Kanamori, 1981, and Pechmann and Kanamori, 1982). The radius of the aftershock zone inferred from the waveform data is only about 350 m, which is a factor of 3 or 4 smaller than the radius of the mainshock fault break determined above from the $\tau_{1/2}$ measurements.

The aftershock distribution of Figure 10 shows a systematic spatial migration of activity for aftershocks 1 through 7, which are the first eight aftershocks of the sequence minus the magnitude 2.5 aftershock at 11:01 on October 11, 1983, which was not used for the waveform study because the records were clipped. The evidence for this can be seen most easily in the cross-correlation matrices in Figure 8, where the events are arranged chronologically. If we disregard the last two columns and rows, the circles representing aftershock-aftershock cross correlations generally decrease in size with increasing distance from the diagonal, indicating that the successive events tend to be the best correlated. The migration pattern cannot be seen in the master event relocations. In fact, the relative locations of the relocated aftershock epicenters look nothing at all like the aftershock pattern shown in Figure 10. Thus, it appears that waveform cross correlation can illuminate details of seismicity that are below the resolution of master event locations.

CONCLUSIONS

An earthquake of M_L 4.3 occurred on October 8, 1983, within a seismically active region of the western Salt Lake Valley. The depth of this earthquake is problematic, but probably lies within the range of

4-11 km. A well-constrained focal mechanism for this event indicates normal faulting on a north-northwest striking fault plane that dips either steeply to the east or gently to the west. The method of Frankel and Kanamori (1983) was successfully applied to determine a source radius of about 1 to 1-1/2 km and a stress drop of a few tens of bars. Analysis of waveforms for nine aftershocks that occurred during the two months following this earthquake suggests that the radius of the aftershock zone was a factor of 3 or 4 smaller than the estimated fault radius for the mainshock. There is evidence in the waveform data for aftershock migration during the first part of the sequence. The mainshock was not preceded by any unusual seismic activity within 20 km of the epicenter during 1981-1983.

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FLUID PRESSURE, TEMPERATURE, AND COMPOSITION AT DEPTH ON THE WASATCH FAULT, UTAH

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ABSTRACT

Hydrothermally altered Oligocene quartz monzonite of the Little Cottonwood stock forms the footwall of the Wasatch Fault at the southern end of the Salt Lake segment. Hydrothermally altered and structurally deformed rocks form a partially preserved carapace up to 100 m thick on the western and southern margin of the stock. Cataclasite and phyllonite contain two syndeformational alteration mineral assemblages: an early epidote, chlorite, sericite assemblage and a later laumontite-prehnite assemblage. Fluid inclusions associated with the formation of alteration minerals are preserved in healed fractures in quartz grains.

Fluid inclusions associated with the chlorite-epidote-sericite alteration were trapped at a minimum temperature of 295°C and minimum fluid pressure of 1100 bars. The fluids average 10 mole percent CO_2 and 6.7 weight percent NaCl. Published radiometric and fission track dating suggests that the age of the alteration is about 24 m. y. and a thermal gradient of 30° C/km suggests that the depth of alteration is about 9.5 km. Estimated hydrostatic pressure at 9.5 km is 930 bars and lithostatic pressure is 2400 bars. Estimated fluid pressure on the fault is thus 170 bars in excess of hydrostatic pressure.

INTRODUCTION

Hydrothermal vein systems are common in the upper 10-15 km frictional regimes of fault zones and flow of aqueous fluids often accompanies shallow crustal faulting (Sibson, 1981). The presence of aqueous fluids in fault zones determines the shear stresses which can be supported and the strain mechanisms by which deformation occurs. Hot aqueous fluids reduce the work of fracture, enhance crack growth rates, chemically weaken the rock, promote recrystallization to new mineral assemblages, and reduce the effective normal stress that controls friction, crack growth, and megascipic fracture (Etheridge, et al., 1984; Hobbs, 1984; Parks, 1984; Dunning et al., 1984; Atkinson and Dennis, 1982; Hubbert and Rubey, 1959).

The Wasatch Fault is a 370 km long zone of active normal faulting that extends from southern Idaho to central Utah (Swan et al., 1980; Cluff et al., 1975; Gilbert, 1928). A prominent salient in the fault occurs southeast of Salt Lake City in the Traverse Mountain-Corner Creek area (Figure 1) where the fault curves around the Oligocene Little Cottonwood quartz monzonite stock. The quartz monzonite forms the footwall of the fault and Paleozoic sediments and Tertiary volcanic rocks form the hanging wall of the fault. Both footwall and hanging wall rocks have been extensively hydrothermally altered. Cataclasite and phyllonite formed from alteration and mechanical deformation of the Quartz monzonite comprise a partially preserved carapace up to 100 m thick on the southern and western margin of the stock (Figure 2). This fault rock grades laterally and downward into weakly altered quartz monzonite. Two distinct syndeformational alteration mineral assemblages are present in the footwall rock. A late, low-temperature assemblage of laumontite, prehnite, and clay minerals is superimposed on an earlier assemblage of chlorite, muscovite, and epidote. The sequence of high to low temperature alteration records the continued upward displacement of the

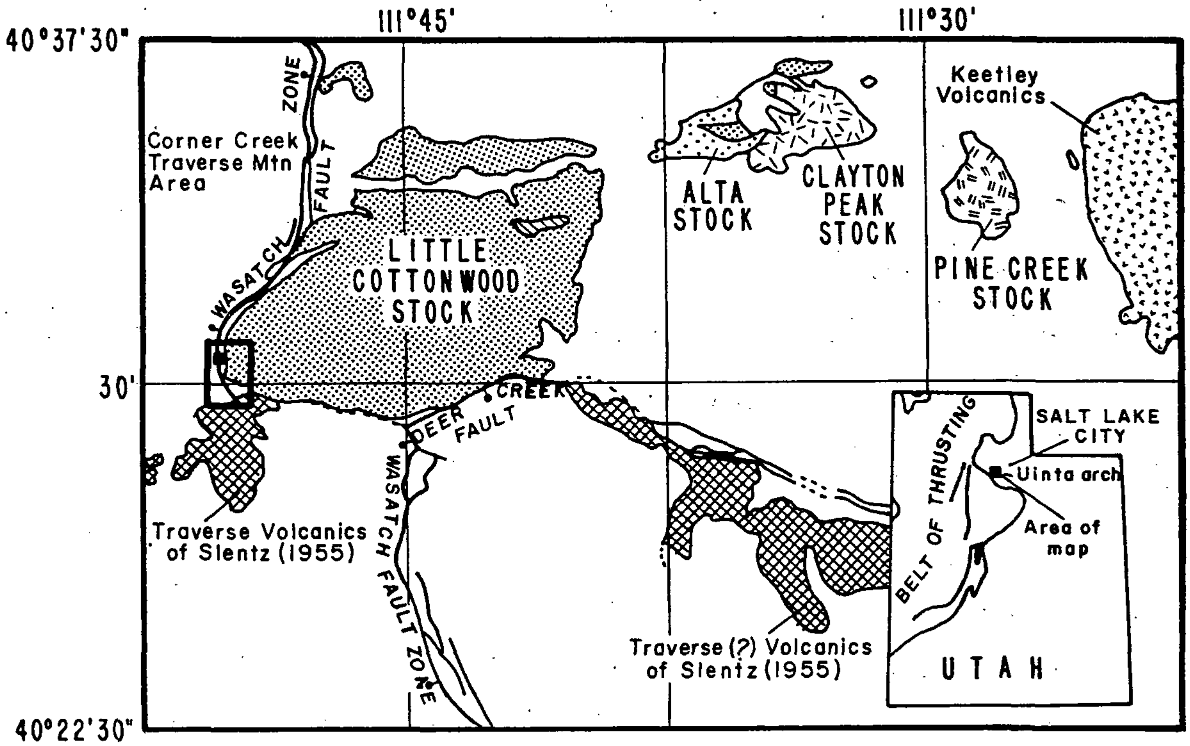
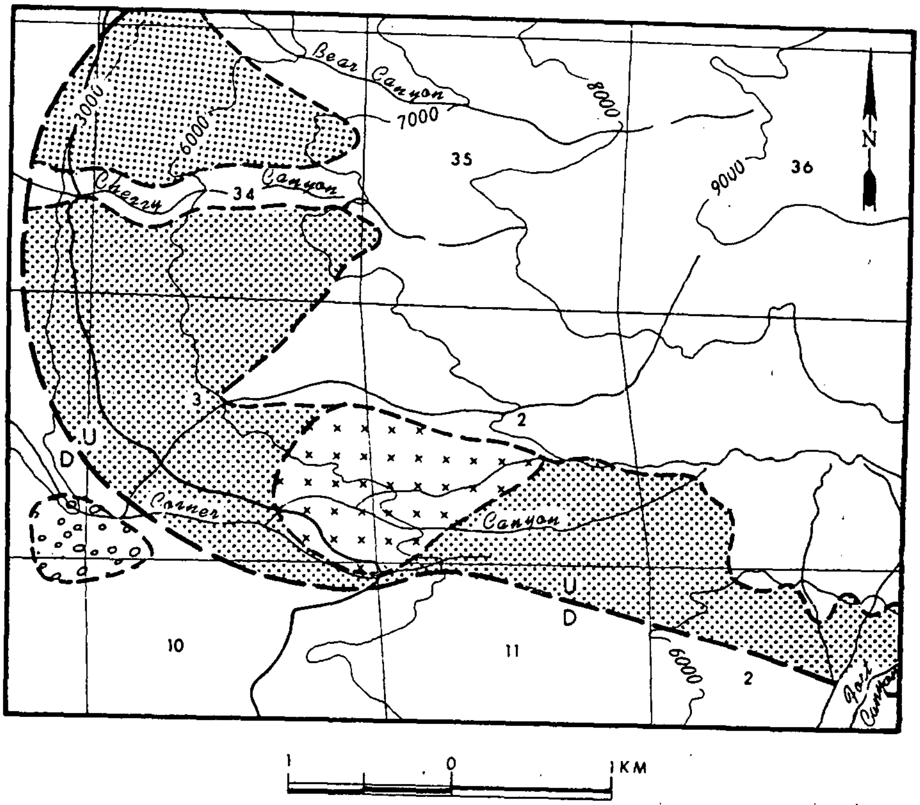


Figure 1. Index and geologic maps of the Corner Creek-Traverse Mountain area (modified from Crittenden et al., 1973)



EXPLANATION

- Quartz monzonite of the Little Cottonwood stock
- Traverse volcanics and Oquirrh formation
- Laumontite, prehnite, and clay alteration in footwall quartz monzonite
- Chlorite, epidote, and sericite alteration in footwall quartz monzonite
- Kaolinite, smectite, and sericite alteration im hanging wall volcanics and Oquirrh formation
- U/D Wasatch Fault

Figure 2. Hydrothermal alteration zones in the Corner Creek-Traverse Mountain area.

footwall. Healed fractures in deformed quartz grains in both alteration assemblages contain fluid inclusions that are samples of the fluid present during faulting. In this report we describe characteristics of fluids in inclusions associated with the early, chlorite-epidote-sericite assemblage. Methods for estimating fluid pressure from fluid inclusion observations are reviewed by Roedder and Bodnar (1980).

Observation of fluid inclusions on the heating-freezing stage and of the mineral assemblages in the fault rock have provided an estimate of fluid pressure, temperature and composition on which to base estimates of the rheological behaviour of the fault.

FAULT ROCK MINERALOGY AND TEXTURE

The footwall rock on the Wasatch Fault in the Corner Creek-Traverse Mountain locality is the Little Cottonwood stock which is a prophyritic quartz monzonite consisting of 25% plagioclase (An 30-35), 40% orthoclase, 25% quartz, 7% biotite, and 3% hornblende with trace amounts of apatite, zircon magnetite and sphene (Berge, 1960). The texture is coarse phaneritic with phenocrysts of orthoclase reaching 15-50 mm in diameter. The age of intrusion is established at 31 m. y. by potassium-argon dating of hornblende (Crittenden et al., 1973); fission track ages of sphene and zircon and potassium-argon ages of biotite are concordant at 24 m. y. and date a 300° C thermal event on the western edge of the pluton.

Near the Wasatch Fault, footwall rock has been subjected to multiple alteration and deformation episodes with progressive displacement of the fault. Successively younger, lower temperature, lower pressure mineral assemblages are superimposed upon older, higher temperature, higher pressure assemblages. Mechanical deformation is ductile to brittle in character in the early alteration stages and becomes successively more brittle with later lower temperature alteration.

Mechanical deformation and hydrothermal alteration have produced striking textural changes. Igneous quartz grains show pronounced undulatory extinction, deformation lamellae, and healed fractures decorated with fluid and solid inclusions. Igneous biotite has kink bands, has recrystallized to an aggregate of smaller biotite grains, or has been replaced by chlorite. Igneous hornblende has been replaced by chlorite. Sericite is disseminated throughout the feldspars which also contain veinlets of sericite, calcite, chlorite, and epidote. Twin lamellae in plagioclase show kink bands. The rock also contains numerous seams of crushed quartz and feldspar in a matrix of sericite and chlorite.

FLUID INCLUSIONS

Fluid inclusions are present in vein quartz and in igneous quartz of the quartz monzonite. Vein quartz in chlorite-sericite-quartz veins contains primary fluid inclusions consisting of carbon dioxide and a solution of water and salt. These inclusions are generally smaller than 1 or 2 micrometers and phase changes on the heating stage could not be reliably observed.

Igneous quartz which shows pronounced undulatory extinction and deformation lamellae contains abundant trains of secondary fluid inclusions that decorate healed fractures. In some cases solid inclusions of chlorite, sericite, or calcite accompany trains of fluid inclusions and sericite veinlets mark the extension of the fluid inclusion trains into surrounding feldspar. The linear trains of fluid inclusions often bisect the angle between zones of undulatory extinction (subparallel to c) and the deformation lamellae (subperpendicular to c). The trains of fluid inclusions thus coincide approximately with the maximum principal stress (Carter and Raleigh, 1969). The relationship between fluid inclusion trains, the stress system, and alteration mineral assemblage is established. These inclusions are similar to smaller inclusions in quartz veins in content. A carbon dioxide vapor bubble is often surrounded by liquid carbon dioxide and an aqueous salt solution. These inclusions reach 10 micrometers in size and phase changes could be observed on the heating-freezing stage. No solid daughter minerals were observed in any of the fluid inclusions.

Careful observation of thin sections from widely spaced localities in the Little Cottonwood stock shows that no part of the stock is completely free of hydrothermal effects and fluid inclusions are not uncommon. The presence of carbon dioxide rich inclusions in highly deformed quartz grains is uniquely restricted to the vicinity of the footwall of the Wasatch fault in the Corner Creek-Traverse Mountain locality and the abundance of inclusions is directly related to proximity to the fault.

MICROTHERMOMETRY

Identity and characteristics of fluid inclusion contents were determined by observation of phase changes on a Chaix-Meca heating-freezing microscope stage. Phase changes which characterize the fluid are the carbon dioxide triple point at -56.6° C (disappearance of solid CO_2 on slow heating), melting of clathrate ($CO_2.5.75H_2O$) in equilibrium with liquid and vapor CO_2 at +10 to -1.7° C depending on salinity of the aqueous phase, CO_2 liquid-vapor homogenization, and homogenization of CO_2 fluid and aqueous salt solution. An additional phase change, melting of ice in the aqueous salt solution, could not be reliably observed.

Carbon dioxide triple point temperatures are displayed in Figure 3 and are tightly grouped around -56.6° C confirming the identity of CO_2 with undetectable concentrations of methane. Above this temperature a clathrate forms in the inclusions. Melting of the clathrate has been converted to equivalent weight percent NaCl using the

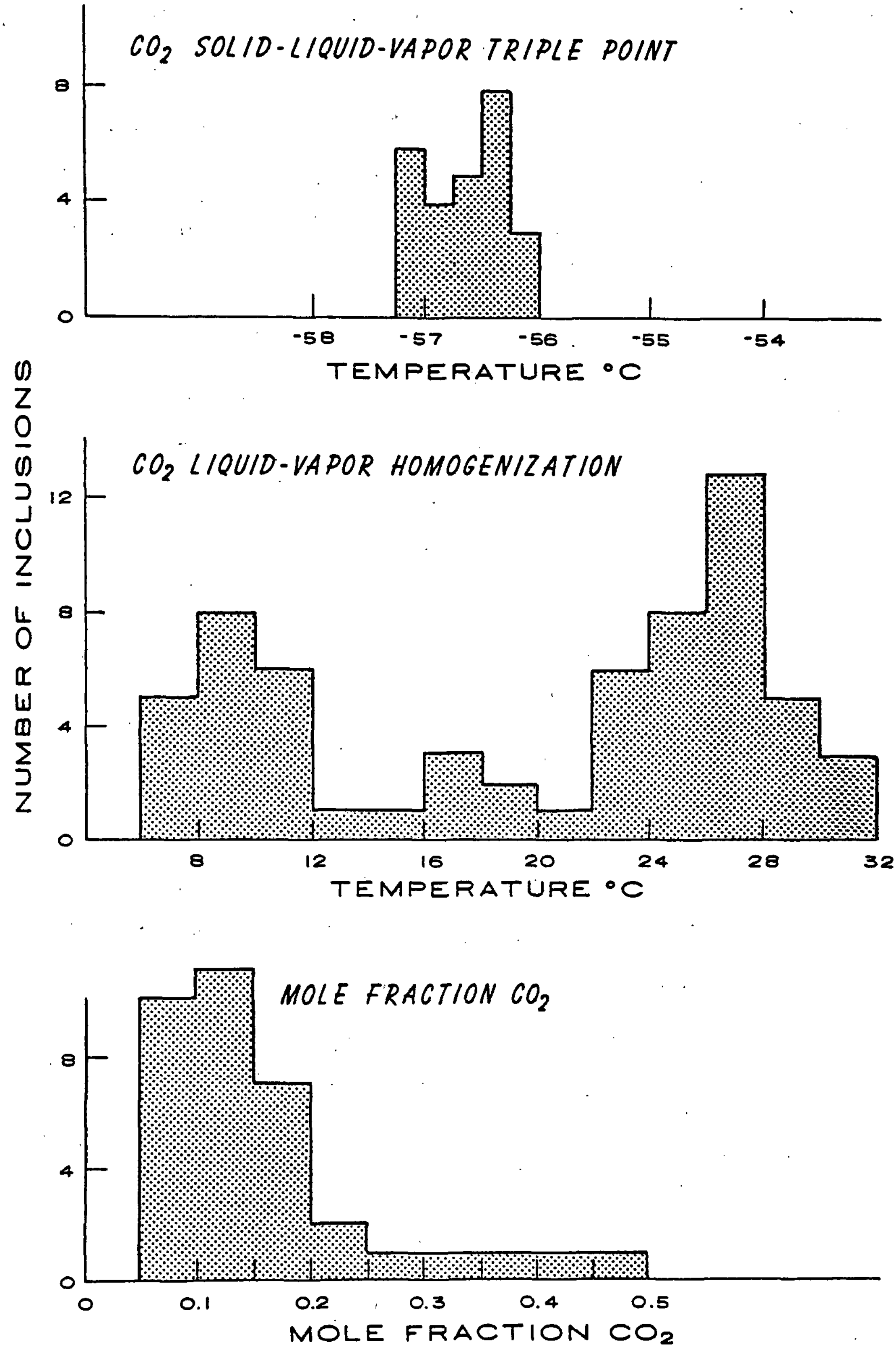


Figure 3. Histograms of CO_2 triple point temperatures, CO_2 liquid-vapor homogenization temperatures and mole fraction CO_2 in fluid inclusions from the Corner Creek area.

data of Bozzo et al. (1973). The average weight percent NaCl of the data displayed in Figure 4 is 6.7% NaCl.

Homogenization of liquid and vapor CO_2 takes place at 7.0 to 30.5° C as shown in Figure 3. These temperatures define the density of the carbon dioxide portion of each fluid inclusion and are used in subsequent calculations of inclusion composition and pressure.

Finally, the temperatures of homogenization of CO_2 with the aqueous phase are shown in Figure 4. Approximately two-thirds of the inclusions decrepitated before this temperature could be reached due to the high pressures reached in the inclusions. The mean homogenization temperature for inclusions that did not decrepitate is 295° C.

FLUID INCLUSION COMPOSITION

Interpretation of the microthermometry data in terms of entrapment temperatures and pressures requires that the composition of the homogenous fluid be estimated. The mole fraction CO_2, NaCl, and H_2O in each inclusion were estimated using the procedures outlined by Burrus (1981) which are based on an estimate of the salinity of the aqueous phase from clathrate melting temperatures, the density of the CO_2 phase from CO_2 liquid-vapor homogenization and an estimate of the relative volume of CO_2 and aqueous phases at 40° C. Density of the CO_2 phase was calculated from the data of Angus et al. (1973), density of the aqueous phase was calculated from Potter and Brown (1977) and mole fractions of each component were then computed from volumetric and density estimates. The mole fraction CO_2 in the inclusions shown in Figure 3 averages 0.10.

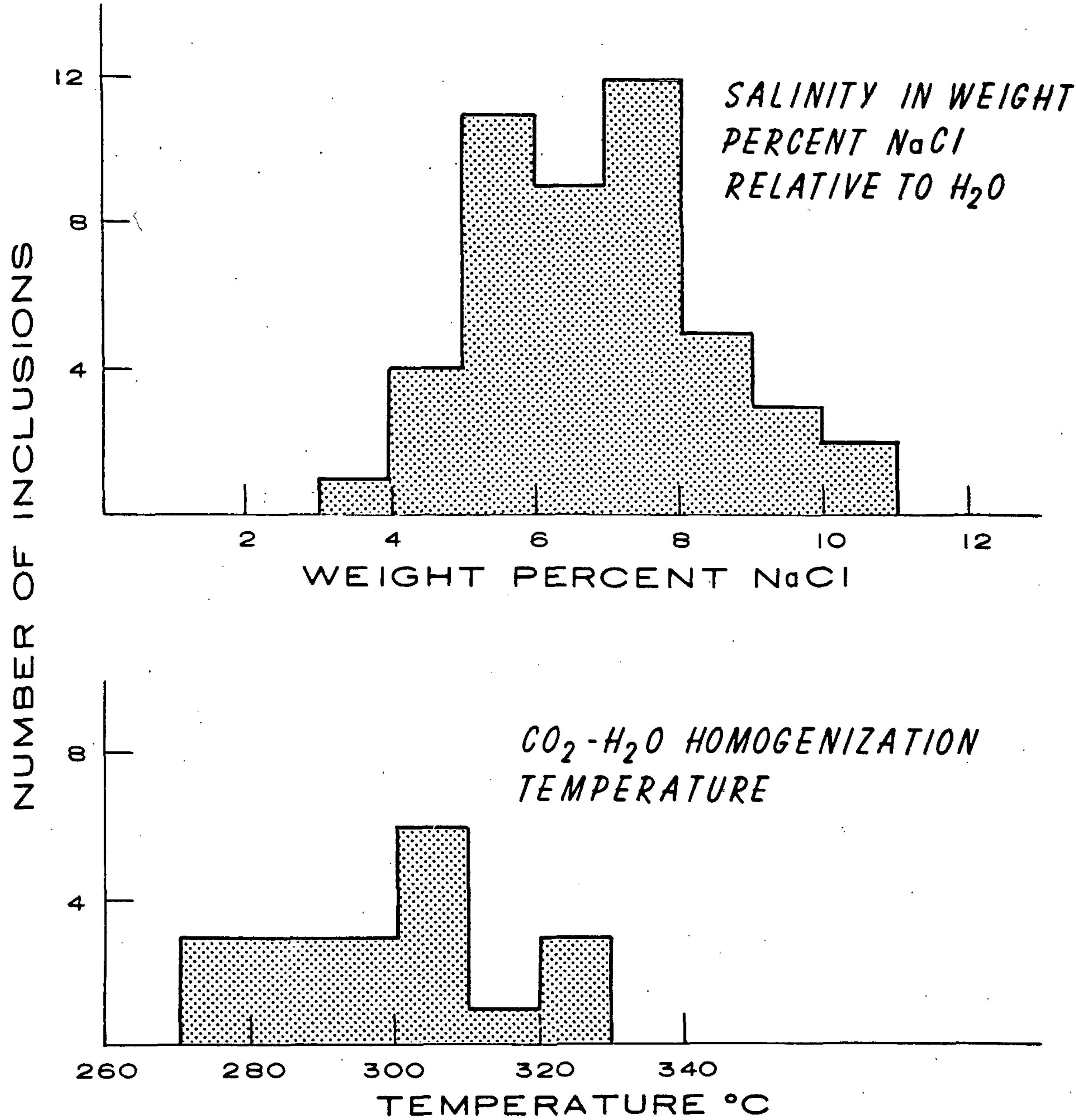


Figure 4. Histograms of salinity in weight percent NaCl and homogenization temperatures of fluid inclusions from the Corner Creek area.

FLUID PRESSURES AND TEMPERATURES

Estimates of fluid pressures and temperatures are based upon the asumption that microfractures in quartz grains trap inclusions of a single homogeneous fluid as they heal soon after a mechanical, fracture-producing event. The contents and volume of the inclusion then remains constant as uplift of the footwall rocks proceeds and cooling produces phase changes in the inclusions. These phase changes are reversed in the microthermometric measurements, i.e., separation of a CO_2 fluid from the aqueous salt solution and then separation of a CO_2 vapor bubble from CO_2 liquid.

Compositions of homogenous fluids and their densities in the CO_2-NaCl-H_2O system have been reviewed by Bowers and Helgeson (1983a, 1983b). The pressure and temperature limits of the two phase region (solubility of CO_2 in an aqueous salt solution) are dependent upon salinity of the aqueous phase and mole fraction CO_2. The pressure-temperature projection of the two phase region for 10 mole percent CO_2 and 6.7 weight percent NaCl (relative to H_2O) is shown in Figure 5 which is compiled from the summary of Bowers and Helgeson (1983b). Homogenization of fluids at 295° C defines a minimum entrapment pressure of 1100 bars and the density of the trapped fluid calculated from the MRK coefficients of Bowers and Helgeson (1983a) of 0.8890 gm/cc. The pressure-temperature conditions required for this density in the homogenous phase region are shown by the isochore in Figure 5. The actual temperature and pressure of the fluid at the time of entrapment must lie along this isochore.

Fluid pressure and temperature are further constrained by the mineral assemblages present in the rocks. The assemblage epidote, sericite, feldspar, and quartz suggest univariant equilibria according to:

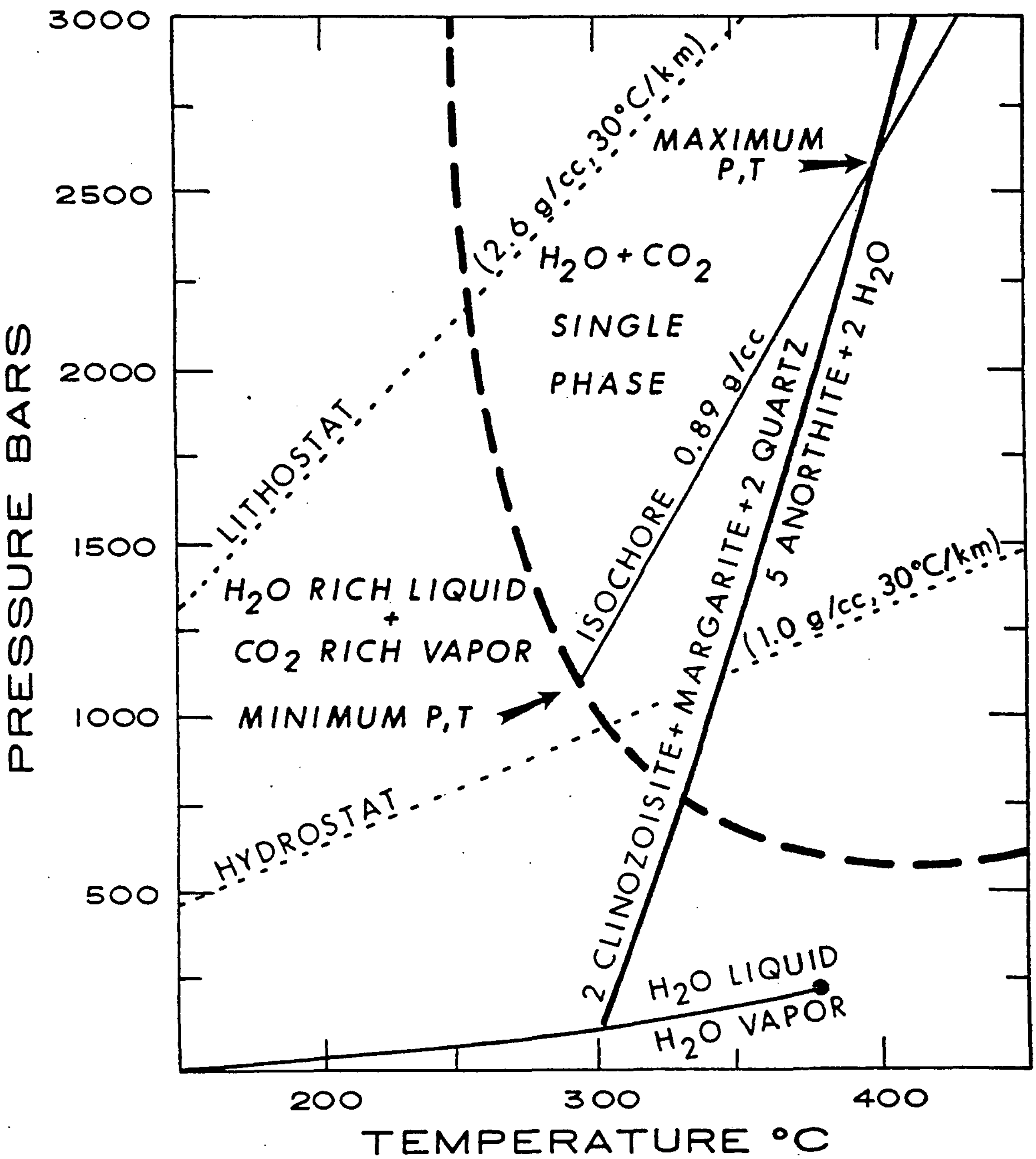


Figure 5. Two-phase boundary for the CO_2-NaCl-H_2O system at 6.7% NaCl and 10 mole % CO_2 from Bowers and Helgeson (1983b). Also shown are the boiling curve for water, the isochore difined by a 295^0 C homogenization temperature, univariant curve for an epidote reaction, and pressure-temperature conditions for lithostatic and hydrostatic pressures.

$2Ca_2Al_3Si_3O_{12}(OH)$ + $CaAl_4Si_2O_{10}(OH)_2$

2 clinozoisite in epidote + margarite in sericite

+ 2 SiO_2 = 5 $CaAl_2Si_2O_8$ + 2 H_2O

+2 quartz in rock = 5 Anorthite in feldspar + 2 water in fluid

The univariant equilibrium curve adjusted for mineral composition for this region has been computed using the computer program SUPCRT (Helgeson et al., 1978) and is shown in Figure 5. While the rocks contain the minerals in this reaction, equilibria among the minerals is not unequivocally established in textural relations in the rocks. The univariant mineral reaction curve intersects the isochore defined by fluid inclusion measurements at maximum temperature and pressure permitted by dehydration of epidote.

DEPTHS AND AGES

Our estimates of temperatures and pressures of pore fluids leads naturally to estimates of other parameters of the Wasatch fault including depth of formation of the fault rock, minimum throw on the fault, minimum age, and displacement rate. The geothermal gradient in this portion of the Western United States is near 30^{o} C per km placing the minimum fluid inclusion entrapment temperature of 295^{o} C at a depth of 9.5 km. Hydrostatic pressure of a cold water column at this depth is 930 bars, and lithostatic pressure (2.6 g/cc) is 2400 bars. Minimum fluid inclusion pressure of 1100 bars is therefore 170 bars above hydrostatic pressure and the ratio of pore fluid pressure to lithostatic pressure is 0.46.

Fission track and potassium argon ages of apatite, zircon, sphene, and biotite have been determined for the western edge of the Little Cottonwood stock by Crittenden et al. (1973). The age of the intrusion is best indicated by a hornblende potassium-argon age of 31 m. y. Fission track ages of zircon and sphene and K/A ages of biotite are concordant at 25 m. y. These ages represent a thermal event of approximately 300° C. The age of a 100° C thermal event is represented by apatite fission track age of 8 m. y. The dated samples come from the Temple Quarry locality 9.6 km northeast of the Corner Creek site and 3 km east of the mapped trace of the Wasatch Fault, but may represent the age of the thermal event producing the CO_2 rich fluid inclusions. A minimum uplift rate required to bring alteration mineral assemblages and fluid inclusions formed at 295° C to the surface on the footwall of the fault is 0.5 mm/yr. Fission track dating of apatite from the Archean Farmington Canyon complex 50 km north of Corner Creek suggest uplift rates of 0.012 mm/yr. from 90 m. y. to 10 m. y. and accelerated uplift of 0.4 mm/yr from 10 m. y. to the present (Naeser et al., 1980). If uplift of the CO_2 rich fluid inclusions began 10 m. y. ago then the uplift rate must be 0.95 mm/yr in good agreement with rates of 0.8+0.6 or -0.2 mm/yr reported by Swan et al. (1981) for the last 19,000 years.

CONCLUSIONS

The Oligocene Little Cottonwood quartz monzonite stock forms the footwall of the Wasatch fault in the Corner Creek-Traverse Mountain area southeast of Salt Lake City. Syndeformational hydrothermal alteration of the stock and fluid inclusions in minerals record the temperature, pressure, and composition of fluids present at depth on the fault. An epidote-sericite-chlorite alteration assemblage occurs with fluid inclusions that are rich in CO_2. Microthermometric observations of fluid inclusions indicate a minimum entrapment temperature of 295° C, a minimum fluid pressure of 1100 bars, and mean fluid composition of 6.7 weight percent NaCl relative to H_2O and 10 mole percent CO_2. A 30° C per km gradient places this hydothermal event at a depth of 9.5 km.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Figure 1. Index and geologic maps of the Corner Creek-Traverse Mountain area (modified from Crittenden et al., 1973).

Figure 2. Hydrothemal alteration zones in the Corner Creek-Traverse Mountain area.

Figure 3. Histograms of CO_2 triple point temperaturess, CO_2 liquid-vapor homogenization temperatures and mole fraction CO_2 in fluid inclusions from the Corner Creek area.

Figure 4. Histograms of salinity in weight percent NaCl and homogenization temperatures of fluid inclusions from the Corner Creek area.

Figure 5. Two-phase boundary for the CO_2-NaCl-H_2O system at 6.7% NaCl and 10 mole % CO_2 from Bowers and Helgeson (1983b). Also shown are the boiling curve for water, the isochore defined by a 295° C homogenization temperature, univariant curve for an epidote reaction, and pressure-temperature conditions for lithostatic and hydrostatic pressures.

INVESTIGATION OF HISTORICAL SEISMICITY IN THE SALT LAKE CITY PORTION OF THE WASATCH FRONT REGION OF UTAH USING DOCUMENTARY SOURCES

by

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ABSTRACT

Extensive investigation of the historical documentary record is being undertaken by this study as a part of determining the frequency of occurrence and the extent of physical effects of earthquakes in the Salt Lake City portion of the Wasatch Front area of Utah. Although the investigation is preliminary at this time, it is evident that (1) untapped primary sources are available for investigation, (2) many of those sources have a high degree of historic reliability, (3) some of the sources have a significant homogeneity through time and space, and (4) the numerous types of sources available for the Salt Lake City region are sufficient to provide an accurate picture of historic seismicity in that area. The three phases of this study include collecting information from intensive checking of original documentary sources from 1850 to the present to uncover as much data as possible on the following:

Phase I--dates and times of events felt in the area

Phase II--intensity (M.M.) or magnitude (M_L) and effects of those earthquakes including damage reports

Phase III--in-depth investigation of specific site response to larger ($I_o \geq VII$) earthquakes within Salt Lake City

The investigation will include those events that affected Salt Lake City in particular. However, any data located during the course of the study that will aid in a more complete record of the historic seismicity for the State of Utah as a whole will be made available.

Phase I--Identifying the dates and times of events in Salt Lake City, 1850 to present

Pre-instrumental Utah earthquakes have been listed in catalogs (Holden 1898, McAdie 1907, Townley and Allen 1939, Williams and Tapper 1953, Coffman and von Hake 1973, U.S. Geological Survey, 1976, Arabasz and others, 1979, Askew and Algermissen 1983) and in bulletins and journals (for example, United States Earthquakes or the Bulletin of the Seismological Society of America). The published catalogs listed above were checked and the data on earthquakes were traced to the original sources. The original sources used in those compilations were not always primary sources but sometimes secondary ones. Errors, omissions, and duplications in such compendia are often perpetuated from one list to another through time because of that practice. The use of primary sources eliminates those compilation errors (Oaks 1981, Ambraseys 1983). Therefore, earthquake accounts in published works were traced to the primary sources to determine which ones had been used. Additional primary documentary sources (some types have been used in published lists and some have never been used, for example, army medical records) were checked to solve the problems which included uncertainties surrounding the date or time. Those primary sources were subjected to strict tests of reliability (S. D. Oaks 1981, unpub. rept., 1984).

Investigations of historic seismicity using documentary sources in areas of the Basin and Range province, which lie outside the present study area, have shown that as many as 50 percent more historic earthquakes have occurred in some of those places than are listed in catalogs (Dubois and others, 1981, Oaks and Algermissen, in preparation). Preliminary investigations for Utah indicate similar conclusions although the record for Salt Lake City is more complete.

Phase II--Identifying intensity, magnitude and felt effects of earthquakes in Salt Lake City, 1850 to present

The existing catalogs were also checked for poorly documented events (those where felt area, intensity, epicentral region, or all of the above were uncertain). Again, primary sources were checked to ascertain the most reliable data available. As in phase I, additional documentary sources for phase II were not only located, but subjected to reliability tests.

More information to help define the effects of specific regional earthquakes on Salt Lake City is being gathered. This task will be accomplished over the course of the next year.

The information gathered during the implementation of phase I and phase II will be presented in a list of earthquake effects for the Salt Lake City urban area from 1850 to the present. By conducting a systematic and complete reading of several types of historic documentary evidence it is assumed (based on preliminary investigations) that a new listing, with increased accuracy and completeness, will emerge for the Salt Lake City urban area of the Wasatch Front including events $\geq$III M.M. This research goal will be accomplished by examining documentary sources including the daily abstracts and monthly reports of weather observers, the daily logs from military installations, daily issues (and weekly issues when daily issues did not exist) of newsapers in Salt Lake City, and historic seismograph records (when available).

Within each category every piece of data will be tested in terms of historic source reliability criteria. Every historic documentary source will be evaluated according to those criteria which include examining who recorded the data and under what conditions the data were recorded. Each source will be coded according to the determined reliability. Therefore, only a complete list of the time, date, and intensity (M.M.) of pre-instrumental events and the magnitude (M_L) of instrumental events, but the sources used and the reliability factor assigned to the data will be included. This will allow a great amount of information to be presented, but the certainity of each set of data used will be evident as well. This is valuable for weighting policy decisions to certain events and, in addition, will contribute to the facility of revising the listing as additional documentary evidence becomes available in archival repositories in the future.

Phase III--Investigation of significant earthquake events in Salt Lake City, 1850 to present

Specific earthquakes with a maximum intensity (I_o) $\geq$VII (M.M.) will be investigated in detail in an attempt to determine more about the degree of damage caused by the events especially in the Salt Lake City urban area. Effects at various sites and to different building types will be detailed whenever possible. This part of the study will investigate large events which were epicentered in or near Salt Lake City. The important criteria will be whether they caused damage in the area.

Historic documentary evidence including previously unused documentary sources will be evaluated and used to reconstruct felt and damage reports in the region. Isoseismal maps will be drawn for the events investigated. Few historic earthquakes in Utah have been investigated in detail. Once the chronology of the earthquake events has been determined from the documentary sources examined in phase I and phase II (in progress), the events which produced damaging effects in Salt Lake City will be investigated in phase III of the study to be conducted in 1985.

CONCLUSION

The new data on earthquakes and their effects in the Salt Lake City urban area produced by this study will serve as a detailed contribution to the historical seismicity of the Salt Lake City portion of the Wasatch Front. The methods employed will illustrate the importance of using primary sources and of using different types of primary sources in historical seismicity research. In addition, a chronology of the physical effects of earthquakes in the region will be used in the assessment (S. D. Oaks, in progress) of the perception by institutions (for instance the Mormon Church) to the earthquake hazard in Salt Lake City from 1850 to the present.

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Preliminary investigations of late Quaternary slip rates along the southern part of the Wasatch fault zone, central Utah

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Introduction

The southern part of the Wasatch fault zone (WFZ) consists of the Levan and Nephi segments (fig. 1; Schwartz and Coppersmith, 1984). Recent field reconnaissance shows that young fault scarps extend for 38 km along the Levan segment, from 2 km northeast of Fayette to 5 km northeast of Levan (fig. 1, index map). Along the Nephi segment, the young scarps extend 33 km, from the north edge of Nephi to about 1 km northeast of Spring Lake, a small community about 5 km south of Payson. These two segments are separated by a 16-km-long gap where young scarps are not present.

Trench investigations by Schwartz and others (1983; also in Schwartz and Coppersmith, 1984) at North Creek, near the center of the Nephi segment, reveal three episodes of surface rupturing, each having 2.0-2.6 m offset, and an estimated average recurrence interval of 1,700-2,600 yrs. The most recent movement, however, occurred within the past 1,100 yrs and perhaps in the past 300-500 yrs. The youngest surface ruptures and scarps of the whole WFZ appear to be on the Nephi segment (Schwartz and Coppersmith, 1984).

In the Salt Lake and Utah Valleys extensive, relativley young deposits of Lake Bonneville cover most of older (Quaternary) deposits and consequently the pre-Bonneville Quaternary history of faulting has not been well documented. Only rarely can pre-Lake Bonneville age deposits be related to the WFZ (W. E. Scott, pers. commun., 1984), and even then the deposits typically are exposed only on one side of the fault. Conversely, Lake Bonneville could only have occupied the Juab Valley for a few thousands of years of its last cycle (Scott and others, 1983) and nowhere do deposits of Lake Bonneville straddle the Nephi segment of the WFZ. Because of these contrasting histories, Quaternary deposits of pre-Bonneville age, are better preserved in the Juab Valley than at most other localities to the north and thereby provide datums from which pre-Bonneville age slip rates can be determined.

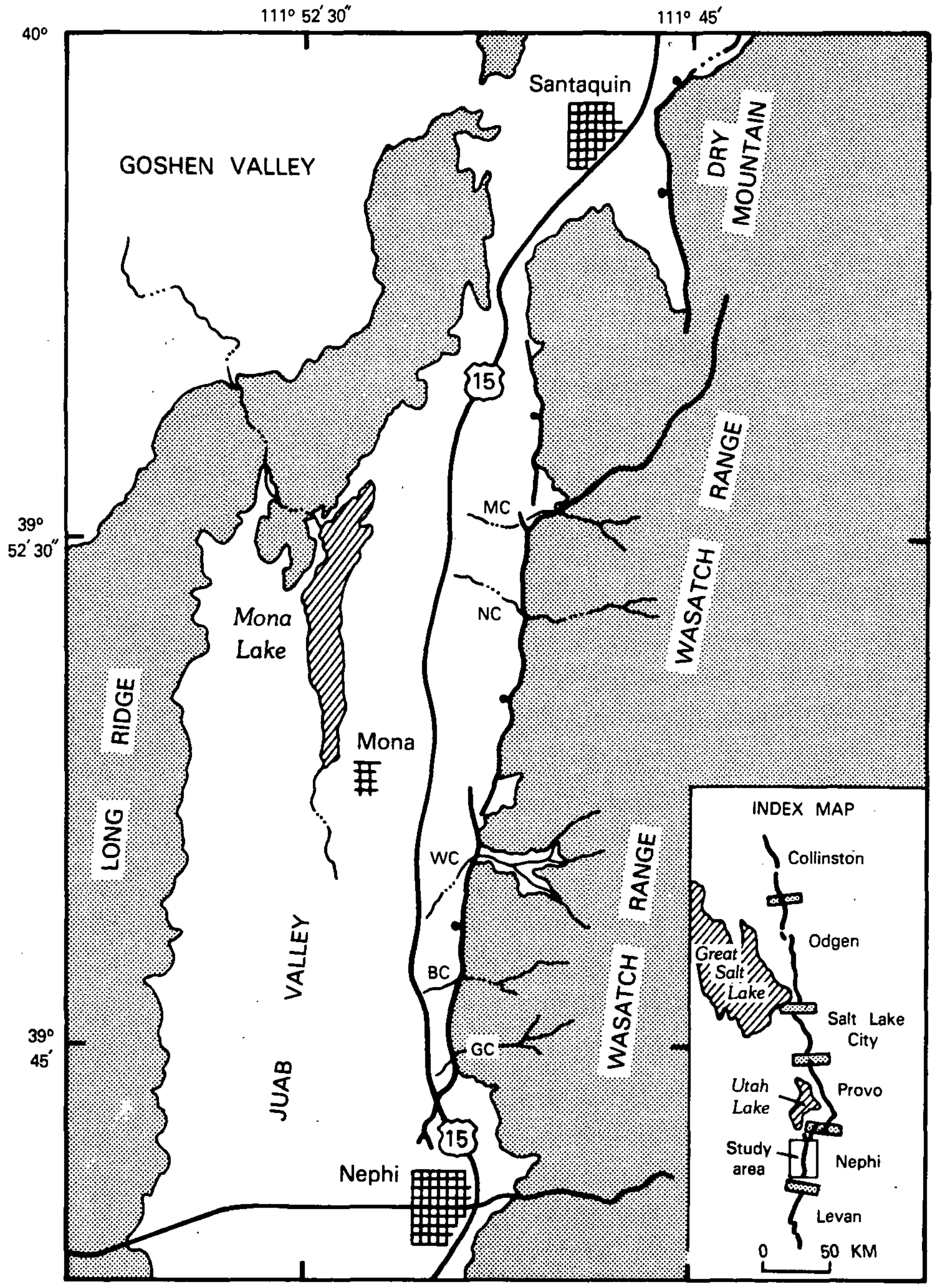


Figure 1. Generalized map of the Wasatch fault zone north of Nephi, Utah. Index map (inset) shows fault segments proposed by Schwartz and Coppersmith (1984).

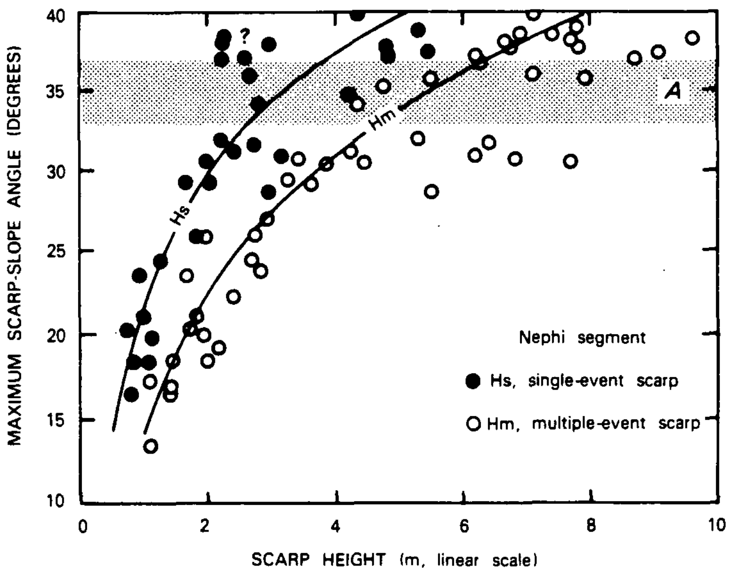
Geologic investigations

Studies were conducted in order to better understand the 1) paleoseismicity of the Nephi and Levan segments as well as the 2) spatial and 3) temporal relations between young faulting events and 4) bedrock structure, and 5) mass-movement processes (landsliding, emplacemment of debris flows, and colluviation). The detailed investigations include surface mapping at scales of 1:12,000 and 1:24,000 of a several-km-wide zone along the fault, systematic measurement of about 100 topographic profiles of fault scarps, stratigraphy of selected exposures of Quaternary deposits, description and sampling of surficial deposits and soils for characterization and age determinations, and compilation of bedrock geology of selected areas. Also being investigated is the influence of bedrock structures and lithologies on the location, geometry, and magnitude of surface faulting. For example, the Manning Canyon Shale, a relatively incompetent unit that is sandwiched between very thick packages of Paleozoic limestones and sandstones, may act as a zone of decoupling for some of the faults along the WFZ.

Scarp morphology data is being collected from many sites along the southern part of the WFZ to investigate the relation between maximum scarp-slope angle (θ) and scarp height (Hs, single-event scarps; Hm, multiple-event scarps; Machette and McGimsey, 1983). This data will be compared to Buchnam and Anderson's (1979) morphologic data from scarps in central Utah to estimate the recency of faulting, and used to construct a general surface rupture envelope for young surface faulting events. Comparison with the rupture envelope of the 1983 M_S 7.3 Borah Peak earthquake (Crone and Machette, in press, 1984) may help model ground breakage based on "characteristic" amounts of offset that might occur along individual segments of the WFZ.

Results of current research

1) The steepness and height of the Nephi fault scarps formed in unconsolidated deposits indicate late Holocene movement at least from Mendelhall Creek (MC, fig. 1) on the north, to Nephi on the south. The data analyzed so far show that most of the single-event scarps that are less than 2.5 m in height (Hs, fig. 2A) have maximum slope angles less than 32°, whereas larger scarps have even larger maximum slope angles, many of which exceed the angle of repose of unconsolidated surficial deposits (33° to 37°). The Nephi Hs data plot above (younger than) that of the Fish Springs fault (fig. 2B;



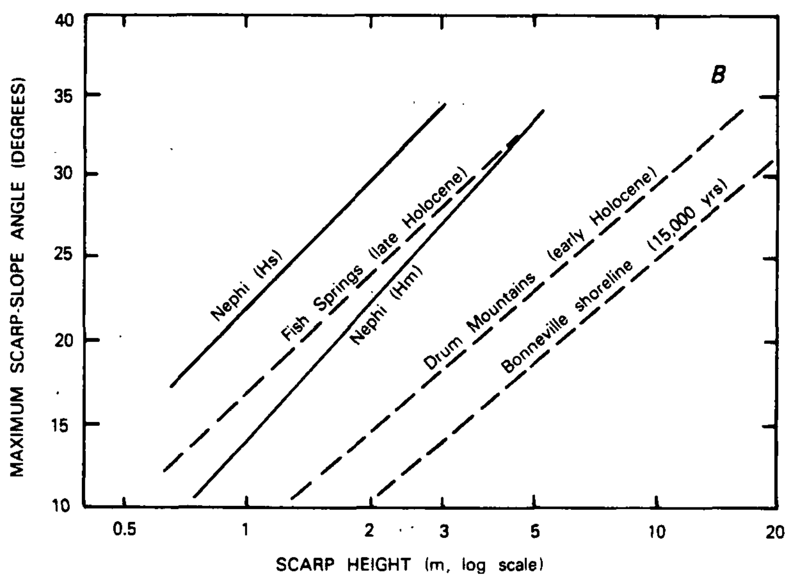


Figure 2. A) Morphometic data for single-event and multiple-event fault scarps along the Nephi segment of the Wasatch fault zone. Curved lines labelled Hs and Hm are the lines of best fit for respective data sets. Gray stippled area indicates the angles of repose that are common in unconsolidated surficial materials (33°-37°). B) Lines of best fit for data from the Nephi segment (Hs and Hm) and data from other scarps in central Utah (modified from Bucknam and Anderson, 1979).

Bucknam and Anderson, 1979), which I consider to be late Holocene. The Fish Springs fault scarps range from 0.5 to 4 m in height and appear to have been formed during a single surface rupture event; thus, their scarp heights should be compared with other Hs data (Bucknam, oral commun., 1984). However, the height-angle relation for the composite, multiple-event Nephi scarps (Hm, fig. 2B) plot below that of the Fish Springs fault and suggest that the older two components of the scarps may pre-date the Fish Springs fault scarps.

The relation between Hs and θ for the Nephi scarps suggests very young movement along the main strand of the segment: these data support Schwartz and others (1983) minimum age limit age of 1,100 ^{14}C yrs B.P. for the most recent surface rupture at the North Creek site, but do not necessarily support their estimate of only 300-500 years for the age of the most recent rupture. Along the Nephi segment the small scarps and the youngest element of larger, compound fault scarps are old enough to have had their free faces removed. Similar-size scarps from historic faulting in the Basin and Range usually still have an element of free face where formed in unconsolidated materials. This relation suggests that fault scarps produced during the most recent rupture event on the Nephi segment may be closer in age to the Fish Springs fault scarps, perhaps a thousand years, than to the 300-500 year estimate of Schwartz and others (1983).

About 40 scarp profiles have been measured along the Levan segment and only 10 scarp profiles been measured from the Santaquin Valley part of the Nephi segment (fig. 1). These profiles, and additional ones yet to be measured along the Provo segment, will be analyzed in the coming year.

2) Although the Nephi and Levan segments are separated by a 16-km-long gap in Holocene and latest Pleistocene surface faulting (fig. 1, index map), both geomorphic and geologic evidence indicate earlier Quaternary faulting in the gap. Levan Ridge is a large, composite mid(?) to late Quaternary alluviual fan that separates the northern and southern parts of Juab Valley. The gradient of the alluvial fan steepens across the projection of a major north-south fault that separates the adjacent bedrock hills from the east side of the Juab valley. The steepened gradient probably represents the remains of an old, degraded multiple-event fault scarp. If correct, this interpretation implies a definate fault connection between the Levan and Nephi segments that has been inactive for tens(?) of thousands of years.

3) Three buried A horizons having disseminated charcoal were collected from scarp colluvium in the Birch Creek (BC, fig. 1) gravel pit. ^{14}C ages from the charcoal should help estimate rates of deposition of scarp colluvium adjacent to the fault and may indicate the amount of time separating individual surface rupture events. The dates should also give a maximum age for the overlying fan alluvium of Little Birch Creek (the small drainage on the south side of the Birch Creek gravel pit).

4) Deep incision along the south side of Willow Creek (WC, fig. 1) during the spring flooding of 1983 exposed a fault and two colluvial wedges derived from the degradation of the associated scarp. The stratigraphic relations exposed in the cut require at least two surface faulting events, and evidence of third event may be present below the level of exposure. The fault scarp across the Willow Creek terrace/fan has an average height of 6.6 m, a maximum scarp-slope angle of 37°, and a minimum surface offset of 5.2-6.0 m (the base is buried by post-fault alluvium). Similarily, the fault scarp at the North Creek site (NC, fig. 1) of Schwartz and others (1983) has a height of 7.2 m, a maximum slope angle of 38°-40° and is the product of three discrete surface faulting events since the mid Holocene. Charcoal from the faulted alluvium at North Creek was dated at 4580 ^{14}C yrs B.P. (R. C. Bucknam, cited by Schwartz and others, 1983). This ^{14}C date converts to calendar dates of about 5130-5490 yrs B.P. (Schwartz and Coppersmith, 1984). Both R. R. Shroba's studies of soils at North Creek (pers. commun., 1984) and my studies of soils at Willow Creek suggest a mid(?) Holocene age for the surface of the faulted alluvial deposits. These soils are characterized by profiles having an A, a weak Bs, and a stage I Cca horizon.

Both soil development and the ^{14}C dates from alluvium suggest that some of the fans at the mouths of major canyons along the Nephi segment were deposited during the Altithermal portion of the Holocene, about 4,000-6,000 yrs ago, and then repeatedly offset by faulting. An additional constraint on the age of the faulted deposits may be forthcoming from wood collected about 100 m east of the fault scarp. A tree stump along Willow Creek was found buried in growth position and rooted in the third oldest of 12 units exposed along the south wall of the creek. The stump was broken off during deposition of unit 5, a massive light gray-brown pebbley debris-flow deposit. A ^{14}C age from the wood will date material about 2 meters below the surface of the faulted fan/terrace and thus provide a maximum age for the 5.2-6.0 m of offset seen at Willow Creek.

5) Perhaps the most interesting result of these preliminary studies is the estimation of a pre-Lake Bonneville slip rate for the Nephi segment. Faulted fan deposits of pre-Bonneville age are preserved at the mouth of Gardner Creek (GC, fig. 1), a moderate-size stream valley that drains the southwest end of the Wasatch Range about 3 km northeast of Nephi. Recurrent late Pleistocene and Holocene faulting along the Nephi segment has left a series of three alluvial-fan complexes both north and south of Gardner Creek (fig. 1). These deposits are informally referred to as young (Qfy), middle (Qfm), and old (Qfo) fan alluvium. Unit Qfy is probably mid-Holocene, based on the degree of soil development and correlation with mid-Holocene alluviual fan deposits at Willow Creek and North Creek. Most of this alluvium probably was deposited during the warm, dry Altithermal (about 4,000-6,000 yrs ago); it forms thin, but broad alluvial fans almost everywhere on the downdropped fault block.

The mid(?)-Holocene deposits are offset about 3.9 m at Gardner Creek (scarp heights are about 4.2 m). If one uses an average age of 5,000 yrs for the faulted deposits at Gardner Creek, their average slip rate is about 0.8 m/ka, or about 60 percent of the Holocene slip rate at North Creek (1.3 m/ka). The difference in the two slip rates may reflect 1) the location of Gardner Creek near the southern end of the Nephi segment, where displacement amounts should diminish.

In the Nephi region middle and old fan alluvium (units Qfm and Qfo), which usually are preserved only as remnants on the upthrown side of the fault, may have been deposited in response to climatically induced changes in sediment supply and stream flow such has been recognized to the south in the Beaver basin (Machette, in press, 1984). Uranium-trend age determinations from soils and quantitative analyses of soil-carbonate content (Machette, in press, 1984) suggest that the major constructional alluvial landforms (piedmont slopes, terraces, and alluvial fans) in the Beaver basin were formed during major changes in climate, probably from glacial to interglacial conditions. By analogy, in north-central Utah the middle and old fan deposits probably were deposited during the interglacials that followed the two major pre-Pinedale glaciations. The younger of the two interglacials probably is about 130,000 yrs old and the older is probably about 250,000 yrs old.

A recent excavation into the surface of Qfo just north of Gardner Creek revealed a well developed soil that is characterized by a one-meter-thick K horizon (a master soil horizon of carbonate accumulation). Thin laminae (weak stage IV morphology) are discontinously formed in the upper 10 cm of the K horizon; downward, the morphology grades from strong stage III to weak stage III. Overlying the K horizon is a 10 cm thick Btca horizon, and a thin A horizon (a large unseen part of the B horizon probably has been engulfed by the K horizon). Even though the soil is formed in limestone-rich alluvium, the overall development and thickness of the K horizon represent a substantial accumulation of pedogenic carbonate, the majority of which probably is supplied by airborne dust (Machette, in press, 1985). This soil probably represents several hundreds of thousand of years of soil-carbonate accumulation, an interpretation which is consistent with the assumed 250,000 year age for the deposit on which it is formed. This soil appears better developed than the type Promintory Soil of Morrison (1965) that is formed in gravel bars of Little Valley age, which Scott (1982, p. 3) considers to be 150,000 ± 25,000 yrs old. The Little Valley material is generally correlative with tills of the Bull Lake glaciation of the Rocky Mountains occurred about 140,000 yrs ago (Pierce and others, 1976).

Fault scarps formed in unit Qfo adjacent to the mouth of Gardner Creek are 26-28 m high, have slope angles of 38°-40°, and are buried at their bases by an unknown thickness of young fan alluvium (fig. 3). In the depositional interfluve between the fans of Gardner Canyon and Red Canyon (the next major drainage to the south), the scarps are least buried and have a maximum height of about 32 m. Using an average height of 30 m, I have attempted to reconstruct the amount of offset that could be associated with the fault scarp. In the upper example, (fig. 4) I have drawn a hypothetical cross where there is insignificant backtilting and graben formation on the downdropped block, and deposition of a thin mantle of young alluvium. This senario shows that a 30-m-high fault scarp in unit Qfo may reflect as little as 25 m of offset along the fault.

However, a portion of the fault scarp must be buried because the steepest portion (θ) of the scarp in unit Qfo is on the lower 1/3 of the slope and because there is not enoung space in the colluvial wedge (unit Qc) to accomodate materials eroded from the upthrown block. Typically, θ is found in a mid-slope position: this relation has been confirmed by numerous trench

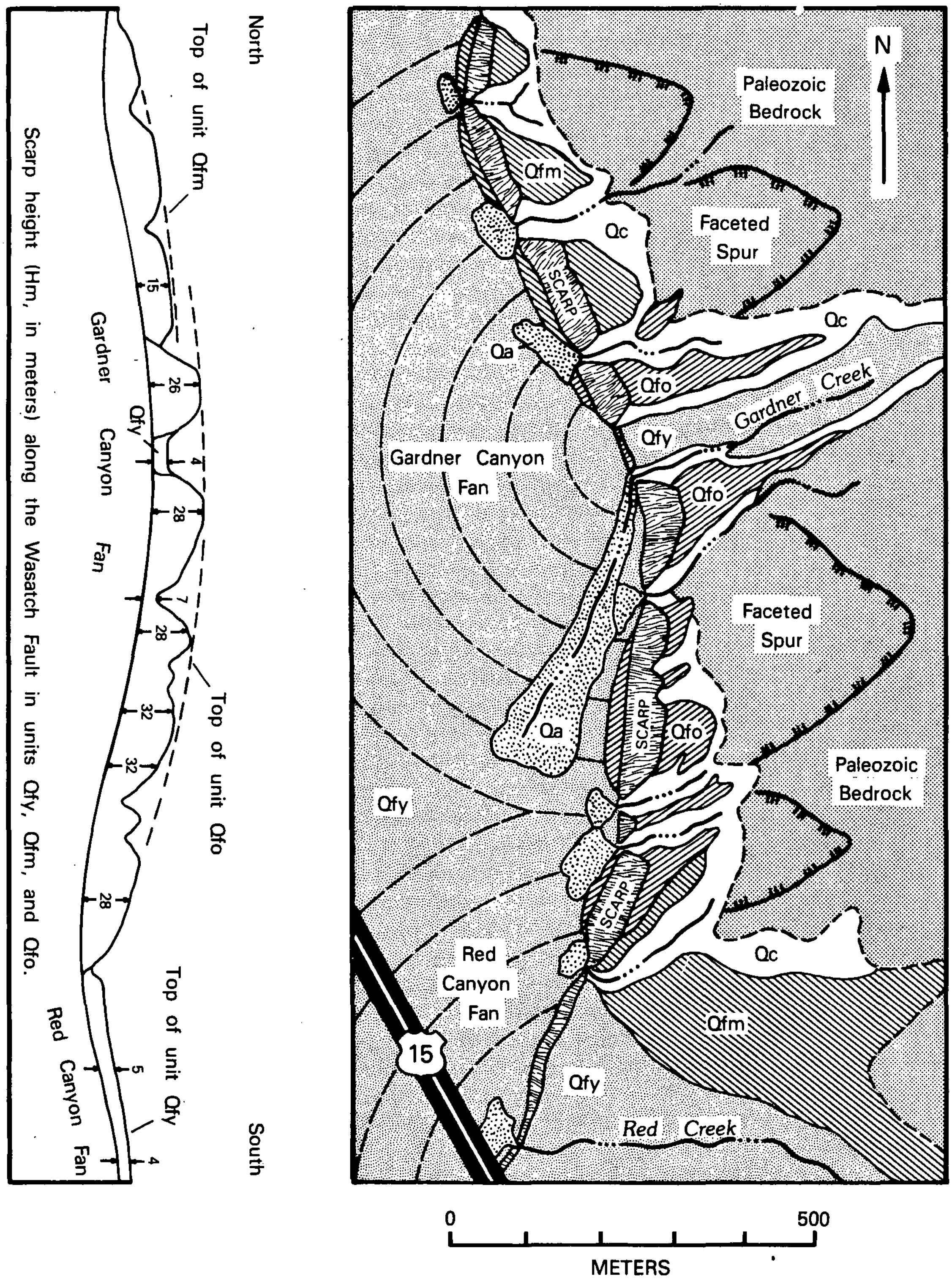
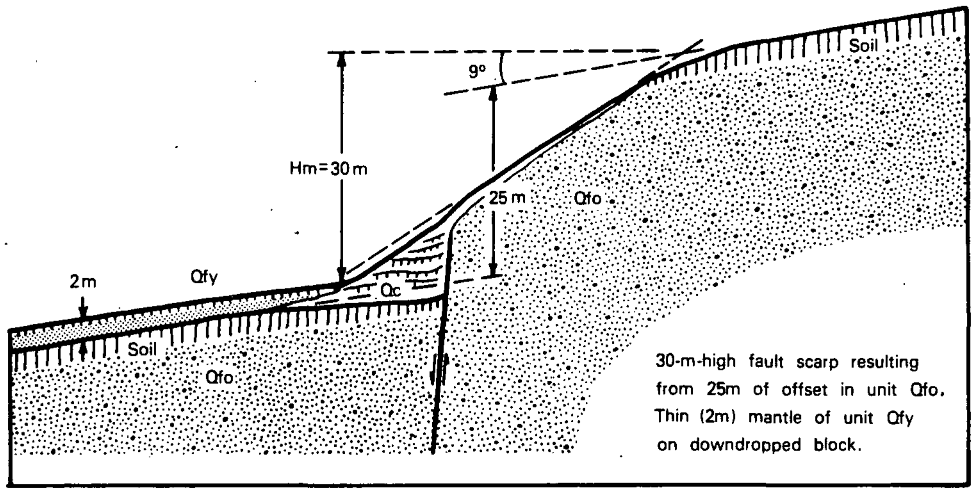


Figure 3. Sketch map of Quaternary deposits and scarps along the Nephi segment of the Wasatch fault zone between Gardner Creek and Red Creek. Schematic cross section is drawn parallel to the fault scarp.



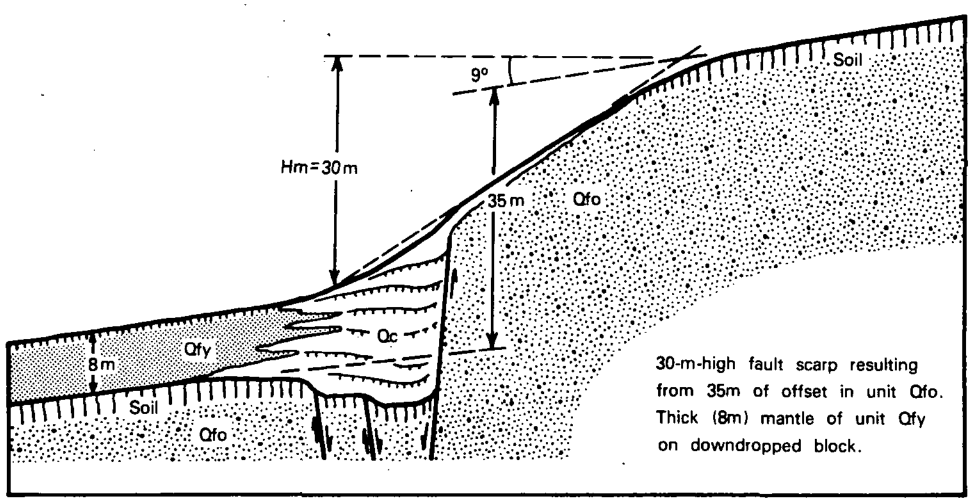


Figure 4. Two hypothetical reconstructions of offset in old alluvium (unit Qfo) just south of Gardner Creek. Note that, in the lower drawing, the half-height of the scarp is about one-half of the projected surface offset (35 m).

exposures along the WFZ and by the fault scarps formed during the 1983 Borah Peak earthquake (Crone and Machette, in press, 1984). The steepened portion θ is interpreted here as the position of most recent surface rupturing. Thus, one should argue that an unseen, lower portion of the large fault scarp is buried on the downthrown fault block. Using this line of evidence, a second reconstruction of the fault scarp (fig. 4, lower part) permits about 35 m of surface offset. If the steepest part of the scarp reflects the true position of the fault, then the offset recorded in the uppper half of the scarp (about 17 m) should be one-half of the total offset. Using this value as a half-height of offset yields 34 m offset in unit Qfo, an independent estimate that compares favorably to the 35 m of offset in the second reconstruction. Backtilt and grabens such as those shown in figure 4 further complicate the reconstruction of offset amounts, but both features reduce the amount of surface offset compared to the height of the main scarp (see discussion of these factors in Swan and others, 1980).

For the pre-Bonneville slip rate at Gardner Creek, I favor a intermediate offset value of 30 m (-5 m, + 5 m). On the basis of this intermediate value and an assumed age of 250,000 yrs for unit Qfo, the cumulative late Quaternary slip rate at Gardner Creek is 0.12 m/ka (the range in values is 0.10-0.14 m/ka). The preferred slip rate is only 15 percent of the mid-Holocene slip rate (0.78 m/ka) determined from young alluvium at the same locality (table 1).

Speculations about the mechanism and timing of apparent changes in slip rate

As shown above, there is strong evidence that the slip rate on the Nephi segment in post-Bonneville time (past 15,000 yrs) is at least five times faster than that recorded in late Quaternary time (pre-Bonneville, more than 25,000 yrs ago). Although not presented here, there is also compelling evidence for a similar temporal contrast in slip rates on the Provo, Salt Lake City, and Odgen segments of the WFZ. I propose that the anomalously high slip rates during the past 15,000 yrs (latest Pleistocene and Holocene) along the WFZ may be related to empoundment of Lake Bonneville. The high slip rates could reflect pertubations of ambient shear stresses along the WFZ that are related to increased hydrostatic head and subsurface pore pressure from the lake, as well as by loading and unloading of the crust during rapid expansion and contraction of the lake in latest Pleistocene and earliest Holocene time.

The Holocene slip rates at the Hobble Creek and North Creek sites are fast, about 1.3 m/ka (table 1); yet they are apparently slower than those recorded by offset of the Provo- and Bonneville-age surfaces (estimates range from about 0.85 to 1.8 m/ka; Swan and others, 1980; Schwartz and Coppersmith, 1984). Thus, there also may be evidence for progressively declining slip rates in the Holocene, from a peak in Bonneville time (15,000-25,000 yrs ago; Scott and others, 1984).

Table 1. Cumulative slip rates (m/ka) for various age Quaternary deposits along the southern Wasatch fault zone

[Ages used for slip rate calculations by authors are shown in parentheses.]

Time interval	Hobble Creek	North Creek	Gardner Creek
Mid-Holocene to present	[1]1.3 (6 ka)	[2]1.3 (4.5 ka)	0.78 (5 ka)
Post-Provo to present	[1]0.85-1.0 (13.5 ka)	n.d.	n.d.
Post-Bonneville to present	[3]1.8 (17 ka)	n.d.	n.d.
Pre-Bonneville to present	n.d.	[4]0.20 (250 ka)	0.12 (250 ka)
Late Cenozoic to present	0.4 for the central Wasatch fault zone[5]		

1 Data from Swan and others, 1980.

2 Data from Schwartz and others, 1983.

3 Most likely rate of Swan and others, 1980: range is <1.7 to <3.3 m/ka.

4 Calculated from ratio of pre-Bonneville to mid-Holocene slip rates at Gardner Creek times mid-Holocene slip rate at North Creek.

5 Data from Naeser and others, 1983.

Along the southern WFZ slip rates recorded by faulted Pleistocene deposits of pre-Bonneville age are considerably slower (0.1-0.2 m/ka) than in the Holocene, as evidenced by relatively small amounts of offset in the Gardner Creek fans. Similar constrasts in slip rate are recorded along the central part of the Wasatch fault zone by disproportionately small offset of Little Valley age (Bull Lake) tills at Dry Creek and at Little Cottonwood Canyon (W. E. Scott, pers. commun., 1984). If the mid-Holocene slip rates at Gardner Creek are extrapolated to the older fans and tills, about 200 m of offset should have occurred in the past 250,000 yrs, compared to the 25-35 m of offset that can be shown (see fig.4). Thus, there is compelling evidence of a 6-8 fold increase in cumulative slip rates through the latest part of the Quaternary. The differences in slip rates during specific intervals (for example during Bonneville time versus pre-Bonneville time) must be even greater.

The characteristic earthquake model of Schwartz and Coppersmith (1984) infers repeated rupture events that produce about 2 m of vertical offset on discrete segments of the Wasatch fault zone. Accepting this model, a pre-Bonneville slip rate of 0.2 m/ka at North Creek on the Nephi segment requires of about 10,000 yrs between events, whereas the recurrance interval for the central four segments of the Wasatch fault zone during post-Bonneville time is generally between 1,000 and 2,000 yrs (Schwartz and Coppersmith, 1984).

The Cenozoic slip rate for the central part of the Wasatch fault zone is about 0.4 m/ka based on apatite-fission-track ages in uplifted basement rocks (Naeser and others, 1983). This rate falls between the post- and pre-Bonneville rates as one might expect, especially if it records cyclic, long- and short-period fluctuations in slip rate. For example, a combination of 20,000-yr-long intervals of 1 m/ka average slip rate and 100,000-yr-long intervals of 0.2 m/ka average slip rate (a ratio of 5:1) yield a cumulative slip rate of 0.4 m/ka.

The reason for the large changes in slip rate is not known. These changes may relate to temporal grouping of faulting events as suggested by Wallace (1984) elsewhere in the Basin and Range province. For the Wasatch fault zone, the coincidence of high slip rates with intervals of rapid change in the depth of Lake Bonneville during the latest Pleisocene may reflect a causal interrelation. Perhaps the changes in slip rate are related to a hydro-tectonic mechanism. A large lake would produce hydrostatic head and increased pore pressure, and could have a triggering mechanism related to isostatic loading and unloading during lake expansion and contraction. The combination of these factors could result in an increased slip rate by focusing regional stresses on a primed structure (the Wasatch fault zone). Without a large lake, the pore pressure should decrease to the ambient level, the hydrostatic load would be removed, and strain rates might return to a more even pattern over the eastern Basin and Range Province. I am uncertain, however, that deep communication of lake water and ground water along the fault zone is a reasonable hypothesis. Nevertheless, the presence of a large lake such as Bonneville and anomalously high slip rates along the WFZ appear to be more than a coincidence.

Further research

Mapping and stratigraphic studies of the Quaternary geology along the Wasatch Fault zone will continue northward into the Utah Lake Valley from Payson on the south to Alpine on the north. This part of the fault zone is essentially the 55-km-long Provo segment proposed by Schwartz and Coppersmith (1984). Data from the Hobble Creek site suggest that the Provo segment has a relatively fast post-Provo (<13,500 yrs B.P.) rate of offset (0.85-1.0 m/ka) and has been most recently active about 1,000 yrs ago (Swan and others, 1980). Six to seven rupture events have been suggested for displacement of the Provo-age surface, which equates to an average recurrence interval of 1,700-2,600 yrs. A specific effort will be made toward better defining the amount of offset in Provo, Bonneville, and pre-Bonneville age deposits, although the latter are not particularily well exposed in the Utah Valley.

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EARTHQUAKE RECURRENCES ESTIMATED BY CALIBRATING QUALITATIVE GEOLOGICAL RATE ESTIMATES

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Introduction

Large scale mapping of regional probabilistic ground motion hazard encourages fine discriminations in source zonation. This will result in smaller source zones. However, as the source zones become progressively smaller, the number of historic earthquakes contained in the zones decreases. Statistically-derived rates of earthquake activity for individual zones, therefore, become increasingly less reliable. We need alternatives to the usual statistical methods which depend entirely on historical seismicity.

During a series of workshops held to define regional source zones for part of the conterminous United States (Thenhaus, 1983), we asked the workshop participants for estimates of maximum magnitude and earthquake rates for each proposed zone. Quantified estimates based on fault scarp studies provided a basis for these estimates throughout the Great Basin. However, in much of the Rocky Mountain region, lack of systematic investigation of young faults precluded quantitative geologic estimates of the recurrence of large earthquakes. Estimates in this region, therefore, were qualitative and sampled the participants' intuition as to the relative earthquake hazard among zones. These qualitative recurrence estimates were not actually used in the production of the 1982 national hazard map. Instead, an analysis of the historical seismicity was used to estimate zone recurrence rates. However, when the 1983 Borah Peak (Idaho) earthquake occured in a source zone for which a very low recurrence rate was estimated from the historical seismicity, we decided to look again at the qualitative geological estimates made at the workshops that dealt with the northern and southern Rocky Mountains. Could these qualitative estimates have been used to get a better estimate of the recurrence rate for the vicinity of the Borah Peak earthquake as well as for other source zones in the Rockies?

Figures 1a and 1b show the Rocky Mountain source zones suggested by the attendees of the two workshops. Table 1 shows the qualitative estimates of seismicity and a rough quantitative estimate of relative rate. The question we asked ourselves was whether the qualitative estimates could be calibrated to provide numerical recurrence estimates which could be used in estimates of probabilistic ground-motion hazard.

Calibrations

We compared the rates obtained in the source-zone analysis for the national hazard map (Algermissen and others, 1982) with the qualitative geological estimates. The rates used were normalized to the rate per unit area of the estimated recurrence of magnitude 4.0 to 4.6 earthquakes (intensity V). Table II shows the zone numbers in the northern Rockies from figure 1, the letter indicating geological recurrence estimates for those zones, and the corresponding rate per unit area of the zones from Algermissen

TABLE I

Qualitative Estimates of Recurrence...
Letters A through D indicate decreasing rate of recurrence.
For southern Rocky Mountain Zones A:B:C:D is roughly 40:10:3:1.

Zone No. from Figure 1	Relative recurrence rate
15	C
16	B
17	C
18	D
19	B
20	A
21	B
22	B
23	A
24	C
25	C-D
26	C
27	C
29	B
30	D
31	A
32	A+
33	C
34	A-
35	C-D
36	C
37	C
38	A-B
38	A
39	D
42	C
43	B
44	A
46	C
47	C
49	A
50	A
51	D
52	B
53	D
54	D

TABLE II

Correspondence between qualitative estimates of source zone recurrences and area normalized rates of recurrence for related source zones from analysis of historical seismicity.

Thenhaus (1983)		Algermissen and others (1982)	
Zone No. from Fig. 1	Relative Rate	Area-normalized Rate	Corresponding Zone Numbers
32	A+	36	40
20	A	25	55,57
23	A	55	56
31	A	14	38 (part)
34	A-	14	38 (part)
38	A-B	4	43
	A-Group Average	25	
16	B	13	64
19	B	3	61
21	B	19	59
22	B	2	58
29	B	7	38,51,52,52
	B-Group Average	9	
15	C	2	63
17	C	2	65
24	C	2	58 (part)
26	C	2	45 (part)
27	C	2	45 (part)
33	C	2	45 (part)
36	C	2	45 (part)
37	C	2	45 (part)
	C-Group Average	2.2	
25	C-D	0.7	54
35	C-D	2	45,50
18	D	0.9	16,44,45
30	D	1.8	49,66
	D-Group Average	1.4	

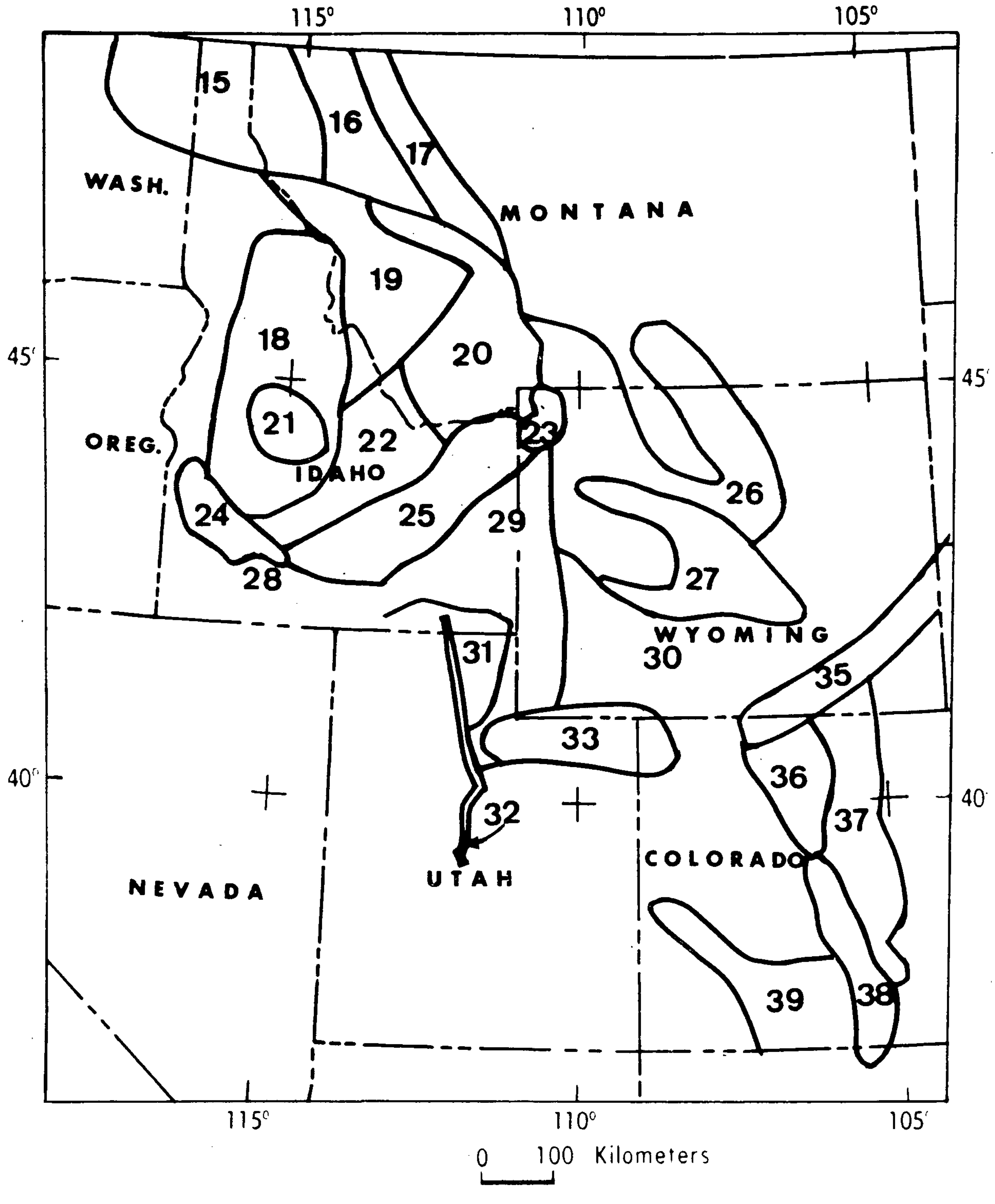

Figure 1a. Seismic source zones for the northern Rockies, from Thenhaus, 1983.

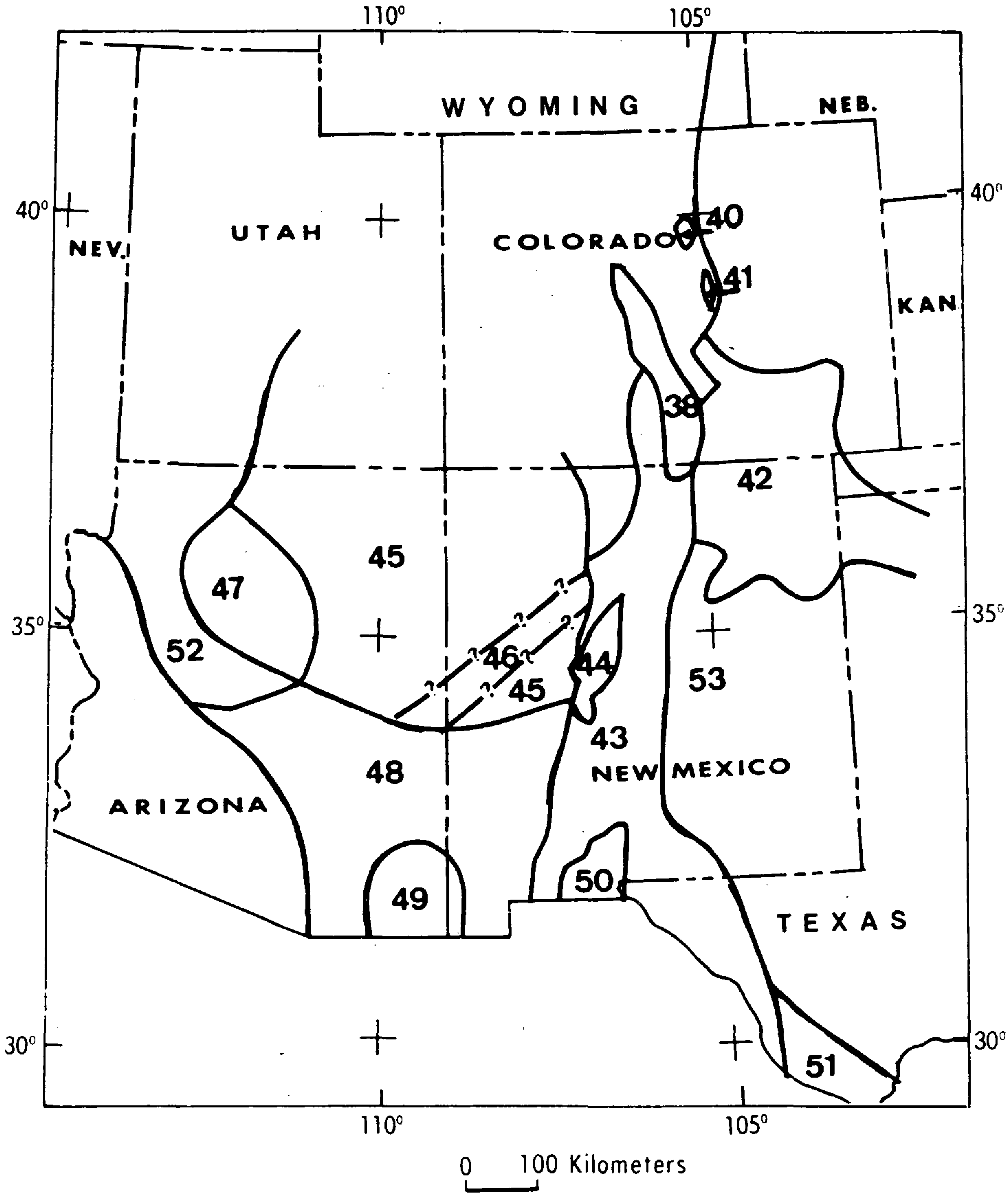

Figure 1b. Seismic source zones for the southern Rockies, from Thenhaus, 1983.

and others (1982). The zones for the national map were somewhat modified from those suggested in the source zone meetings, as have their serial numbers, so a fourth column in the table gives the serial number of the corresponding zone from figure 3 of Algermissen and others (1982, p. 17). In Table II, a rough calibration method groups the geological estimates into four categories and averages the historical recurrence estimates for the four categories.

This method does not give rates for intermediate geological estimates which the workshops participants indicated by using + or - values or by intermediate specifications (e.g., A-B or C-D), because there is not enough rate information available to group at these values. A natural next step, then, is to assign numbers to these distinctions. Figure 2 shows a plot of the natural log of the area-normalized zone rates vs one possible numeration of the qualitative estimates. The numeration was purely arbitrary. It places A, B, C, and D at 9, 6, 3, and 0, respectively, and provides unit differences between A- and B+ and between A and A-, etc. The log of the rates was taken because a plot of the unlogged rates appeared to be exponential. The figure also shows a line indicating the results of a linear least squares regression of the log rates on the numerated qualitative estimates. The regression line gives values for the intermediate qualitative estimates and also provides values for the groups located at a single qualitative estimator. (In a later section we show hazard estimates derived for four source zones, using these estimated normalized rates from the regression line.)

It must be emphasized that the numeration of the qualitative estimates is arbitrary. We could have assigned to A- and B+ the same number. We might even have assigned numbers having a ratio relation. Furthermore, there is no necessary reason for imposing a regression line--we could have just connected cluster centroids. What is interesting in this calibration is that the

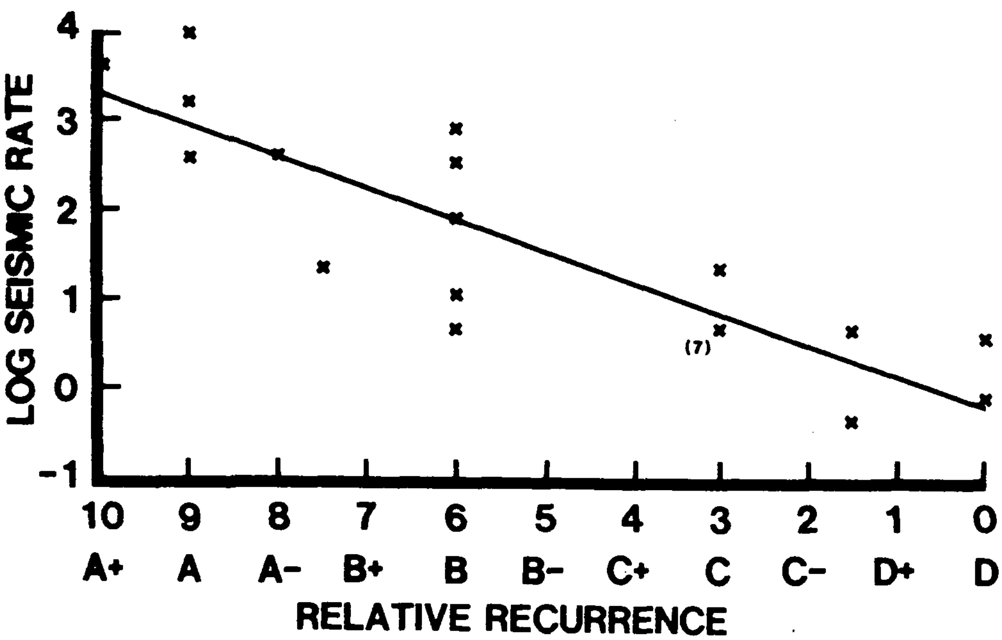

Figure 2. Calibration of qualitative geological rate estimates using regression. Ordinate: natural logarithn of area-normalized rates of source zones of national hazard map (Algermissen and others, 1982). Abscissa: arbitrary numeration of letter-value rate estimates.

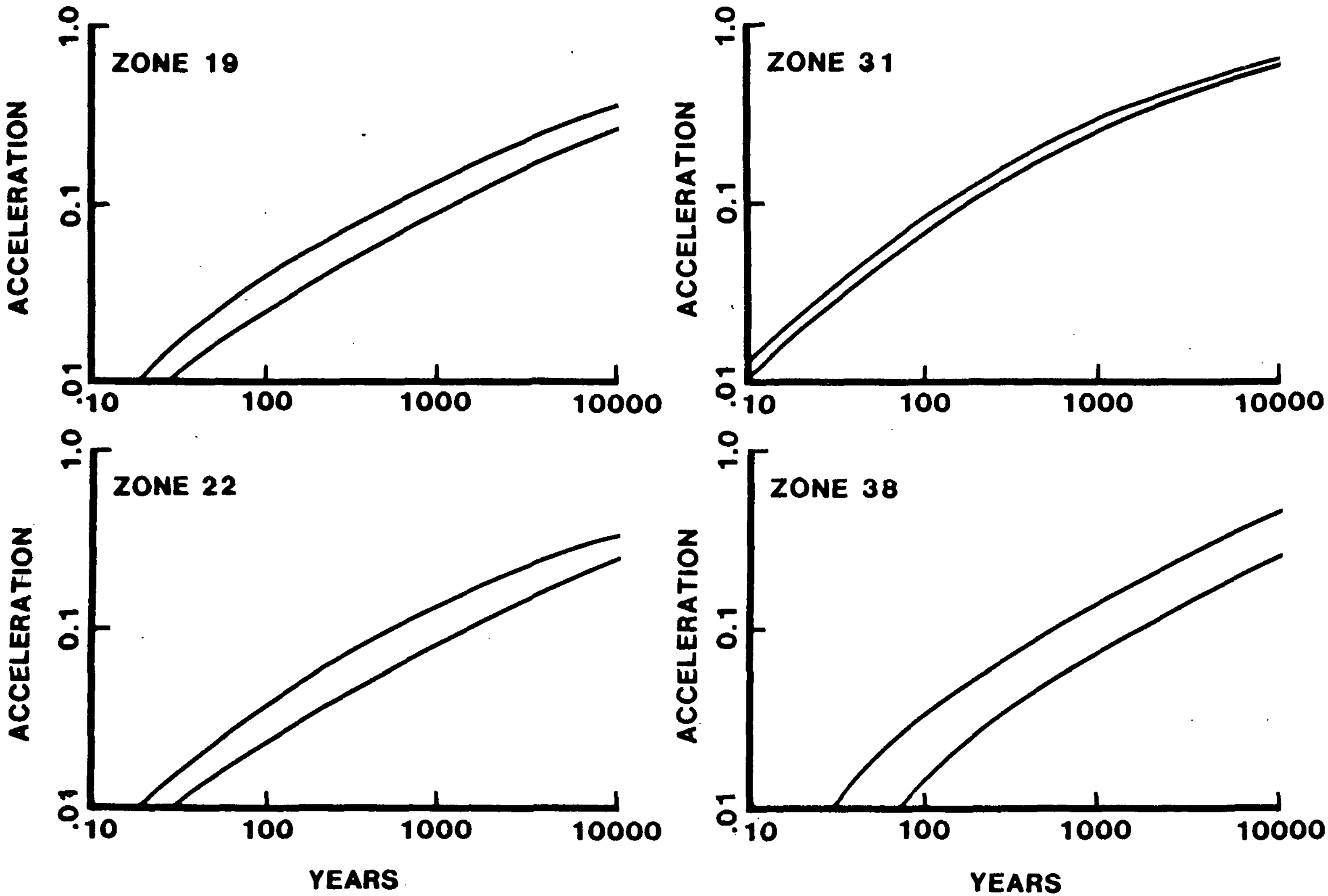

Figure 3: Acceleration vs. return Period estimates for 4 sites central to their respective zones. Curve with lower ground motion value is for seismic rates of national hazard map (Algermissen and others, 1982). Curve with higher value is for recurrence from regression calibration.

predicted rates are values which bear a reasonable relative relation to the quantitative relative estimates made by the workshop participants. The regression rate values for A, B, C, and D are, respectively, 19.4, 6.7, 2.3, and .57. If we normalize so that the value for B is 10.0, the respective values are 29, 10, 3.5, and .85, compared with 40, 10, 3 and 1 for the geologists' estimates of quantitate relative rate.

Application to Borah Peak Vicinity

An indicator of the reasonableness of even the crude, first calibration by grouped averages (Table I) can be obtained by comparing several estimates of the recurrence of an event the size of the 1983 Borah Peak, Idaho earthquake. The earthquake occurred in zone 22. The seismic rate for this zone, from Algermissen and others (1982), yields a recurrence rate for magnitude 7 to 7.6 earthquakes of about one chance in 5000 per year within the approximately 200 km by 100 km area in the vicinity of the earthquake. The zone containing the Borah peak earthquake was rated in category B by the geologists. For all zones rated B in the northern Rockies, the average historical seismicity rate per unit area is about five times the rate for the zone containing the Borah Peak earthquake. Simply increasing the zone rate estimate by the factor of five, we obtain a recurrence rate of about one chance in a thousand in the 200 km by 100 km area.

Further perspective on these two estimates is provided by Ruppel (1964) and by M. H. Hait and W. E. Scott (1978, written communication). Ruppel investigated the faults in a 50-mile by 150-mile area in which the Borah Peak earthquake later occurred, and concluded that "the major displacements probably were completed by late Pleistocene time . . . nevertheless, some movement is more recent . . . ." Hait and Scott reported evidence of Holocene displacements. The fault near the Borah Peak epicenter "has experienced recurrent activity over a period of 10,000 to 100,000 years, the last major event being of Holocene age." Depending on how one interprets these geological estimates, one can calculate recurrences according to the number of such faults in the 20,000 km^2 area of interest.

Under an assumption that one fault has a recurrence interval of 30,000 years (a rough geometric mean of Hait and Scott's ten and hundred thousand), it would take six such faults in the area to yield a recurrence of 5000 years, about that of the extimate derived from historical seismicity. It would take 30 such faults to yield a recurrence interval of 1000 years for the area. It seems unlikely that there are as many as 30 faults with Holocene displacements in the vicinity of Borah Peak. This would be a higher rate of Holocene faulting than that estimated by Bucknam and others (1980) for one of the more densely faulted areas of western Utah.

Suppose, however, that one fault has a recurrence interval of 5000 years. Then it would require only one such fault to produce the historical recurrence interval and five such faults could produce the recurrence interval derived by calibrated geological estimates. Numbers of this order seem more reasonable. The lack of many historical intensity V earthquakes would argue for an areal recurrence interval at the longer end of the 1000- to 5000-year recurrence estimate. A recurrence interval of 5000 years for the 100x200km area is identical to the recurrence estimate of Bucknam and others for magnitude 7 to 7.6 earthquakes in the previously mentioned area in western Utah, characterized by numerous pre-Holocene faults. The area-normalized rate ($1x10^{-5}$ per 1000 km^2) for this recurrence interval is also consistent with the area-normalized rate ($5x10^{-6}$ to $5x10^{-5}$) of faulting (M>7) estimated by Wallace

(1978) for zones of Holocene faulting in Utah, western Nevada, and eastern California, exclusive of the rupture zones of historic earthquakes. Thus, the recurrence estimate obtained by averaging the historic rates for B-rated zones in the northern Rocky Mountains is consistent with recurrences estimated for other regions of Basin and Range faulting.

Recurrences at Four Points in Rockies

We used the regression calibration values for the geological recurrence estimates to adjust the areal rates for zones 19, 22, 31, and 38 (Figure 1). The ratio of the regression rate to the rate used in the national hazard map, was used to increase the seismicity in those zones. Figure 3 shows the old vs new ground motion recurrences for four sites, each central to their respective zones for four zones in which the calibration produces increased rates. For a given return period there is an increase in ground motion ranging from a factor of only about 10-25 percent (zone 31) to as much as 150 to 250 percent (zone 38). Zone 38, the northern Rio Grande Rift in Colorado, had particularly concerned geologists as one for which the geomorphology suggested much greater hazard than the historic seismicity would indicate.

Examination of figure 2 shows that just as using the regression estimates increases recurrence rates at some zones where the historical seismicity rate is relatively low, using these estimates will decrease recurrence rates for some zones that have relatively high historical seismicity. We might be somewhat more reluctant to decrease high seismic rates than increase low ones, if we felt that a high seismic rate could be a precursor to larger events. In any case, a general use of the regression estimates for all zones would narrow the range of recurrence rates and hence lower the contrast in ground motion hazard among the zones.

Critique and recommendations

First it should be noted that there are other ways to calibrate qualitative recurrence estimates. Exact numeration is not needed if we just connect cluster centroids and (perhaps) smooth the connections. On the other hand, the numeration could have been one which preserved the 40:10:3:1 quantitative relative rates suggested by the geologists. And as far as the treatment of ordinates is concerned, we could have taken the log of the historical rate estimates one more time before regressing. Clearly, the more one messes around in these ways, the more subjective judgment is brought to bear, and the less consistent may be the results from different analysts' interpretations. However, it is also possible that the calibration process is relatively robust. Different calibration methods may produce rates whose differences are not very significant in their effect on probabilistic ground motion.

A more important subjective judgment to quantify is an estimate of the relative weight to assign to the geologic and seismicity evidence available for each zone. In a regression calibration, individual points might bear greater weight the more one believed the value of the historical seismic evidence in certain zones. However, in assigning a rate to a zone, use of only the regression estimate would force all zone B's, say, to have the same rate, unless some further technique were used to balance the regression estimate against the historic estimate, on a zone-by-zone basis.

The use of calibration techniques of the sort discussed here still depends upon having sufficient seismicity among a number of zones to perform the calibration. We have presented an application which uses the seismicity of much of the Rocky Mountains. Clearly, in attempting a similar analysis for smaller source zones for a smaller portion of the Rockies, we would be presented with considerably less seismicity and hence more scatter in the rates estimated from historical data.

Recommendations

1. It would be useful to attempt the other techniques suggested above, in order to assess the robustness of the calibration in the northern Rockies.
2. To test the reliability of our calibration, we should see how the rate values for the southern Rockies are predicted by this calibration.
3. We should attempt to find a rationale for weighting the application of historical rates not only in regression calibration but also in assigning rates to individual zones.
4. We should look for an opportunity to apply such an analysis to other regions and sets of smaller source zones. In the one case, there may be a poorer geological basis for rate estimation. In the other case, the historical seismicity is more sparse. These applications will test the limits of application of the technique.

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Strain Rates in Utah From Seismic Moments, Paleoslip and Geodetic Surveys

(Expanded Abstract)

by

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Introduction

Crustal strain and its distribution between seismic and aseismic deformation is important to understanding earthquake hazards. If an estimate of energy balance in terms of strain, strain rates and deformation rates can be estimated from paleoslip (Quaternary geology) and contemporary slip (historic seismicity), then the spatial-temporal variations in seismic slip can be used to estimate zones or volumes of strain accumulation or strain loss. In addition, estimates of stress inferred from strain may be used to evaluate zones of stress concentrations that could precede future earthquake activity.

The use of the seismic moment tensor to evaluate contemporary strain rates has been documented for the general Utah region by Doser and Smith (1982) and for the Great Basin by by Greensfelder et al., (1980) and Smith (1982). An evaluation and testing of algorithms by Renglli and Smith (1984), also discussed regional strain rates for the western U.S.

In the discussion presented here, we present the results of our latest calculations for the strain rate contribution of historical earthquakes focusing on the Wasatch Front and the state of Utah (Figure 1). In addition we will compare strain rates estimated from pre-historic (or paleoslip) based on geologic observations of Late Cenozoic (primary Quaternary) deformation as well.

Method

The mathematical basis for seismic moment inversion of earthquakes for contemporary and paleoslip is beyond the scope of this paper and will not be discussed here. The reader is referred to the discussions by Doser and Smith (1982), Wesnousky et al. (1982), Anderson (1979) and Molnar (1979) for details of seismic moment inversion. The primary difference of the technique used here from those above is that the cumulative seismic moment tensor is diagonalized to provide the best estimate of the directions and magnitudes of the component tensors (Rengl1i and Smith, 1984).

The general steps of the seismic moment-strain rate calculations are as follows: (1) the study areas are assumed to undergo homogeneous strain and their boundaries are selected on the basis of Quaternary geology, faulting, and contemporary seismicity (Figure 1); (2) earthquakes (in the case of our study of $M > 4$) are sorted for each area and their magnitudes are converted to moment following the moment-magnitude relationship of Doser and Smith (1982):

$$\log M_0 = 1.1 M_L + 18.4 \qquad (2)$$

(3) estimates of the principal directions of strain are then computed from fault plane solutions; P-, T-, and B-axes (Figure 2), where single event

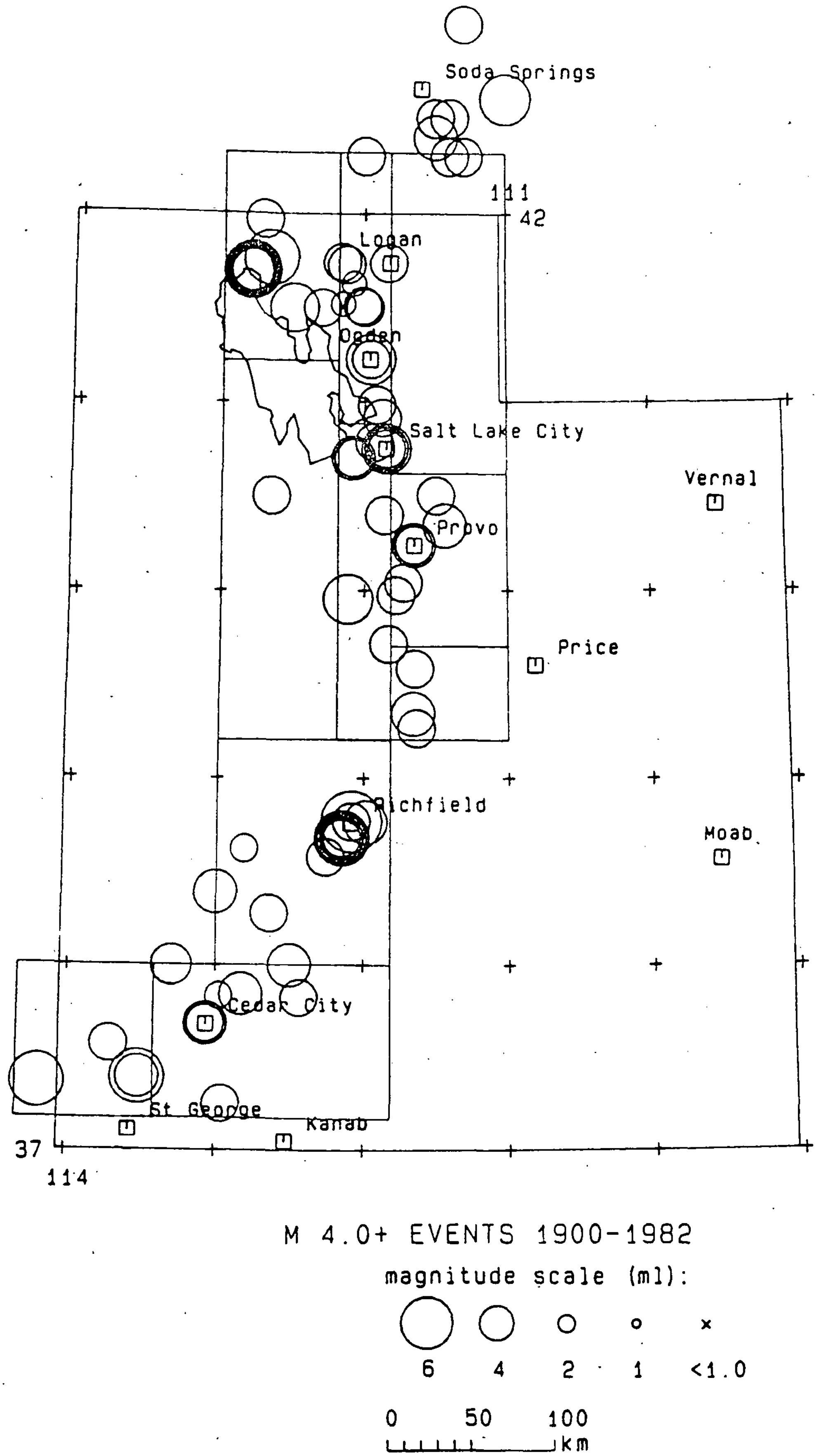

Figure 1. Epicenter map of Utah for events of magnitude greater than 4.0 from 1900-1983, edited from University of Utah Seismograph Station data files. Individual areas of study are outlined by solid lines.

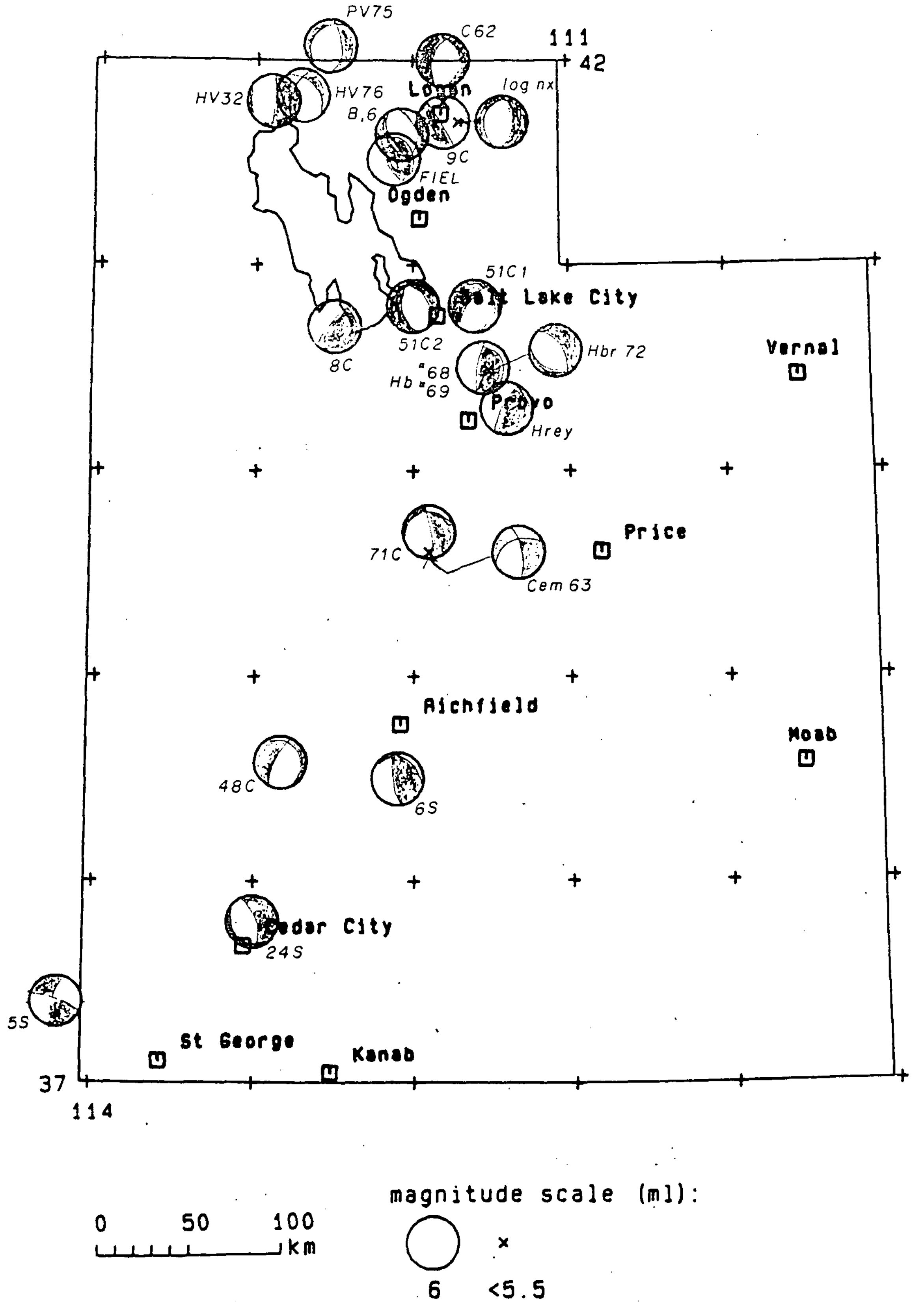

Figure 2. Fault plane solutions used study. Data taken from Smith and Arabasz (1979) and unpublished data.

solutions of earthquakes of M > 4.5 a few composite solutions were used to estimate the direction of contemporary strain; (4) the seismic moment tensor is then formed by summing the contributions of the scalar tensor giving the averaged directions of the P-, T-, and B-axes for each area. Earthquakes of magnitude <4.5 were assigned the directions of the average fault plane solution from the larger earthquakes in the respective areas; (5) the moment tensor is then diagonalized and gives the eigenvalues of the moment tensor per unit area and the theoretical, P_0, B_0, and T_0 axes for the volume; (6) from these data slip vectors, S_1 and S_2, are calculated; (7) the calculated P_0- and T_0-axes are then rotated about the B-axis to form two sets of conjugate P_0- and T_0-axes; (8) the conjugate P- and T- axes and the S_1, and S_2 values are then used to calculate the averaged strike and dip of faulting for the two plausible fault planes; (9) the strain rate is then converted from the theoretical fault plane solution following the method given by Doser and Smith (1982); and (10) strain rates are then rotated into the horizontal and vertical components for presentation.

Data

The earthquake data used in this study are from the University of Utah catalog of events M > 4 from 1900 to 1983 (Figure 1). Fault plane solutions were taken from available data summarized by Smith and Arabasz (1979) and updated to 1983 (Figure 2).

Strain and Deformation Rates in Utah

Contemporary Slip-- The averaged, maximum horizontal strain rates (in units of strain per year) are shown in Figure 3 for the nine study areas. The important observations from these data are the general E-W extension in

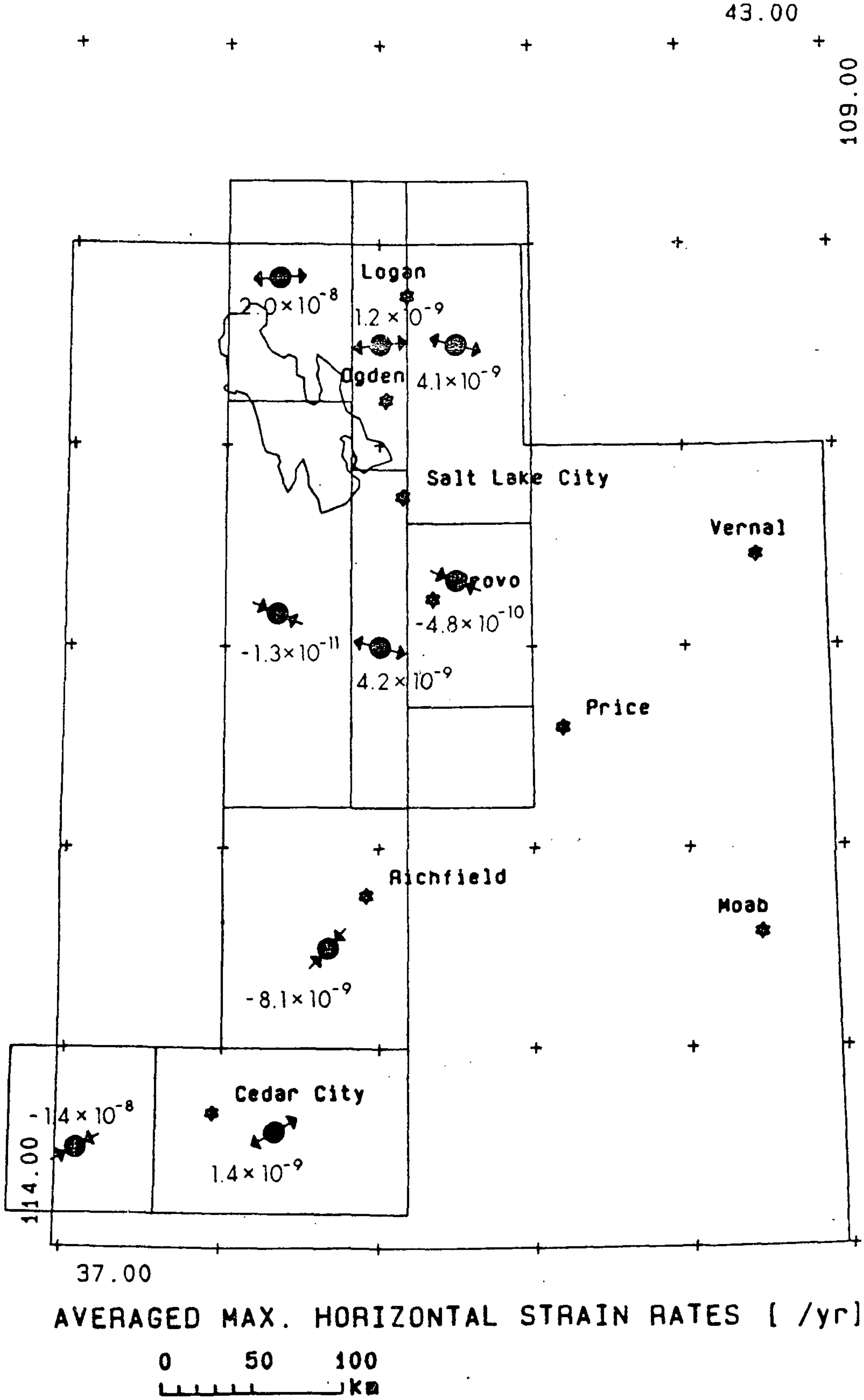

Figure 3. Averaged horizontal strain rates in units of strain per years. Directors of principle horizontal components shown by outward directed arrows for extension and inward directed arrows for compression.

the northern Wasatch Front corridor, the adjacent Hansel Valley to the west and Cache Valley to the east where strain rates vary from 2 x 10^{-3} to 4 x 10^{-9} per year. To the south, the southern Wasatch corridor shows WNW-extension, but a significant change to apparent compression east of the Wasatch fault. This rapid strain change is not a surprising, recognizing that the strain field east of Provo includes the northern end of the Colorado Plateau that has generally been found to be in compression.

To the south, the Richfield area including the Sevier and Tushar fault zones shows a distinct trend of NE compression. The strain changes to NE extension near Cedar City and to the west, the strain field rotates again to NE compression at the Utah-Nevada border.

Converting the horizontal strain rates to deformation rates in mm/yr, Figure 4 documents that the highest rates occur in the Hansel Valley area of northwestern Utah at 1.5 mm/yr. The strain-rates decrease markedly, by an order of magnitude, to less than 0.1 mm/yr in the northern Wasatch Front corridor but slightly increase to 0.3 mm/yr in the East Cache area. To the south, the southern Wasatch Front shows relatively higher deformation rates, 0.1 mm/yr, than the northern Wasatch Front but distinct order of magnitude decrease to the east near Provo and to the west in the Tooele area are evident. Strain rates increase markedly into a compressional regime at Richfield to 1.3 mm/yr, then decrease to 0.2 mm/yr extension near Cedar City, but change again to 1.0 mm/yr compression at the Utah-Nevada border.

Paleoslip-- A map of locations for geologically determined slip rates is shown in Figure 5. These are locations for which fault length, age, and slip rates were available from the literature (detailed references will not

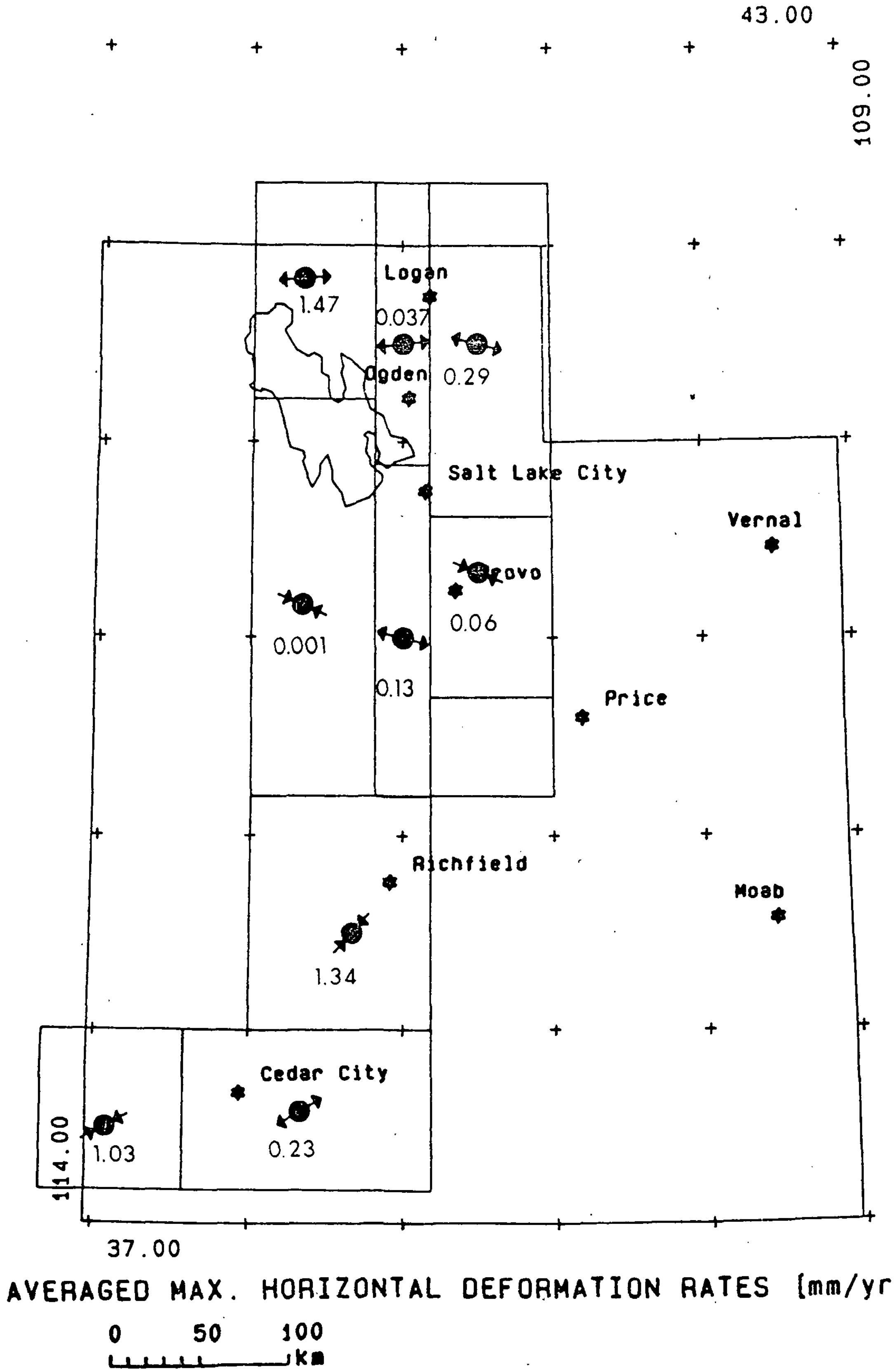

Figure 4. Maximum horizontal deformation rates in mm/yr converted from strain rates.

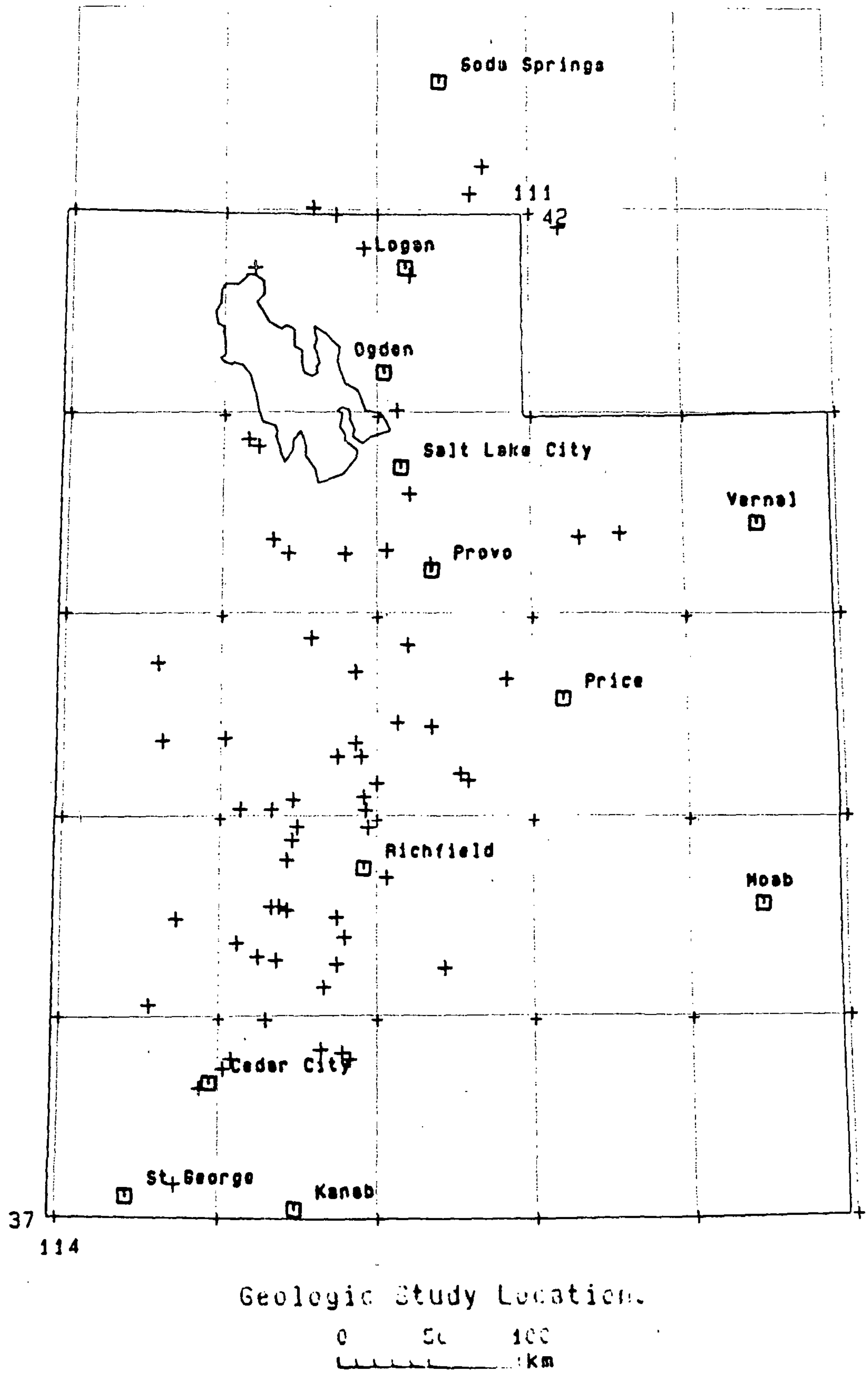

Figure 5. Location map of sites for which fault length, fault age, and slip rates were available for the State of Utah.

be given in this brief summary). The paleoslip rates and direction of slip from the geologic data were converted to seismic moment from the equation of

$$M_o = \mu A \dot{u} \qquad (2)$$

where μ = shear modulus, A = area of slip and $\dot{u}$ = slip rate as described by Doser and Smith (1982). For this paleoslip study, Utah was divided into approximate $1^0 \times 1^0$ squares, not the same as the seismicity rates because of the differing density of geologic information. Figure 6 shows the preliminary results that suggests paleoslip strain rates vary from maximums of 0.7 mm/yr in the Salt Lake City-Provo area and the Richfield area. These rates are of the same order of magnitude in Hansel Valley, the east Cache fault zone and the southern Wasatch Front.

Comparison of Strain/Displacement Rates-- The importance of the geologically determined strain rates is seen in Table 1 where comparison of contemporary strain associated with historic seismicity and that from paleoslip is given. In addition geodetic information from Snay et al. (1984) are also shown. For the Wasatch Front area (divided into a southern and northern portion), contemporary deformation rates vary from less than 0.1 mm/yr for the northern Wasatch fault to 0.1 mm/yr for the southern Wasatch. These rates compare with paleoslip rates of 1.0 mm/yr to 0.8 mm/yr for the northern Wasatch as well. Note the distinct difference in the strain rates from 1.2×10^{-9} E-W extension to -34×10^{-9} E-W compression inferred from the geodetic data. This difference suggest that significant aseismic creep may currently accommodate strain accumulation. Paleo- and

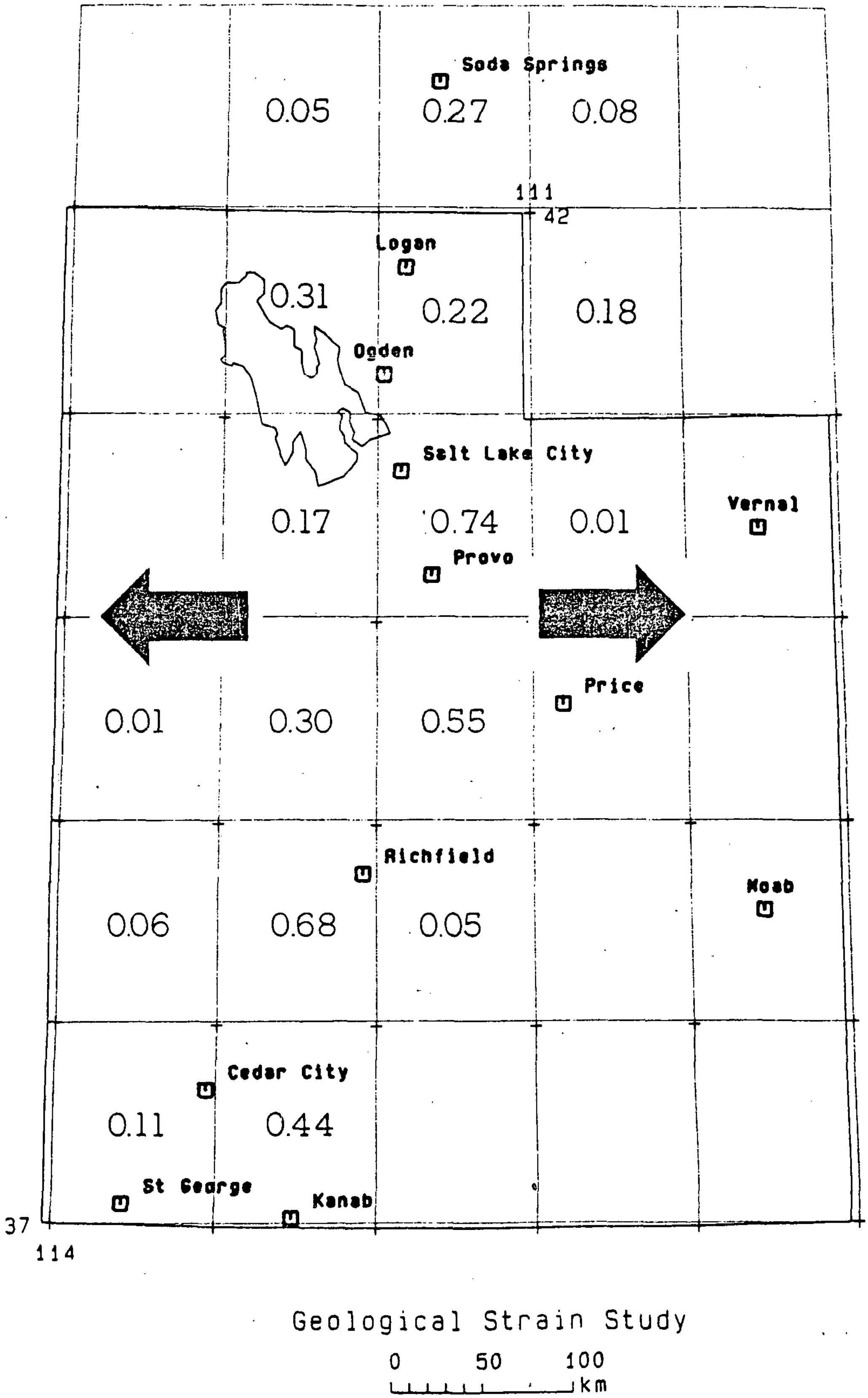

Figure 6. Calculated displacement rates (in mm/yr) principally from Quaternary-Holocene geologic data.

Table 1.

Displacement/Strain Rates In Utah
(mm per yr / x10-09 per yr)

Area	Seismic	Paleo-seismic	Geodetic
Northern Wasatch Front	<0.1 1.2	1.0	 -34.0
Southern Wasatch Front	0.1 4.2	0.8	 1
Hansel-Pocatello Valleys	1.5 20.0	0.3	NA
Bear River Range-East Cache	0.3 4.1	0.2	NA
Provo-Heber	<0.1 -0.48	0.7	NA
Tooele-Dugway	<0.01 -0.013	<0.1	NA
Richfield-Cove Fort	1.3 -8.1	0.7	NA
Cedar City	0.2 1.4	0.7	NA
Caliente (Ut-Nev border)	1.0 -1.4	NA	NA

Average Displacement Rate:
mm/yr 0.5 0.6

contemporary strain rates in the southern Wasatch Front are of the same order.

Strain rates in the Hansel-Pocatello Valley area exceed 1 mm/yr of east-west extension, but decrease to less than 1 mm/yr in the Bear River Range Cache area but are of the same order as the paleoslip. Contemporary displacement rates decrease in the Provo-Heber area and the Tooele-Dugway areas to less than 1 mm/yr or lower; whereas paleoseismic estimates of strain in these areas are of order 0.2-0.7 mm/yr.

In the Richfield-Cove Fort area swarm seismicity has contributed to the 1.3 mm/yr rate compared to 0.7 mm/yr estimated from the paleoslip. Further south the displacement rates from seismicity decrease.

Conclusions

An important result of the comparisons is that the averaged earthquake induced deformation rates of 0.5 mm/yr compare very well with that inferred from the geologic paleoslip of 0.6 mm/yr. This conclusion suggests that the deformation mechanisms that produces the contemporary state of seismicity have been active for several million years. Thus as a working hypothesis, estimates of future seismicity based upon Quaternary-Holocene geology appears to be a reasonable model for the future occurrence of seismic activity. This conclusion should be cautioned however with the findings in northern Utah where the Wasatch fault zone, in part, has had seismic quiescence (Arabasz et al., 1980) associated with individual fault segments may not be characteristic of the long-term strain.

The results of the above calculations are to be considered preliminary and are being updated with newer data and a revised moment tensor calculation algorithm. Thus, the results should be considered only as a guide to the regional seismicity and the earthquake hazards of the state of Utah.

Acknowledgments

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Analysis of Earthquake Ground-Shaking Hazard For the Salt Lake City-Ogden-Provo Region

by

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INTRODUCTION

We are presently conducting a study to provide an assessment of the earthquake ground shaking hazard in the Salt Lake City-Ogden-Provo region. This investigation is being done for the U.S. Geological Survey as part of the Earthquake Hazard Reduction Program. Work to date for this study has focused on earthquake source characterizations, which are required as key inputs to the ground motion analysis. Ground motions have not yet been calculated but will be in the next two to three months. This paper provides a summary of the scope of and approach to the study, illustrates the earthquake source characterizations developed, and summarizes the future work to be done.

SCOPE AND APPROACH

The regional assessment of ground motion hazard will be made using a probabilistic approach, often termed a seismic exposure or a seismic hazard analysis. The seismic exposure or seismic hazard is expressed as levels of a ground motion parameter, such as peak ground acceleration, having certain probabilities of being exceeded during a specified time period. The results of this study will be shown on regional maps as contours of peak ground acceleration for selected probabilities of exceedance. Also, acceleration response spectra corresponding to selected probabilities of exceedance will be developed for representative locations in the study region for use in further establishing the damage potential of ground motions to buildings.

The seismic exposure at any particular site location in the region depends on:

1) The location and geometry of earthquake sources relative to the site.

2) The frequency of occurrence (i.e., recurrence) of earthquakes of various magnitudes on the sources, up to the maximum magnitude for each source.

3) The attenuation of ground motions from the sources to the site.

In the basic seismic exposure analysis, these factors are incorporated in three probability functions:

1) The probability that the earthquake rupture surface is a specified distance from the site is assessed by considering both fault location and geometry and the relationship between earthquake magnitude and rupture area.

2) The recurrence rate is used to calculate the probability that an earthquake of a particular magnitude will occur during a specified time period. The magnitude range is limited by the maximum magnitude possible on the source.

3) The probability that the ground motions from an earthquake of a certain magnitude occurring at a certain distance will exceed a specified level at the site is based on the selected attenuation relationship.

By combining the three probability functions, the probability of exceeding a specified level of ground motion at a site within the specified time period is computed. A relationship between ground-motion level and probability of exceedance is obtained by repeating the exposure computation for several levels of ground motion. The ground-motion level corresponding to a specified probability of exceedance (or return period) is then obtained from this relationship. A schematic diagram of the basic seismic exposure analysis model is shown in Figure 1. The mathematical formulation of the basic analysis model is described by Kulkarni et al., 1979, and is similar to other models (Cornell, 1968; McGuire 1974, 1978; Der Kiureghian and Ang, 1977).

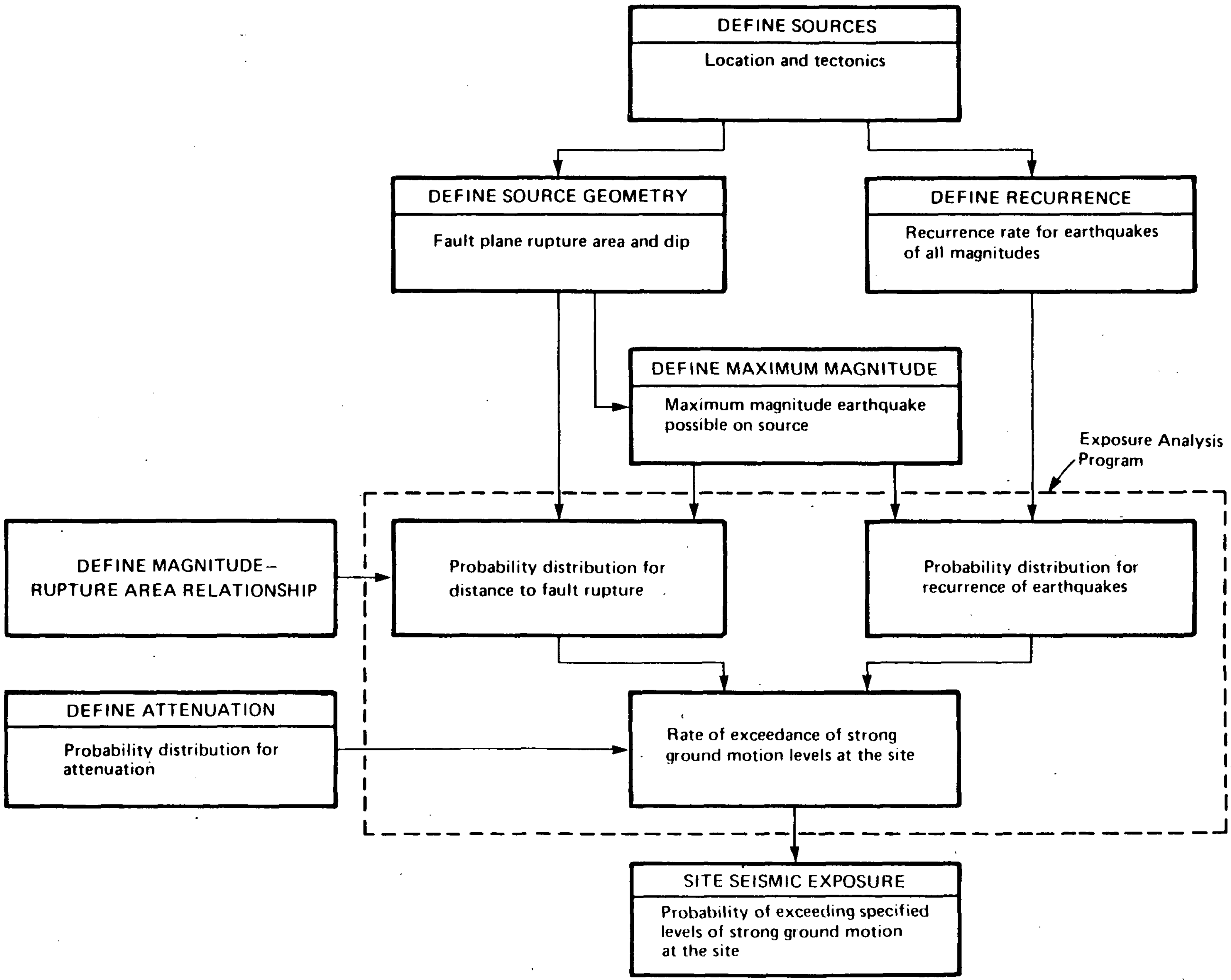

Figure 1. Schematic Diagram of Seismic Exposure Model

In a basic seismic exposure analysis, it is assumed that certain source characterization parameters, including fault segment length, fault dip, fault width, maximum earthquake magnitude, and earthquake recurrence rate, are known with certainty. In fact, there usually is uncertainty in these parameters, which can significantly affect estimates of the seismic exposure. In the present study, these uncertainties in source characterization parameters are incorporated through an extended seismic exposure model using logic trees. The methodology for using logic trees to treat source parameters probabilistically is described by Power and others (1981) and Kulkarni and others (1984). An example of a logic tree for one of the faults in the study region is presented in the following section.

EARTHQUAKE SOURCE CHARACTERIZATION

A major aspect of the seismic exposure analysis is the selection and characterization of the seismic sources that contribute to the seismic exposure of the study area. Two different types of sources are being examined: Known faults that can produce moderate to large magnitude earthquakes and a "floating" source that accounts for smaller magnitude earthquakes that cannot be associated with known geologic structures. The selected sources are shown in Figure 2. These are: segments of the Wasatch fault (sources 1-6), the East Cache fault (source 7), the Strawberry Valley fault (source 8), the Oquirrh-Boulter-Tintic fault (source 9), the Oquirrh Marginal fault (source 10), and a fault zone in Great Salt Lake (source 11). Sources 1 through 10 are each defined by lake Pleistocene and/or Holocene

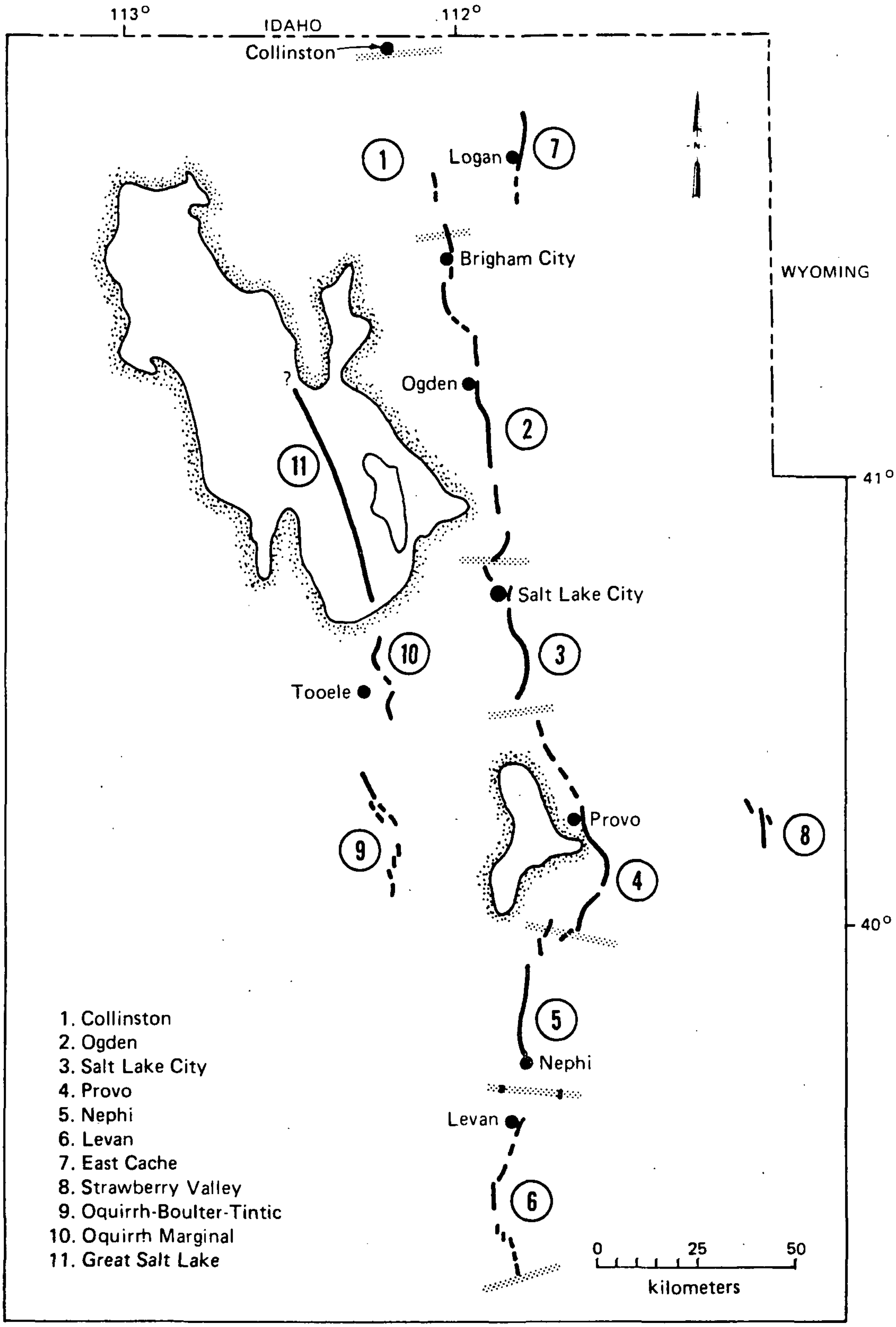

Figure 2. Map of Proposed Sources (faults and fault segments) for Seismic Exposure Analysis of Ogden-Salt Lake-Provo Corridor. Wasatch Fault Zone Segments Are from Schwartz and Coppersmith (1984)

fault scarps; source 11 is interpreted from seismic reflection profiles presented by Smith and Bruhn (1984).

For each fault data are being obtained that characterize it in space (geometry) and time. These data include potential fault rupture length, fault width (based on dip and down dip extent), displacement per event, slip rate, average recurrence intervals, deviation from mean recurrence, and elapsed time since the most recent event. Data from the Wasatch and East Cache faults are summarized in Table 1. Potential rupture lengths are being estimated using fault segmentation techniques suggested by Schwartz and Coppersmith (1984). Subsurface geometry is being evaluated on the basis of instrumental seismicity data, seismic reflection profiles, local crustal models, and alternative models of listric and high angle normal faulting. Maximum earthquake magnitudes are being estimated for each source. A variety of approaches exist for estimating maximum earthquake magnitudes and these relate magnitude to specific fault characteristics such as fault rupture length, fault rupture area, maximum displacement per event, and seismic moment. Probabilistic approaches will be used to incorporate the range of source parameters and magnitude estimates based on these parameters. Figure 3 is a logic tree that shows the way in which maximum earthquakes, in this case for the Provo segment, are evaluated. It can be seen that a range of possible values for each source characterization parameter can be considered. Each value of a parameter is given a weight (in parentheses) as to its relative likelihood of being the correct value based on evaluation of available data. Each path through the logic tree leads to a particular value for maximum magnitude. The

TABLE 1

FAULT BEHAVIOR DATA
WASATCH FAULT ZONE

			Displacement per Event (m)		Recurrence			
Segment	Site	Slip Rate ($mm\ a^{-1}$)[a]	Measured	Average[b]	Interval	Average (yr)	Elapsed Time (yr)[c]	Reference
Collinston	-	≥ 0 (13,500)	-	-	-	-	≥ 13,500	Schwartz and others (1983)
Ogden	Kaysville	1.3 (+0.5, -0.2)[e] (8,000; +1000, -2000)	1.6 1.7	- -	2 (after 1580)[d]	2000	≤ 500	Swan and others (1980)
Salt Lake City	Little Cottonwood Canyon	0.76 (+0.6, -0.2) (19,000 ± 2000)	-	2 (2)	-	2400-3000	-	Swan and others (1981); Schwartz and Coppersmith (1984)
Provo	Hobble Creek	0.85 - 1.0[e] (13,500)	2.7	1.6-2.3 (6-7)	6-7 (after 13,500)	1700-2600	> 1000	Swan and others (1980)
Nephi	North Creek	1.27-1.36 (± 0.1) (4580)[d]	2.0-2.2 2.0-2.5 2.6	2.3 (3) -	2 (between 4580 and 3640)[d] 1 (after 1100)[d]	1700-2700	300-500	Schwartz and Coppersmith (1984)
Levan	Deep Creek	≤ 0.35 ± 0.05 (7300)[d]	2.5	-	1 (after 7300)[d]	-	<1750[d]	Schwartz and Coppersmith (1984)
East Cache	Logan	0.1-0.2 (14,000-15,000)	1.35 1.4	- -	1 (between 15,000 and 13,500) 1 (after 13,500)	-	6000-10,000	Swan and others (1982)

a Age of displaced datum (years B.P.) on which slip rate is based is shown in parentheses.
b Number of events on which average is based is shown in parentheses.
c Time in years since the most recent surface faulting earthquake.
d Age in ^{14}C yr B.P.
e Modified from Swan et al. (1980).

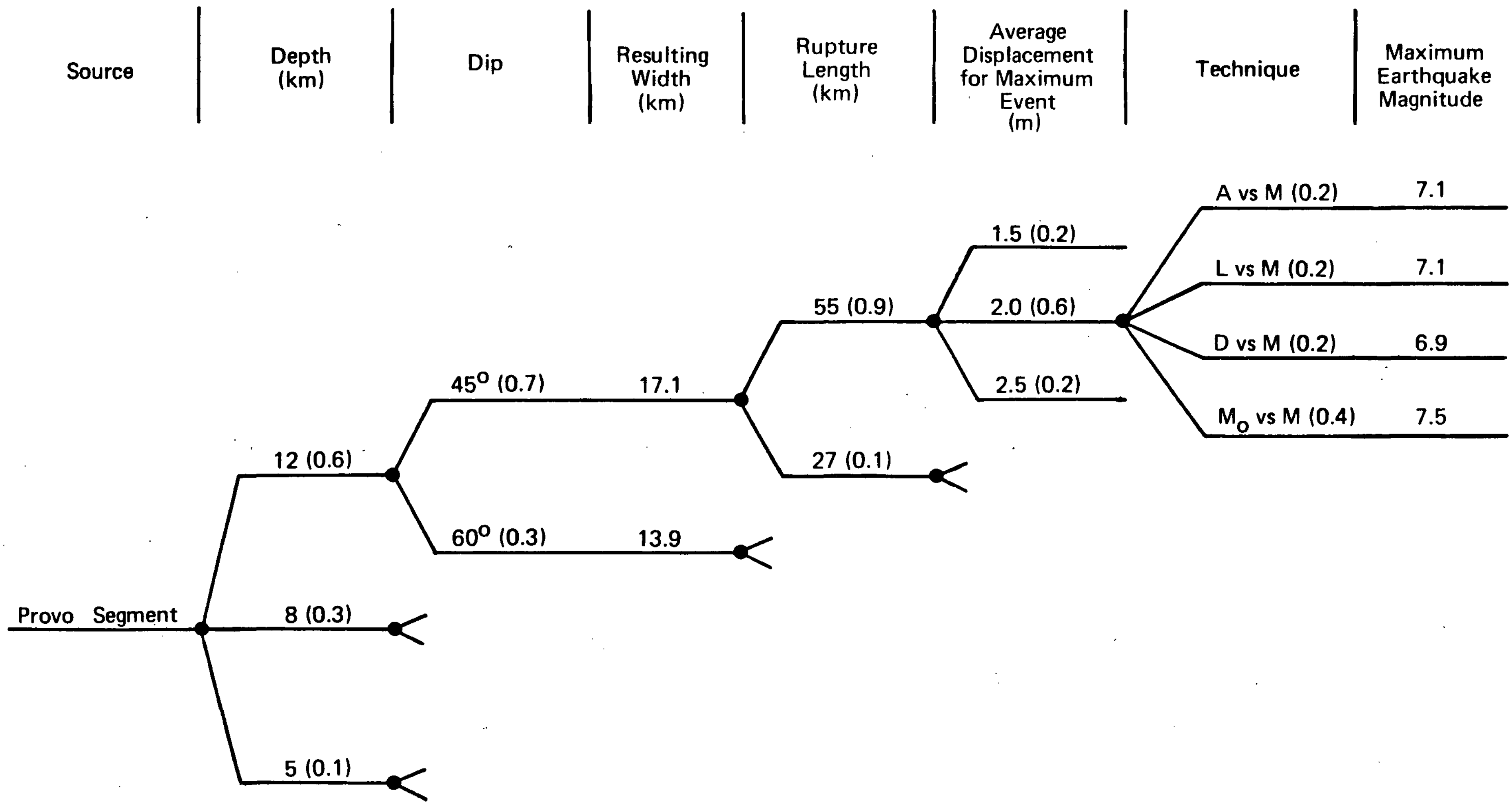

Figure 3. Example of Use of Logic Tree in Treatment of Uncertainty in Source Characterization

resulting range or distribution of maximum magnitude estimates for each source will be included in the seismic exposure analysis, thus reflecting the uncertainty inherent in these estimates and allowing the sensitivity of the exposure analysis to maximum magnitudes to be assessed.

The characterization of seismic sources also requires the selection of a model that represents the frequency of occurrence of earthquakes of various magnitudes for each source. The historical record of seismicity in a region is commonly used to estimate recurrence. In the Salt Lake City-Ogden-Provo region, however, this method is particularly inadequate because the historical record is short relative to the recurrence intervals of large earthquakes. For example, although the geologic data indicate that multiple major earthquakes have occurred along the Wasatch fault in Holocene time, the Wasatch fault zone has not been associated with an earthquake larger than magnitude 5.5 since settlement of the region in 1847 (Cook and Smith, 1967; Cook, 1972; Arabasz and others, 1980). Geologic techniques for assessing earthquake recurrence are source-specific and are often based on a period of record that is several thousands of years long. Geologic approaches include estimating the actual time interval between surface rupture events by identifying and dating individual prehistoric events; and identifying multiple surface rupture events over a known time interval to calculate the average recurrence interval. In addition, the geologic fault slip rate may be used to constrain the rate of earthquake occurrence on specific faults and fault segments.

In order to use earthquake recurrence estimates in a seismic exposure assessment, a model that represents the earthquake recurrence process must be selected. Several different recurrence models have been developed. Typically, recurrence intervals for regions, as well as individual faults, have been estimated by a linear recurrence model having the form Log N = a -bM, where N is the number of earthquakes having magnitude M or larger per year. The relative frequency of various magnitudes is defined by the b-value, which is assumed to be constant over a wide range of magnitudes. This model has been shown to be most appropriate for characterizing the seismicity of large regions. However, it may not accurately reflect the recurrence of earthquakes occurring on individual faults or fault segments. Recent studies of the Wasatch Fault zone have indicated that the segments of this fault generate characteristic earthquakes having a relatively narrow magnitude range (Schwartz and Coppersmith, 1984). Earthquakes having magnitudes somewhat less than the characteristic earthquake occur less frequently than would be predicted by a linear (constant b-value) model. Figure 4 is a cumulative frequency magnitude plot of instrumental seismicity (1962-1983) on the Wasatch fault zones and geologic recurrence data. The most striking feature is the distinct absence of a moderate magnitude earthquakes (M 5.5-6.5) during the 20-year period of instrumental record. This is in agreement with the previous 112-year historical period (1850-1962), which contains no earthquakes larger than intensity VII (approximately M 5.7) within a corridor extending 50 Km west and 25 Km east of the Wasatch fault. A linear extrapolation of the recurrence curve from the smaller magnitudes assuming a constant b value leads to underestimates of the frequency of large earthquakes.

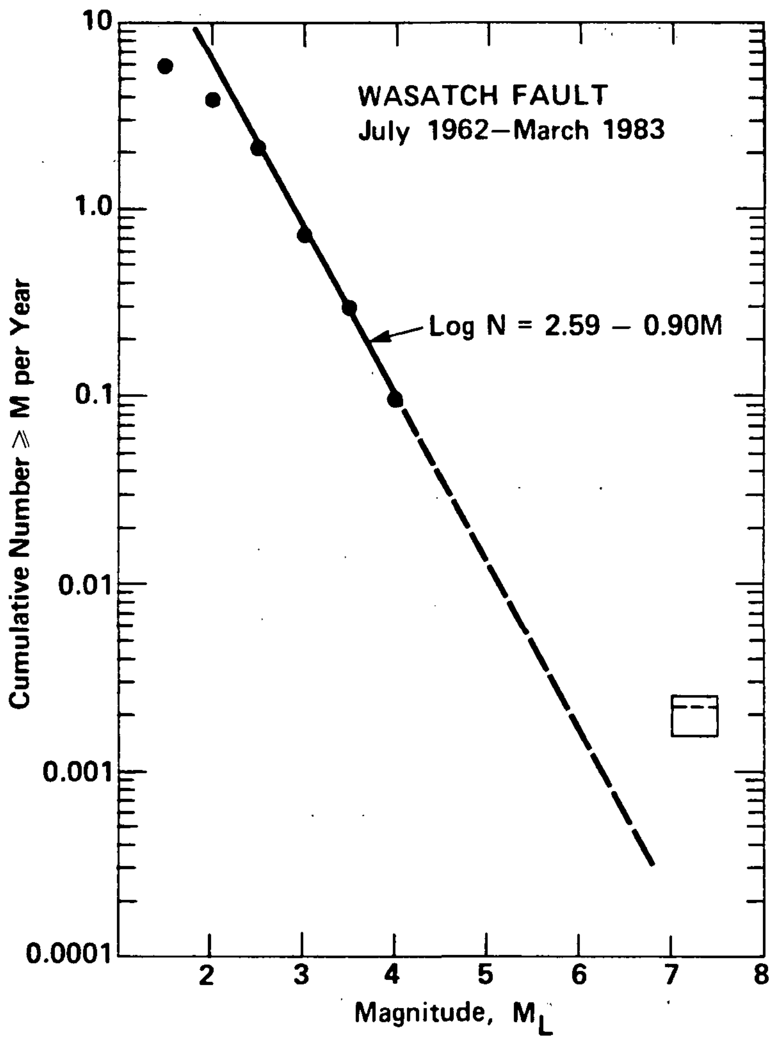

Figure 4. Cumulative Frequency-Magnitude Plot of Instrumental Seismicity for the Period July 1962 to March 1983 along a Zone Containing the Wasatch Fault. The 370 km Long Zone Extends Approximately 20 km to the West of the Fault and 10 km to East. The Dashed Portion of the Recurrence Relationship Is a Linear Extrapolation. The Box Represents the Range in Recurrence Intervals (400 to 666 yr) and Magnitudes (7 to 7½) Based on the Geologic Data. The Preferred Recurrence Interval Estimate of 444 yr Is Indicated by a Dashed Line within the Box. (from Schwartz and Coppersmith, 1984)

Recurrence models may be differentiated by the manner in which they address the temporal and spatial relationships of earthquakes. Two examples are the Poisson model and the semi-Markov model. The Poisson model assumes that the occurrence of one earthquake does not affect the likelihood of the occurrence of a similar earthquake at the same location in the next unit of time; that is, there is a temporal and spatial independence of all earthquakes. In the semi-Markov model (Patwardhan and others, 1980), the size of the next earthquake and the time until its occurrence are dependent upon the amount of strain energy released in the previous earthquake and the length of time during which strain has been accumulating without any significant release. The applicability of this model is strongly dependent upon the available evidence for the size of the most recent earthquake and the time elapsed since its occurrence.

Each of these recurrence models is being carefully reviewed for applicability to the geologic and seismic conditions that characterize fault sources in the Salt Lake City-Ogden-Provo region. A model, or combination of models, will be selected to represent the earthquake generation process in the region. A set of recurrence relationships will be selected and tested to assess the sensitivity of the seismic exposure to the recurrence parameters.

A "floating," or random, earthquake source that accounts for earthquakes that cannot be assigned to known faults is also characterized. Becaused the larger earthquakes in the region are expected to occur on known faults, the maximum magnitude assigned to random earthquake sources will be smaller than maximum magnitudes assigned to faults. Historical seismicity data is being analyzed in selecting maximum magnitudes and recurrence parameters for randomly-located earthquakes.

FUTURE STUDIES

Completion of the analysis of the earthquake ground shaking hazard of the Salt Lake City-Ogden-Provo region will involve the following activities: Evaluation of the range of recurrence models and parameters to be incorporated in the analysis; construction of logic trees for each source; selection of ground motion attenuation relationships; and calculation of ground motions (seismic exposure) throughout the region.

Ground motion attenuation relationships are a key input to the seismic exposure analysis. Very little strong ground motion data are available from the region to use in evaluating attenuation. To the extent possible, the applicability of attenuation relationships developed from mainly California data to the study region will be evaluated. This activity will include examination of the strong ground motion data from the Borah Peak, Idaho, earthquake and aftershocks which occurred in a similar tectonic environment as that of the study region. Separate sets of attenuation relationships will be selected for broad categories of subsurface conditions within the study region (such as rock, and deep firm soils above rock). The incorporation of the regional variation in subsoil conditions into the selection of attenuation relationships and mapping of ground motion will be based on examination of regional geological mapping (e.g. Miller, 1980; McGregor and other, 1974: Feth and others, 1966) and regional ground amplification studies (e.g. Hays and King, 1982, 1984).

The mapping of peak ground acceleration contours and the development of response spectra will be done for two different probability levels. The probability levels that are selected will be representative of typical levels used in the seismic design of buildings (for example, 10-percent and 50-percent probability of exceedance in 50 years). The degree of confidence or uncertainty in the ground motion estimates presented will be examined by analyzing the effect of uncertainties in source characterization parameters and by performing sensitivity analyses for alternative earthquake source characterizations and attenuation relationships.

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PROBABILISTIC RISK ASSESSMENT
FOR THE UTAH MULTI-HAZARDS PROJECT

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ABSTRACT

As part of a pilot study, the State of Utah Division of Comprehensive Emergency Management, and the Federal Emergency Management Agency (FEMA) undertook a pilot project to develop a multi-hazards emergency management program. Among the tasks performed was the development of a probabilistic risk assessment methodology to evaluate the consequences of the multiple hazards that may impact the state, notably along the populated reaches of the Wasatch Front. A probabilistic approach offers a comprehensive summary of the likely consequences in the event a major disaster should occur. It identifies the possible scenarios that may take place, and estimates the likelihood of their occurrence. For purposes of emergency management planning and public policy decision making, it is important to have a clear understanding of the consequences, in terms of both their possible magnitude and likelihood. With this input, the decision maker can make informed, logical plans to mitigate and respond to the impact of a major disaster. This

work represented an initial effort to develop a comprehensive risk assessment procedure that will become an integral part of an active multi-hazards emergency management program.

In the first part of the project, guidelines were provided for conducting a probabilistic assessment of the consequences to the following primary natural hazards in Utah: earthquakes, floods, dam failures, and landslides. The framework of the probabilistic model included the following elements: hazard evaluation, exposure assessment, vulnerability or damage assessment, and risk quantification. In the final quantification of risk, probabilistic input on each hazard and their consequences is expressed in probabilistic terms. The emergency manager is provided with input on the possible magnitude of casualties (e.g., deaths, injuries, homeless) and the likelihood that such losses would be incurred. Similarly, the availability of emergency services following a disaster is expressed in the same manner.

The multi-hazards risk assessment is intended to provide the emergency planner with a clear picture of the possible hazard/ consequence scenarios that can occur, rather than conservatively selecting the worst situation as a basis to design emergency procedures. The decision maker is provided with an evaluation of the consequences in terms that express the possible extent of losses and their likelihood.

INTRODUCTION

The State of Utah faces the unique challenge of addressing the problem of multi-hazards emergency management. Unlike many other areas in the U.S. that face potential catastrophic loss due to single or multiple hazard occurrences, Utah finds itself in a situation where 90 percent of the state's population lies at the foot of the Wasatch Mountains, which is also the region most susceptible to the major hazards that could occur in the state. The Wasatch Fault, which is a portion of the Intermountain Seismic Belt, is a highly active source of seismicity in the region, capable of producing intense ground shaking and surface faulting due to events as high as magnitude 7.5. The occurrence of earthquakes along the Wasatch Front, in addition to posing a direct threat, could initiate other hazardous events as well, including dam failure and landslides in the canyons above populated areas.

In response to the clear and present danger of the multi-hazards that threaten the major economic, social, and political centers of Utah, the state has embarked on a comprehensive emergency management program. This effort, entitled, "The Utah Multi-Hazards Project," is a pilot program funded by the Federal Emergency Management Agency. It is designed to establish a methodology to identify the hydrologic and geologic hazards in Utah, to assess the consequences of their occurrence, and to establish the groundwork of a methodology to aid local officials in emergency planning and mitigation of the risks to local communities.

Within a comprehensive emergency management plan there are a number of interrelated elements that ultimately lead to the development of measures to mitigate the consequences anticipated from a major disaster. Figure 1 displays schematically the general format of a comprehensive emergency management program. As illustrated in the figure, the results of a risk assessment provide input to the development of emergency operation plans to meet the needs immediately after a major disaster and to formulate long- and short-term mitigation efforts.

In order to provide this information to emergency management planners and public policy makers, a probabilistic risk assessment approach is used. Risk assessment procedures are used extensively in engineering practice and have become an attractive tool for decision makers who must make important public policy decisions involving highly uncertain events, such as extreme floods, earthquakes, landslides, etc. In a probabilistic risk assessment, information is presented in terms of the magnitude of the potential disaster and its likelihood of occurrence.

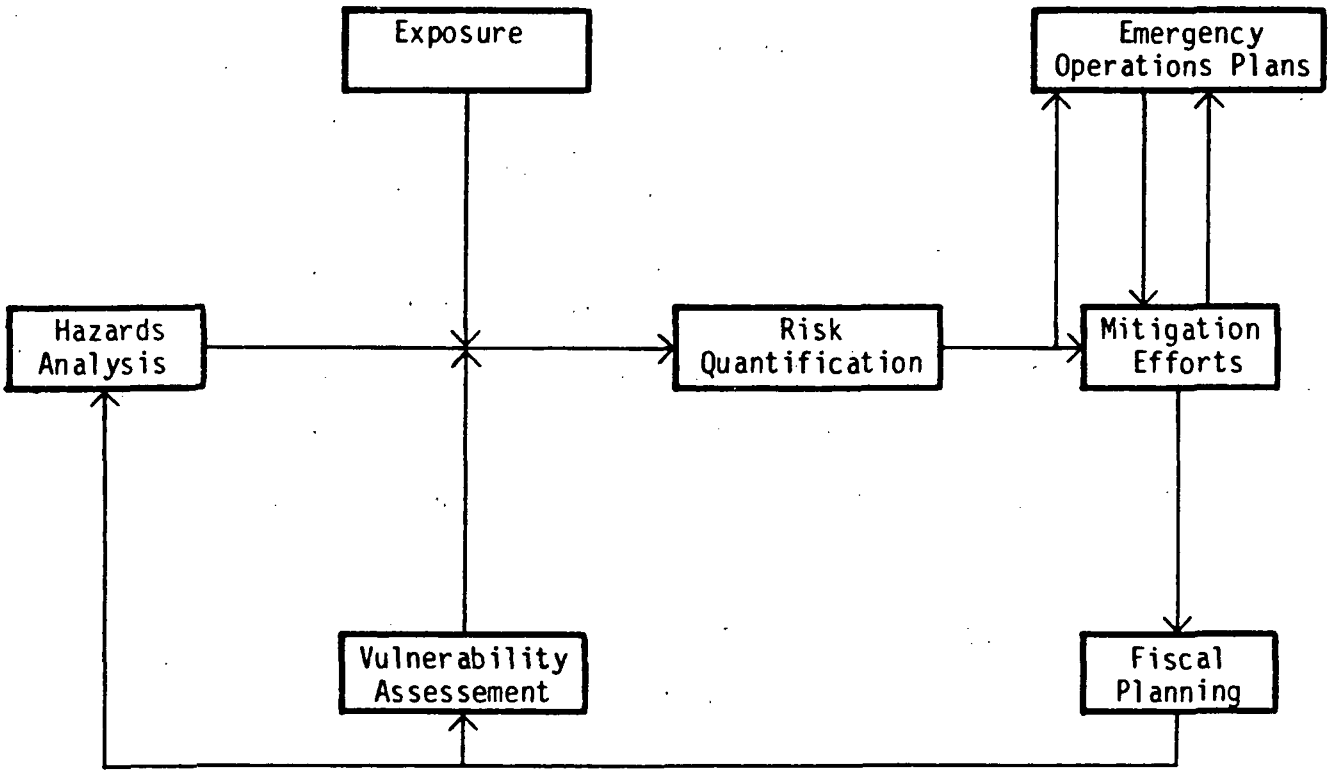

Figure 1 Schematic illustration of the basic elements of a comprehensive emergency management program.

To assess the intensity of major natural hazards and the consequences of these events is highly uncertain. As an example, it is easy to recognize that when a major earthquake occurs there is uncertainty in the prediction of the spatial intensity of ground shaking, in the extent of damage to buildings and other structures, in estimates of how many casualties there will be, or which emergency services will be available. The same can be said for other disasters as well. Where multi-hazard events can occur essentially simultaneously, such as a seismically-induced dam failure, the consequences of serial hazard occurrences become harder to rationally plan for without an indication of their likelihood.

Within the scope of the Utah Multi-Hazards Project, guidelines to perform a probabilistic risk assessment procedure were developed to evaluate the many hydrologic and geologic hazards that threaten the populated areas of the state. In this paper, an overview of the approach taken is presented with particular emphasis given to seismic risk assessments.

METHODOLOGY FOR MULTI-HAZARDS RISK ASSESSMENT

Overview

An important element in the development of an emergency management program is to establish in the planning stages a clear, comprehensive view of the demands that will be placed on local and national emergency services immediately following a major disaster. In the pre-disaster planning stages, it is necessary to know the likelihood and degree of damage to structures and loss of life and injuries that can be expected. Information reported in this manner provides the emergency planner with a composite, two-dimensional view of the potential consequences. By reporting the degree to which emergency services will be available immediately after a major disaster in the same way, a direct comparison and assessment can be made of their adequacy.

An assessment of the consequences of a major disaster is a task that must deal with a variety of uncertainties. For example, there is uncertainty associated with the random occurrence of a disaster such as the chance it will occur in any given year, the location, the time of day, and season of the year. Given its occurrence, there is uncertainty in the assessment of the consequences, including the damage to buildings, availability of emergency services, assessment of life loss, and the response of the public to warnings. Currently, a standard procedure does not exist that systematically incorporates these and other uncertain factors in a consequence evaluation.

The purpose of the work for the State of Utah was to present guidelines to evaluate the consequences of the multi-hazards experienced in Utah in a probabilistic format. Although methods to evaluate the risk due to major natural disasters and to plan mitigation measures are not well established, the basic steps in the process are generally recognized to consist of:

- Hazard evaluation
- Exposure assessment (i.e., the population and property at risk)
- Vulnerability assessment
- Risk quantification
- Establishment of a program of risk mitigation, including emergency operation plans
- Updating emergency operation plans in light of the changing environment (i.e., physical, political, social, economic)

In this work we were concerned with the first four steps that compose the assessment of risk.

A hazard evaluation involves the identification of the natural or man-made conditions that represent a source of danger and an assessment of their likelihood of occurrence. A hazard may be caused by some external initiating event, such as the intense ground shaking produced by an earthquake, or it may occur as a random, isolated event such as the flood produced by a failure of a dam due to foundation instability.

Exposure refers to the property (i.e., buildings, homes, agricultural farmland, factories, etc.), and lives which are exposed to the potential hazards. In other words, that which is at risk.

Vulnerability refers to the expected degree of damage experienced by the elements exposed to the hazard. A relationship describing the expected damage of one-story residences exposed to flood waters is an example of a vulnerability assessment.

When the uncertainty in the hazard and consequence assessments are considered, it is possible to imagine that a variety of scenarios could occur at random. A simple example can illustrate this. Consider that two levels of earthquake ground motion intensity are postulated, each with a probability of occurring. Also, consider that a dam could fail or not fail when exposed to each level of earthquake. Depending on the level of the earthquake, the probability of dam failure would be different. In this case, four possible scenarios might occur. For each level of earthquake intensity, there could be failure or no failure of the dam. The likelihood of each scenario would be the product of the individual event probabilities (i.e., probability of dam failure given the earthquake intensity times the probability of the earthquake).

In the final risk quantification the likelihood of all possible hazard/consequence scenarios is assessed. The formal quantification of the impact of a major disaster involves a logical combination of the random events that result in adverse consequences. The steps in the procedure are described subsequently.

Emergency Planning Events

In order to assess emergency management needs in the event of a major disaster, it is important to quantify the risk on a per event basis. In this way, emergency service capabilities can be directly measured against the demands posed by each disaster. For this reason, individual events are generally defined to serve as the basis for consequence evaluation and the design of emergency operation plans.

In the multi-hazards project work the following initiating hazard events were considered:

- Earthquake
- Flood
- Dam Failure
- Landslide

It is a fairly common practice to develop emergency management plans and mitigation programs on the basis of worst case hazard scenarios. As an example, the consequences to the probable maximum flood might be assessed and used to make emergency operation plans. The concept of considering worst case hazard scenarios as the basis for emergency management planning is not necessarily realistic. One reason is that, as well as not accounting for the uncertainty with respect to event location, there is no concept of the likelihood of occurrence. Also, from an economic perspective it may not be cost effective, or politically feasible to design emergency operation plans for Armageddon. Furthermore, the likelihood of occurrence for different worst case events may be very different. For example, the maximum earthquake that could occur may have a return period of 250 years, while the average waiting time for the probable maximum flood may be 100,000 years. Clearly an inconsistency exists in terms of the level of risk being considered in each case. However, the use of worst case scenarios in the course of an analysis can be informative since it helps to establish an upper bound on the anticipated losses and emergency service needs.

Two planning events were selected as the basis to evaluate losses, prepare emergency operation plans, and develop mitigation programs. A planning event is the primary hazard that initiates one or more of the potential hazards that a community may be exposed to, and is used as the basis to design emergency management systems. It is also referred to as the initiating event which may trigger one or a series of additional hazards. The two planning events considered herein were the events that have an annual probability of 0.01 or a 100-year return period and the worst case or maximum credible event.

To perform the risk assessment, the planning event is conservatively located where its occurrence will result in the most severe consequences. The actual degree of conservatism will depend on the likelihood that an event of the same size could occur elsewhere, without adverse impact on the study area.

Hazards and Hazard Sequences

Given the occurrence of an initiating event, single or multiple hazards may occur in various parts of a region. The occurrence of one or more hazards may be dependent, not only on the fact that the initiating event has occurred (e.g., 100-year flood), but on other hazards as well. In other words, there may be a probabilistic dependence between the occurrence of one or more hazards. The situation of a seismically induced dam failure is an example of the dependence between two hazards, ground shaking and flooding due to a dam break.

Given the occurrence of an initiating event (e.g., 100-year flood, dam break, etc.), an assessment is made to evaluate the likelihood of each hazard that can occur, either individually or in series with other hazards. In order to establish an eventual probabilistic characterization of the multiple hazards and hazard sequences that could occur, a systematic procedure is required. The general steps and examples for the State of Utah are listed below.

- Identify the potential initiating events that could occur in the region.

- Determine the hazards generated by each initiating event, including primary, secondary, etc. throughout the study area.

- Establish the interrelationship between hazard types to determine the dependencies that may exist, in order to develop an event tree of the multiple hazard sequences that could occur.

- Select a model or statistical approach to define the likelihood of each hazard intensity level.

- According to the combination of events depicted in the event tree, evaluate the likelihood of each hazard sequence throughout the region.

Table 1 lists the multi-hazards in Utah addressed in this work. Note that the hazards listed are natural geologic or hydrologic hazards only, with the exception of dam failures. No direct consideration is given to technological hazards such as fires, chemical spills, or radiation release.

The event or logic tree approach to multi-hazard assessment is effective since it can be used to illustrate graphically the potential hazard scenarios that could occur. Figure 2 is an example of the seismic hazard event sequences that could occur. Each branch of the tree represents a possible scenario that could occur within a study area or could be experienced at a given site. The probability that a given sequence would occur is simply the product of the probabilities along the branch. Since each event is typically defined by a number of discrete values, the actual number of branches (scenarios) is far more than shown in the figure.

Table 1

Multi-Hazards Considered in this Work

Initiating Event	Hazard Order*		
	First	Second	Third
Earthquakes	Ground Shaking	Liquefaction	
		Dam Failure**	Flooding
		Landslide	Dam Failure, Flooding
			Reservoir Waves
			Natural Dam Formed
	Fault Offset	Dam Failure	Flooding
Floods	Flooding (depth and velocity of water)	Dam Failure	Flooding
		Erosion	
Landslide/ Debris Flow	Massive Earth Movement	Reservoir Waves	Dam Failure
	Natural Dam Formed	Dam Failure	Flooding
Dam Failure	Flooding		

*Fourth and higher order hazards are not shown.
**Dam failure could be caused by liquefaction, which would in turn be the result of strong ground shaking.

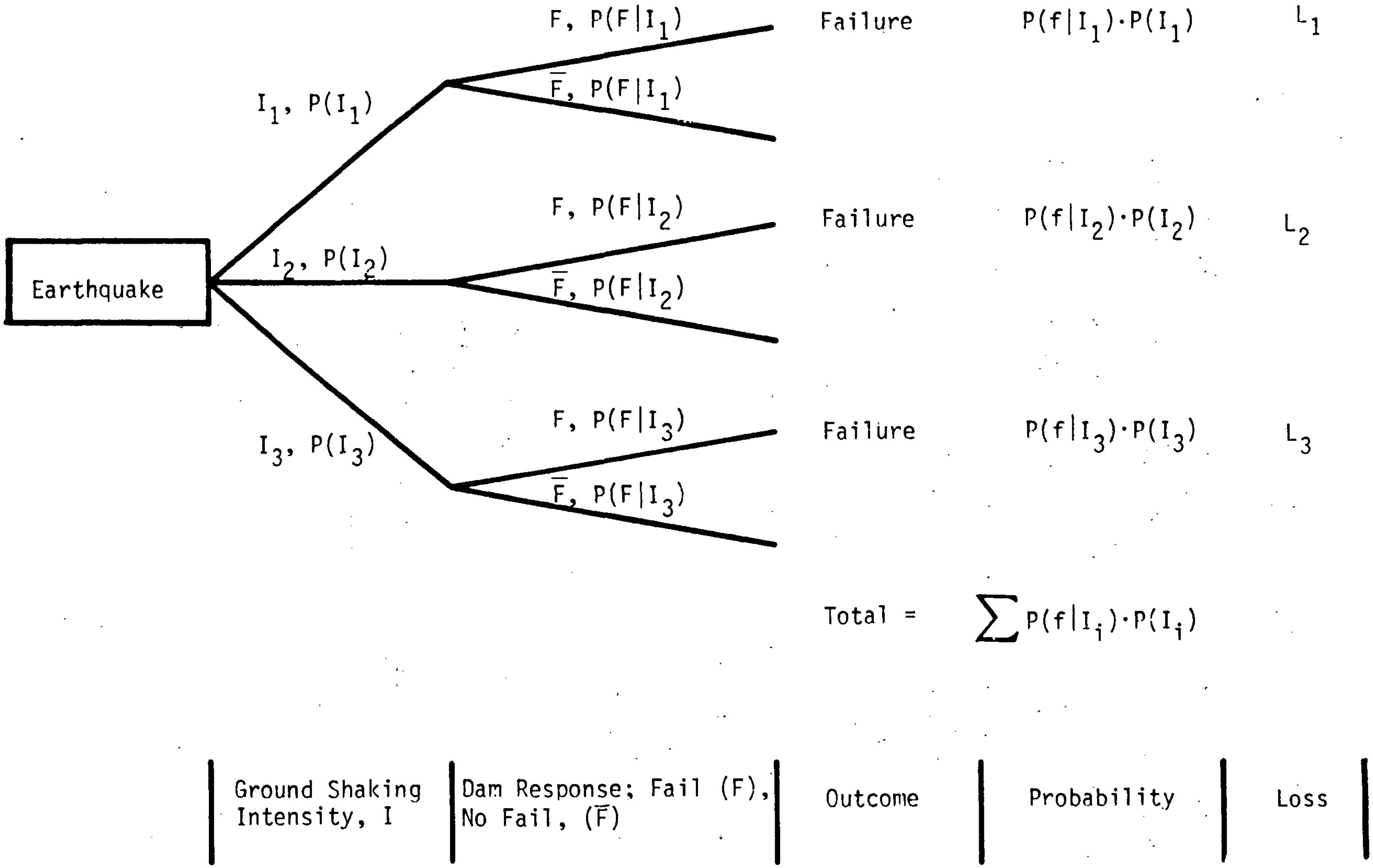

Figure 2 An example illustration of an event tree approach to evaluate the probability of an event sequence.

Exposure

For a prescribed study area, an inventory is required to identify the type, number and location of each element at risk (e.g., property, population). The development of an accurate and complete inventory of the elements at risk is an important phase of the risk assessment. In order that pertinent information be collected, the inventory system should be developed in consultation with the risk analyst and the appropriate experts to ensure completeness. Generally, the step of establishing the inventory system would be performed once, with the exception of possible modifications when applied to a new region or when additional hazards are considered.

Vulnerability Assessment

The vulnerability assessment task is concerned with the evaluation of the likelihood and degree of damage to structures and systems exposed to the variety of hazards considered in the multi-hazards analysis. Also included in this phase of the analysis is the estimation of casualties.

Structure and Component Fragility

Each hazard type imposes on the structures and systems in the vicinity where it occurs some form of external load. Depending on the severity of the applied loads and the capacity of the element being challenged, some degree of damage may be experienced. There are, however, a number of uncertainties involved in assessing the damage to structures. For example, an assessment of the damage to a building exposed to the strong shaking of an earthquake is uncertain because of unknown design and construction irregularities, variability in the strength of construction materials, uncertainty in predicting the actual response of a structure to the violent shaking induced by an earthquake, among other reasons. Although it is difficult to predict the precise level of strong shaking at which damage or failure would occur, it is possible to define a range over which it is likely to take place. Within this range, the assessment of the likelihood of failure or damage increases from a probability of zero (e.g., no chance of damage) to a probability of one (e.g., certain failure). The relationship which describes the probability of failure at various hazard levels is known as a fragility curve. A fragility curve can be defined for structures exposed to ground shaking, flooding, landslide, or any other hazard. A graphic illustration of a fragility curve is given in Figure 3.

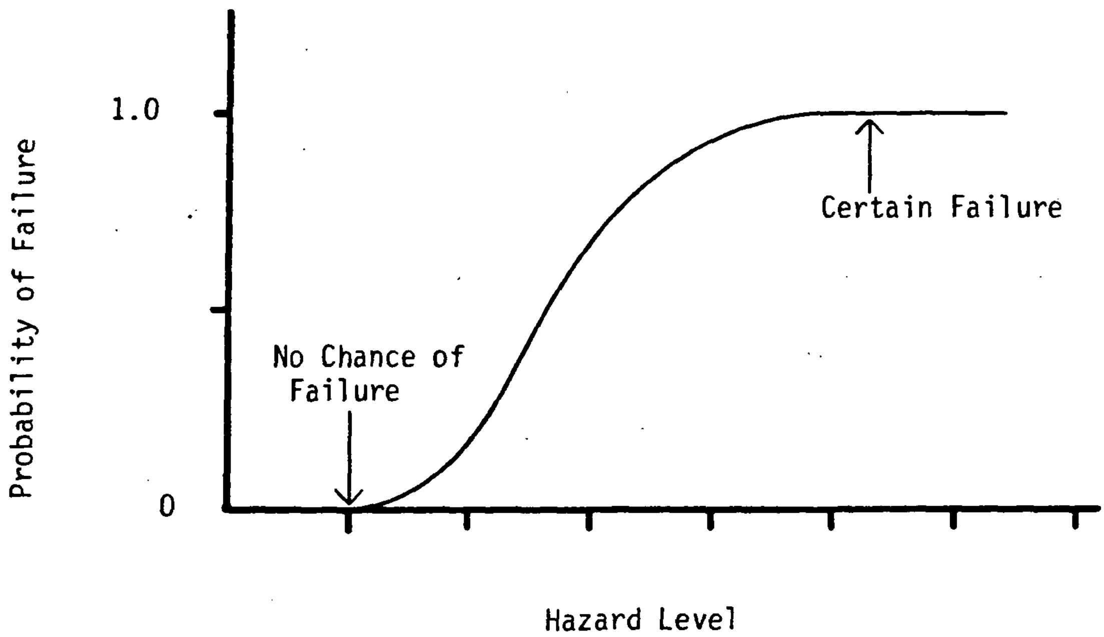

Figure 3 An example of a fragility curve that is defined for each structure and system type exposed to a given hazard.

For the purpose of emergency management planning, fragility curves can be used in conjunction with estimates of the severity of each hazard to predict the probability that a structure will fail or the degree of damage that it is likely to sustain.

Commonly, fragility curves assume that a structure, component or system is in one of two possible states--either completely failed or not failed. In many cases, this distinction is appropriate. However, in some cases damage may occur in varying degrees from no damage to collapse or complete failure. For each hazard and structure type considered, the number and definition of each damage state must be established. An important step in this consideration is to define the damage level at which a loss of function occurs. It is of critical importance in emergency planning to quantify the availability of services, shelter, and transportation routes when a disaster occurs. In many cases, unavailability may occur at a damage level considerably less than complete collapse, and therefore loss of function is more likely to occur than collapse.

For use in risk assessment studies designed to provide input to emergency management planning, it is neither practical nor necessary to develop fragility curves on a structure-by-structure basis. That is, it is not appropriate to develop a fragility curve for every single-family residence exposed to earthquake ground shaking. Rather, it is adequate to have a generic curve for each structure type. This limits the number of fragility curves required, to the number of structure types in the study area. In the case of critical facilities, it may be appropriate to develop structure-specific fragility curves.

Assessment of Casualties and Homeless

An evaluation of the number of casualties due to a major disaster depends on a number of factors including the type of hazard, time of year, time of day, whether a warning system exists, the population distribution with respect to hazards that may result in loss of life (e.g., earthquakes, floods), and the type of structures that house people. Other factors include the fraction of people that would be killed or injured given a particular hazard. Some of the considerations listed above involve the inherent randomness of when a disaster is likely to occur, while others are the result of uncertainties in predicting the outcome of events. In this phase of the risk assessment, the major sources of uncertainty in estimating the potential casualties are considered. Table 2 summarizes the random variables that should be taken into account in the estimation of the number of casualties in the event of a major disaster.

Table 2

Random Variables in the Estimation of Casualties

Variable	Sources of Uncertainty
Time of year	Transient versus permanent population
Time of day	Population distribution during work or commuter hours versus the time in residence
Estimation of the fraction killed	Uncertainty due to the inexactness of methods/information to predict the number of people killed in a major disaster
Estimation of the fraction injured	Uncertainty due to the inexactness of methods/information to predict the number of people injured in a major disaster
Warning and warning systems	In the case of some hazards such as floods and dam failures, some warning to evacuate may be available; if a warning system exists, there is uncertainty as to its effectiveness

To quantify the likelihood and number of casualties, Figure 4 presents an example using an event tree to display the various random events that influence the estimate of casualties. Note that from each hazard type, the number of factors included in the analysis and the method of estimating the number of casualties will differ.

To evaluate the number of people left homeless after a major disaster also depends on a number of factors. Among them are the time of year, type of hazard, type of construction of single-family residences, apartment buildings, etc., and availability of utilities (e.g., gas, electricity) following the disaster. The assessment of the numbers of homeless can be performed in much the same way as the analysis for the number of casualties. The use of data from past disasters is also a useful way to calibrate a model.

Risk Quantification

In this phase of the risk analysis, the individual components of the analysis are combined, to probabilistically quantify the consequences to each initiating event. A generic list of the type of results that can be assessed is given along with a brief discussion of the format for quantifying them.

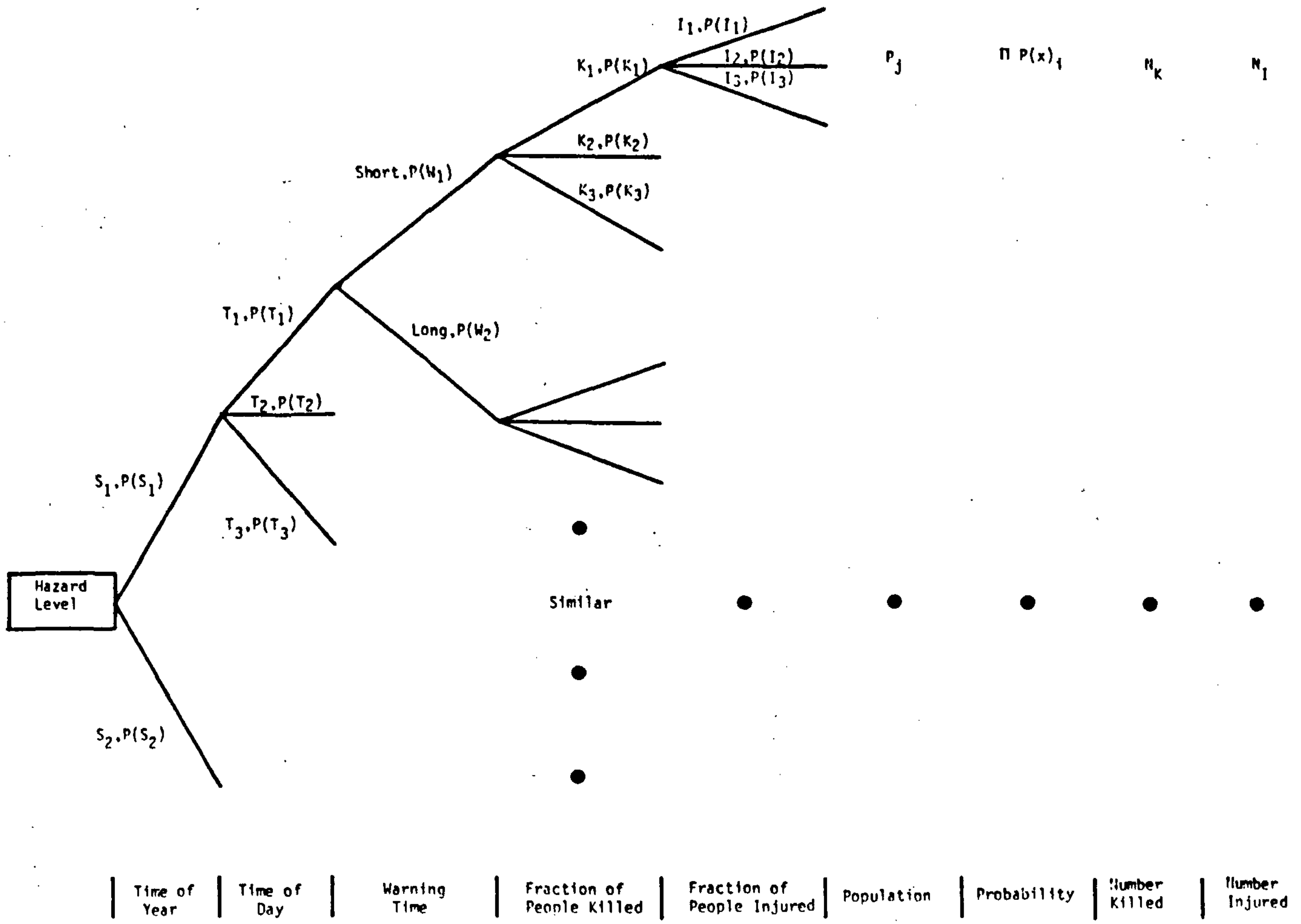

Figure 4 An example of the procedure to estimate the probability distribution on the number of deaths in the event of a major disaster.

In order to effectively plan for a major disaster, answers to a number of questions are required. Among them are:

- How many casualties will there be? How likely is it to occur?

- How many people will require shelter?

- What will the availability of medical services be (e.g., hospitals, beds, doctors, nurses, etc.)?

- What modes of transportation will be available?

- Will public services such as police and fire be operational?

- Will lifeline systems such as water and electricity be available? Where?

From questions such as these, a list of the information required for emergency planning can be established. However, as expressed previously, there are a number of uncertainties involved in estimating the consequences of a major disaster. Therefore, it is generally not possible to provide a single answer to these questions. Instead, the range of hazard/consequence scenarios is considered to estimate the distribution on the possible consequences. Table 3 summarizes the type of results provided by the risk analysis.

Table 3

Partial List of Information and Format of Results Provided by a Risk Analysis

Factor	Result
Casualties	
- Deaths - Injuries - Homeless	Probability distribution on the number in each category
Medical Services	
- Hospitals	Probability that any or all hospitals will be functioning
- Medical Staff	Probability that an adequate staff will be available
Transportation	
- Highways - Railroads - Airports - Ports	Probability that critical transportation routes will be available
Shelters	Probability distribution on the number of people who could be sheltered

SUMMARY

Guidelines for conducting a probabilistic risk assessment for application in multi-hazards emergency management planning were presented. The results of a probabilistic analysis offer the emergency planner a two-dimensional view of the potential impact of a major disaster, providing a measure of the magnitude of the consequences of individual scenarios and their likelihood of occurrence. In a similar manner, the degree and likelihood that emergency services will be available in the period immediately following the disaster are assessed. With this type of input, an emergency manager is in a position of knowing what the likely, as well as incredible or worst case consequences are, thus avoiding overly conservative assessments of the need for emergency services. Given the formal, systematic approach of a probabilistic procedure, the relative contribution of any aspect of the risk analysis can be determined and the level of improvement of proposed mitigation measures can be easily assessed.

NEAR-SOURCE ATTENUATION OF STRONG GROUND MOTION FOR MODERATE TO LARGE EARTHQUAKES—AN UPDATE AND SUGGESTED APPLICATION TO THE WASATCH FAULT ZONE OF NORTH-CENTRAL UTAH

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ABSTRACT

The near-source scaling relationships for peak horizontal acceleration and velocity developed previously (Campbell, 1981a, 1982, 1983) have been revised to incorporate the results of further investigations into the near-source characteristics of strong ground motion. Although preliminary in nature, these revisions are significant enough to warrant presentation at this time in hopes that they will stimulate further discussion and research on this important issue. Major revisions have included changes in the definition of source-to-site distance and in building size and embedment variables, as well as the way in which local site geology is treated. These preliminary results indicate that both peak acceleration and peak velocity become independent of earthquake magnitude (i.e., saturate) at the source of an earthquake, consistent with some geophysicists' interpretations of rupture mechanics. Although preliminary, the scaling relations are considered stable enough to warrant their use in estimating strong ground motion for the near-source region of moderate-to-large earthquakes on the Wasatch fault zone of north-central Utah for purposes of zoning or planning.

INTRODUCTION

Previous studies (Campbell, 1981a, 1982, 1983) have investigated the near-source scaling characteristics of peak ground motion parameters through the relationship

$$\ln Y = a + bM - d \ln [R + c_1 \exp(c_2 M)] + \Sigma e_i K_i + \varepsilon \qquad (1)$$

where Y is the peak ground motion parameter to be predicted, M is magnitude defined as M_L for M<6.0 and M_s for $M \geq 6.0$, R is shortest distance between the recording site and the fault rupture surface, K_i is a set of variables representing the effects of fault mechanism, building embedment, etc., and ε is a random error term with mean of zero and standard deviation equal to the standard error of the regression. The data base was comprised of strong motion data recorded within 50 km of a set of worldwide earthquakes with $M \geq 5.0$. The coefficients a through e were determined from weighted nonlinear regression analysis, where weights were used to control the influence of well-recorded earthquakes.

While only minor revision of the data base used previously has been made, further investigations have indicated that several of the variables require modification to better represent the near-source characteristics of peak ground motion parameters. These modifications are summarized below.

Distance.--The distance measure used previously was defined as the shortest distance between the recording station and the fault rupture surface. The upper boundary of rupture was defined by the fault trace if surface rupture occurred or by the aftershock zone if no surface rupture was observed. While this distance measure was found to be superior to either epicentral or hypocentral distance in modeling the near-source attenuation characteristics of strong ground motion for moderate-to-large earthquakes (Campbell, 1981b), its application to predicting ground motion from earthquakes of magnitude 5.5 and greater is complicated by ambiguity as to the appropriate value for the depth to rupture. For very small earthquakes one can reasonably assume that fault rupture is restricted to the basement rock beneath the sediments. However, for events of $M \geq 5.5$, rupture may or may not propogate into the sedimentary deposits. Even for larger earthquakes for which rupture clearly extends to the ground surface, it is unlikely that the small stresses associated with rupture within the sediments can contribute any substantial energy to ground motions recorded at the surface of the earth.

Taking this into consideration, the distance measure was revised to more closely represent the distance to that part of the rupture surface believed to contribute significantly to the strongest shaking recorded at a site. This revised distance is defined as the shortest distance between the site and the seismogenic zone of rupture, determined from either the depth of aftershocks associated with an earthquake or the depth to basement rock. With this new definition, rupture within the sediments is not considered to be seismogenic unless it is associated with aftershocks, and thus, is neglected in measuring distances to the fault rupture zone. Use of this revised distance measure was found to reduce the standard error of the regression for peak horizontal acceleration.

Site Geology.--Previously we found that shallow soil sites, sites with 10 m or less of fill or soil over rock, were associated with higher accelerations than either deeper soil sites or rock. Once these sites were removed, no significant difference was found in accelerations recorded on soil or rock. A preliminary analysis of peak velocity indicated that basement rock sites were associated with velocities approximately 50 percent less than soil sites and that shallow soil sites behaved as rock sites.

Because of complexities such as surface topography associated with the locations of many of the rock sites in the data base, it was decided that the revised analyses should include only soil sites. This restriction eliminated only a small percentage of the sites, mostly those located on the abutments of dams where there is a potential for substantial modification of the ground motion by ground topography and response of the dam. Having removed rock sites, it was found that peak horizontal velocity was significantly influenced by the depth of the sediments beneath the site. Velocities were found to increase with sediment depth up to a depth of approximately 4 or 5 km after which little additional increase was observed. This effect has been reasonably modeled with a hyperbolic tangent function. A similar dependence on sediment depth was observed for moderate-to-low frequency components of Fourier amplitude spectra by Trifunac and Lee (1978), while Joyner et al. (1983) have attributed this possible depth dependence to differencers in the propagation velocity of shear waves within the sediments.

Building Effects.--In the previous analyses, instruments located in the basements of large embedded buildings (buildings three stories or greater in height) were found to be associated with peak horizontal accelerations approximately 24 percent lower than non-embedded instruments. Instruments in the basements of embedded buildings less than three stories in height were found to be associated with accelerations approximately 11 percent lower than non-embedded instruments. Large buildings, whether embedded or not, were found to have peak horizontal velocities approximately 20 percent higher than small buildings and freefield sites.

Further investigations on peak horizontal acceleration have indicated that the effect of building embedment is distance dependent, with reductions in acceleration due to embedment decreasing with increasing distance. This apparently reflects a shift in frequencies associated with peak acceleration to lower predominant frequencies as distance increases. In addition, this effect was found to be a function of building size, with buildings of ten stories or greater having larger reductions at all distances as compared to three to nine story buildings. Instruments in basements of buildings less than three stories high were not observed to have accelerations significantly lower than non-embedded instruments. Because the observed reductions were found to decrease more rapidly with distance at short distances and approach some limiting value at larger distances, a hyperbolic tangent function was used to model these embedment effects.

Further investigations on peak horizontal velocity indicate that building size affects the rate at which velocity increases with sediment depth. Larger buildings (buildings greater than four stories in height) exhibit velocities that increase faster with depth than smaller buildings and freefield sites. However, for depths greater than about 5 km, for which the effect of sediment depth remains relatively constant, the larger buildings exhibit peak velocities only about 10 percent larger than other recordings. This difference may reflect the effects of soil-structure interaction as it relates to the fundamental frequencies of the structure and the ground motion.

Source Directivity.--While the effects of source directivity have not been fully investigated, a few sites exhibited such strong amplification effects for peak velocity that their observed values fell more than four standard errors above their median predicted values. These sites were all located on deep sedimentary deposits and situated along the direction of unilateral fault rupture. This apparently represents an extreme directivity effect. This bias was so severe that these sites had to be represented by an additional scaling variable in the regression analysis to control their influence on the other variables. While not as strong, a similar effect was found for peak horizontal acceleration.

GROUND MOTION MODELS

The weighted nonlinear regression analysis technique described by Campbell (1981a) was used to establish the coefficients $\underline{a}$ through $\underline{e}$ and ε in Equation (1) for both peak acceleration and peak velocity. For peak horizontal acceleration (PHA), the resulting scaling relationship is given by the expression

$$\ln PHA = -2.817 + 0.702M - 1.20 \ln [R + 0.0921 \exp(0.584M)] + \Sigma e_i K_i \quad (2)$$

where PHA is the mean of the two horizontal components of peak acceleration in units of g (fraction of gravity). The coefficients e_i are given in Table 1. The standard error associated with this relationship is 0.30, representing an 84th-percentile value of PHA that is 35 percent higher than the median.

For peak horizontal velocity (PHV), the resulting scaling relationship is given by the expression

$$\ln PHV = -0.798 + 1.02M - 1.26 \ln [R + 0.0150 \exp(0.812M)] + \Sigma e_i K_i \quad (3)$$

where PHV is the mean of the two horizontal components of peak velocity in cm/sec and the coefficients e_i are given in Table 2. The standard error associated with this relationship is 0.26, representing an 84th-percentile value of PHV that is 30 percent higher than the median.

TABLE 1
Summary of Coefficients e_i in Equation (2)
(Peak Horizontal Acceleration)

Index (i)	Variable (K_i)	Function	Coefficient (e_i)
1	Fault Mechanism	K_1=0 (Strike-slip) K_1=1 (Reverse & reverse oblique)	0.32
2	Shallow Soil	K_2=0 (Soils >10m deep) K_2=1 (Soils $\leq$10m deep)	0.41
3	Source Directivity (Deep sediments)	K_3=0 (Other rupture configurations) K_3=1 (Rupture towards site)	0.52
4	Small Embedded Building	K_4=0 (Other recordings) K_4=1 (Basements of 3-9 story bldgs.)	-0.85
5	Large Embedded Building	K_5=0 (Other recordings) K_5=1 (Basements of $\geq$10 story bldgs.)	-1.14
6	Small & Large Embedded Building (Distance Variable)	$K_6=(K_4+K_5)$ Tanh(0.068 R)	0.87

TABLE 2

Summary of Coefficients e_i in Equation (3)
(Peak Horizontal Velocity)

Index (i)	Variable (K_i)	Function	Coefficient (e_i)
1	Fault Mechanism	$K_1=0$ (Strike-slip) $K_1=1$ (Reverse & reverse oblique)	0.47
2	Source Directivity (Deep sediments)	$K_2=0$ (Other rupture configurations) $K_2=1$ (Rupture towards site)	0.95
3	Building Size	$K_3=0$ (Buildings ≥ 5 stories) $K_3=1$ (Freefield and bldgs. <5 stories)	0
4	Sediment Depth (Freefield & Small Bldgs.)	$K_4=K_3$ Tanh(0.39 D)	0.63
5	Sediment Depth (Large Bldgs.)	$K_5=(1-K_3)$ Tanh(0.75 D)	0.72

The near-source behavior of PHA and PHV is summarized in Table 3, where median values are given for fault distances of 5, 10, 25 and 50 km and for magnitudes of 5.5, 6.5 and 7.5. These values represent the ground motion recorded on a freefield instrument from a strike-slip earthquake. For PHA, the recording is that expected on a soil site, while for PHV, the recording is that expected on a deep sedimentary site (D>5 km). Table 4 gives a similar summary for a site located on basement rock. For these estimates it was assumed that near-source values of PHA are similar on soil and basement rock (Campbell, 1981a). For PHV, sediment depth was assumed equal to zero (D=0).

Equation (3) indicates that PHV attenuates more rapidly with distance than does PHA. This results in ratios of PHV to PHA that decrease slightly with distance for fixed magnitude. This trend is inconsistent with past investigations (e.g. McGuire, 1978; Joyner and Boore, 1981; Nuttli and Herrmann, 1984), but may simply be a result of statistical uncertainty in the two coefficients.

It is possible to assess the reasonableness of the predictions offered by Equations (2) and (3) by comparing them with the results of past studies. A brief comparison is presented below.

Upper bounds.--Table 4 indicates that both PHA and PHV saturate with magnitude at the fault rupture surface (R=0). As defined in this study, the fault rupture surface represents that portion of the rupture confined either to basement rock or the seismogenic zone of rupture as determined by the depth distribution of aftershocks. The median values of PHA and PHV saturate to values of 1.05 g and 88 cm/sec at R=0 for strike-slip faults and to values of 1.45 g and 140 cm/sec for reverse and reverse-oblique faults. These values may be compared with geophysical estimates of acceleration and velocity obtained from an earthquake dislocation model proposed by Brune (1970). From Brune's theory, assuming a simple ramp time function for displacements on the fault, the maximum acceleration and velocity for a point near the center of the dislocation surface are given by the expressions

$$v_{max} = k_v \beta \frac{\sigma}{\mu} \qquad (4)$$

TABLE 3

Median Predictions of Peak Horizontal Ground Motion for Freefield Soil or Deep Sediment Recordings of a Strike-Slip Earthquake

Distance(b) (km)	Magnitude (M)	PHA (g)	PHV (cm/sec)	PHV/PHA (cm/sec/g)
5(0)	5.5	0.26	23	88
	6.5	0.41	47	115
	7.5	0.57	81	142
10(9)	5.5	0.14	11	79
	6.5	0.24	26	108
	7.5	0.38	52	137
25(24)	5.5	0.054	3.8	70
	6.5	0.10	9.7	97
	7.5	0.18	23	128
50(50)	5.5	--(a)	--(a)	--(a)
	6.5	0.047	4.3	91
	7.5	0.089	11	124

(a) There is no data at this distance.

(b) Distance to the seismogenic zone of rupture. Value in parentheses represents the corresponding distance to the surface trace of a vertical fault with 5 km of sediments.

TABLE 4

Median Predictions of Peak Horizontal Ground Motion for Freefield Basement Rock Recordings of a Strike-Slip Earthquake

Distance[(b)] (km)	Magnitude (M)	PHA (g)	PHV (cm/sec)	PHV/PHA (cm/sec/g)
0	5.5	1.05	88	84
	6.5	1.05	88	84
	7.5	1.05	88	84
5(0)	5.5	0.26	12	46
	6.5	0.41	25	61
	7.5	0.57	43	75
10(9)	5.5	0.14	5.8	41
	6.5	0.24	14	58
	7.5	0.38	28	74
25(24)	5.5	0.054	2.0	37
	6.5	0.10	5.1	51
	7.5	0.18	12	67
50(50)	5.5	--(a)	--(a)	--(a)
	6.5	0.047	2.3	49
	7.5	0.089	5.8	65

(a) There is no data at this distance.

(b) Distance to the seismogenic zone of rupture. Value in parentheses represents the corresponding distance to the surface trace of a vertical fault with 5 km of sediments.

$$a_{max} = k_a \, f \, \beta \, \frac{\sigma}{\mu} \quad (5)$$

where β is shear-wave velocity, σ is dynamic stress drop, μ is shear modulus, f is frequency, and k_a and k_v are constants.

The empirical estimates of acceleration and velocity at R = 0 are extrapolations from recordings obtained at the surface of the earth. Therefore, they include such factors as source directivity, radiation pattern, free surface effects, and partitioning of the energy between the two horizontal components. Accounting for the mean effects of these factors gives $k_a = 1.7$ and $k_v = 1.3$. The acceleration constant does not include the effects of directivity, however, which are not expected to be important for frequencies above about 5 Hz. Letting $\beta = 3$ km/sec (3×10^5 cm/sec), $\mu = 3 \times 10^{11}$ dyne/cm^2, $\sigma = 100$ bars (10^8dyne/cm^2), and f = 5-10 Hz as suggested by Brune (1970), Equations (4) and (5) give values of $V_{max} = 130$ cm/sec and $a_{max} = 0.85$-1.7 g. These estimates are remarkably consistent with those obtained from Equations (2) and (3). The Hanks and McGuire (1981) finding that σ is essentially independent of earthquake size indicates that v_{max} and a_{max} are also independent of earthquake size. This lends geophysical support to the results of the regression analysis which require that PHA and PHV be independent of magnitude at R = 0.

Magnitude Scaling.--The magnitude dependence of PHA and PHV at far-source distances is given by the coefficient b in Equation (1). Equations (2) and (3) indicate this magnitude coefficient to be 0.70 and 1.02 for PHA and PHV, respectively. These coefficients may be compared directly with values of 0.89 for PHA and 1.07 for PHV as determined by McGuire (1978) and with values of 0.58 and 1.13 determined for PHA and PHV by Joyner and Boore (1981). From spectral scaling studies, Nuttli and Herrmann (1984) established theoretical m_b magnitude scaling coefficients for PHA and PHV, assuming predominant frequencies of 5 and 1 Hz, respectively. Since their values represent m_b, they cannot be directly compared to the coefficients of Equations (2) and (3). However, they do give a relationship between m_b and M_s which may be used to convert their coefficients to a more compatible scale (Nuttli and Herrmann, 1982). So doing, their theoretically derived magnitude coefficients are 0.58 and 1.15 for PHA and PHV, respectively. Considering our restriction to near-source recordings, the far-source magnitude scaling characteristics of Equations (2) and (3) are quite consistent with those proposed by these other investigators.

The near-source magnitude scaling characterisitics of Equations (2) and (3) cannot be compared with either of the previously referenced studies. McGuire as well as Joyner and Boore assumed magnitude scaling to be independent of distance, thereby imposing a constraint on the near-source behavior of their relations. In addition, McGuire used hypocentral distance and Nuttli and Herrmann used epicentral distance as their measures of distance, measures found to result in substantially different near-source magnitude scaling characteristics than the fault distance measure used in this study (Campbell, 1981b). These differences also make it difficult to compare the near-source distance attenuation characteristics of the various relationships.

Site Geology.--Table 2 indicates that PHV is strongly affected by the depth of the sediments beneath the site. Deep sites were found to be associated with velocities approximately 88 percent higher than sites underlain by very shallow sediments. While Trifunac and Lee (1978) have found a similar depth dependence for Fourier amplitude spectra, no similar study is available for PHV. We can, however, roughly compare differences in PHV between soil and rock established by other investigations with the results of this study. For example, Joyner and Boore (1981) found that soil sites exhibit peak horizontal velocities approximately 50 percent higher than rock sites, while Seed and Idriss (1982) suggest differences of about a factor of two. Both results are reasonably consistent with the results of this study. McGuire (1978), on the other hand, finds that PHV is relatively independent of site geology, but the small number of rock sites in his data base makes his results for rock subject to error.

PHV/PHA ratios.--Ratios of PHV to PHA for deep sediment and basement rock sites are summarized in Tables 3 and 4. These may be compared with ratios suggested by others to assess the validity of the results. Seed and Idriss (1982) indicate that recordings obtained within 50 km of the fault are consistent with PHV/PHA ratios of 55 cm/sec/g for rock and 110-135 cm/sec/g for soil. If we approximate the conditions representative of these ratios as an average of the ratios for R=5-50 km and M=6.5-7.5 in Tables 3 and 4, then we obtain corresponding ratios of 62 and 118 cm/sec/g for basement rock and deep sediments, respectively, in close agreement with those suggested by Seed and Idriss.

Newmark and Hall (1982) suggest PHV/PHA ratios of 92 and 122 cm/sec/g for rock and soil and Mohraz (1976) finds values of 65 and 85-133 cm/sec/g for rock and alluvium, respectively. While it is not clear for which magnitude and distance ranges these values are appropriate, they are found to be in general agreement with the average values given above. Campbell (1984) has estimated the ratios of PHV to PHA for a freefield site located approximately 15 km from a 7.5 M_s earthquake by several methods and suggests ratios of 70 and 125 cm/sec/g for basement rock and soil, respectively, in close agreement with ratios given in Tables 3 and 4.

Finally, the scaling relations of McGuire (1978) may be used to estimate PHV/PHA ratios to be compared with this study. Using R=25 km and M=6.5 as a means of comparison (this is near the centroid of data used in this study), McGuire's predictions give a ratio of 100 cm/sec/g for sites founded on soil, whereas this study (Table 3) gives a ratio of 97 cm/sec/g. Using R=40 km and M=6.0 as a means of comparison (this is near the centroid of the data used by McGuire), the ratio from McGuire's relations is again 100 cm/sec/g for soil sites, while that estimated from Equations (2) and (3) is 79 cm/sec/g. Again, the two studies are found to be in reasonably good agreement. Because of the limited number of rock sites in McGuire's data set, ratios for rock are considered unreliable and no comparisons were made.

CONCLUSIONS

Strong-motion data recorded on soil sites in the near-source region of moderate-to-large earthquakes have been used to update scaling relations for peak horizontal acceleration and velocity. These models may be used to predict ground motion parameters from earthquake magnitude, distance to the seismogenic zone of rupture, and other source, site and structure variables. For peak acceleration, such variables as fault mechanism, source directivity, building size, and instrument embedment are found to be important. For peak velocity, important variables are fault mechanism, source directivity, building size, and depth to basement rock. Regression analyses indicate that both acceleration and velocity are independent of magnitude at the source of $M \geq 5.0$ earthquakes, attaining median values of 1.05-1.45 g for peak horizontal acceleration and 88-140 cm/sec for peak horizontal velocity, depending on fault mechanism. These values are found to agree with geophysical estimates obtained from a simple model of rupture mechanics.

A comparison of this study with the results of other recent investigations indicates that the scaling relations developed in this study are quite consistent with these other studies with respect to magnitude scaling, site geology, and ratios of velocity to acceleration. One area of disagreement involves the relative attenuation rate of peak acceleration and peak velocity. Although not statistically significant, this study has found acceleration to attenuate at a slightly lower rate than velocity, whereas other recent studies have found velocity to attenuate at either the same or at a slightly lower rate than acceleration at similar distances.

Because of the provisional nature of the distance and sediment depth data used in this study, the scaling relations presented in this paper are subject to some revision in the future. However, no substantial modification is anticipated and any revision would probably be no greater than that resulting from a periodic revision of the relations as new earthquake data become available.

RECOMMENDATIONS FOR APPLICATION TO THE WASATCH REGION

The scaling relations presented in this paper are believed to be generally applicable to the prediction of ground motion parameters in the near-source region of moderate-to-large earthquakes associated with the Wasatch fault zone. The attenuation characteristics of the northcentral Utah region have been found to be similar to that of California (King and Hays, 1977; McGuire, 1984) from which the majority of the strong-motion recordings used in this study have come. In any event, differences in anelastic attenuation are not important at these near-source distances.

Of some concern is the fault mechanism of earthquakes on the Wasatch fault zone. Geologic investigations indicate that the predominant mode of faulting is normal or normal-oblique. McGarr (1982) suggests from stress considerations that such events are associated with lower amplitudes of ground motion than those from strike-slip faults, and still even lower amplitudes than those from reverse or thrust faults. This study offers empirical justification for differences in the later two fault mechanisms (strike-slip versus reverse), but the current data are not sufficient to empirically establish differences between normal mechanisms and either strike-slip or reverse mechanisms. This will have to await the addition of normal fault recordings to the data base. For the time being, it is recommended that one make predictions using a strike-slip mechanism with the understanding that these estimates may be somewhat higher than actually observed.

While rock records were specifically excluded from this study, estimates for rock may be obtained using the following guidelines. Consistent with the results of Campbell (1981a, 1983, 1984) and Joyner and Boore (1981), freefield predictions of peak horizontal acceleration for rock may be assumed to be equivalent to those for soil. In this case, Equation (2) should be used with K_4 through K_6 set equal to zero. For peak horizontal velocity, Equation (3) may be used for both soil and rock by using an appropriate value for D, the depth to basement rock (Table 2). Predictions for basement rock may be obtained by setting D=0. For soil and sedimentary rock sites, freefield predictions of peak velocity may be estimated by setting D equal to the depth of sediments for the site of interest, setting K_3 and K_4 equal to zero.

Since near-source scaling relations for response spectra similar to Equations (2) and (3) are not yet available, it is suggested that the relations of Joyner and Boore (1982) or the procedure recommended by Newmark and Hall (1982) for developing spectra from peak acceleration and velocity be used when estimates of pseudo-relative velocity are required. To establish the low-frequency portion of the spectrum using the Newmark-Hall procedure, an estimate of peak horizontal displacement (PHD) will be required. Using the recommendation of Newmark and Hall, this parameter may be estimated from peak acceleration and velocity from the dimensionless ratio $(PHA \cdot PHD)/(PHV)^2$.

Newmark and Hall (1982) suggest a value of 6.0 for this ratio, independent of site geology, whereas Mohraz (1976) suggests values of 4.0 for alluvium and 5.0 for rock.

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AN EFFORT TO DETERMINE POISSON'S RATIO IN SITU FOR NEAR-SURFACE LAYERS

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INTRODUCTION

Intensity of ground shaking during an earthquake is determined in part by local near-surface geological conditions. Intensity differences of three to four units on the MM scale at sites no more than a few kilometers apart have been well established for nearly a century (Lawson et al., 1908). Because of these differences, prediction of individual site response is an important part of earthquake hazard reduction.

To help with urban earthquake hazard evaluation, we are developing and testing shallow P- and S-wave reflection techniques that will allow direct in situ measurement of engineering properties of materials within a few hundred feet of the earth's surface. Medvedev (1965) showed that seismic shear impedance (the product of density and S-wave velocity) can be used to make estimates of relative ground response. The potential for amplification of shaking increases as the impedance contrast between layers increases, provided other parameters are constant.

It is rapidly becoming feasible to produce shallow P-wave and S-wave reflection profiles along the same surface line. This will allow interpretation of far more geological information than use of P-waves or S-waves alone. In addition to determination of velocities, it will be possible to determine Poisson's ratio as a function of depth.

Techniques

Seismic reflection techniques have been used in petroleum prospecting for about a half century. Although examples are occasionally cited in the literature, shallow reflection techniques in engineering and groundwater applications have met with only limited success, because of the difficulty encountered in identifying reflections from layers at shallow depths. The shallowest reflections (other than our work) documented in the literature appear to be those at 30 meters by Hunter et al. (1981). The amplitudes of the reflected waves at commonly recorded frequencies, when present, are smaller than the amplitudes of unwanted waves, particularly ground roll composed of Rayleigh waves and Love waves. Furthermore, the generation and recording of frequencies much above 100 Hz has not been possible on land, or at least has not been adequately recorded in the literature.

Typical energy sources that have been tried include sledge hammer (Hunter et al., 1981, and Meidav, 1969), weight drop (Doornenbal and Helbig, 1983), and small explosive charges (Pakiser and Warrick, 1956). These energy sources produce seismic waves with dominant frequencies of less than 100 Hz. In order to provide better resolution (both precision and accuracy) of shallow reflective interfaces, high frequencies are needed. Since direct resolution of "thin beds" is practically limited to about 1/4 wavelength of the seismic energy (Widess, 1973), the improvement in resolution (and imaging of shallower reflectors) can be obtained directly by increasing the frequency of the energy that is recorded.

A worthy goal of shallow reflection surveys is to provide bed resolution in the approximate dimension of one foot. Typical velocities of near-surface soil and/or alluvial materials range from about 1000 to about 4000 per second. Using the 1/4 wavelength criterion, we can obtain the dominant P-wave frequency needed from the fact that velocity is directly proportional to both wavelength and frequency. The desired one-foot resolution cannot be obtained with a frequency less than 250 Hz for a P-wave velocity of 1000 feet/second. If the P-wave velocity is as high as 4000 feet/second, dominant frequencies higher than 1000 Hz are required for one foot bed resolution.

During the past two years, we have made substantial progress in improving shallow P-wave reflection techniques. We have been able to detect reflections in the depth range of 5 to 50 meters in alluvial valleys by using projectile impacts from ordinary hunting rifles as energy sources. We have built a gun mount that allows rifles to be safely fired vertically into the ground without danger to personnel and equipment. We have test-fired a 30.06 high-power rifle onto a one-inch thick steel plate lying on the ground beneath the mount with no escape of particulate debris. We designed, built, and tested a gun mounted at about 50° from vertical as a source of shear-wave energy in August of 1983.

FIELD EXPERIMENTS

Early in 1984, the USGS and the KGS entered into a cooperative agreement to develop capability of obtaining shallow P- and S-wave reflection data along the same seismic profile. The work discussed in the remainder of this paper reflects results of the first few months' effort on the project.

Geological Field Setting of Test Site

The area selected for our initial field experiments was examined geophysically previously by Steeples (1970) and is located in the Kansas River valley near Manhattan, Kansas. Bedrock beneath the valley fill is composed of alternating beds of Permian-aged limestones and shales ranging in thickness from a few inches to a few tens of feet. The alluvial fill is clearly of Pleistocene age and it varies in thickness from zero at the valley walls to as much as 35 meters at the deepest part of the bedrock valley.

Field Methods

We use an Input/Output, Inc. DHR 2400 seismic recording system with 24 channels to amplify, filter, and digitize the data (word size 11 bits plus sign) in the field and to record the data on digital tape. Our amplifier gains can be adjusted from 42 to 120 dB, depending upon the distance from the shot point to the geophone for the individual channels. The upper limit of amplifier gains, to avoid clipping of signal, is limited by digital word size rather than by the amplifier gains available. Our low-cut filters have 24 dB/octave rolloff to decrease the amplitude of ground roll. Data sample interval on each channel is 1/4 msec for P-wave studies and 1 msec for S-wave studies with a total record length of 1000 samples per channel. High-cut filters are used to attenuate energy at frequencies above the alias frequency.

Relatively severe low-cut filters have the beneficial effect of eliminating substantial amounts of cultural noise. Cultural noise in urban areas is relatively severe at frequencies below 50 Hz, but vehicular traffic and other vibratory noise sources do not produce much energy above 100-150 Hz. The noise that is produced at these high frequencies attenuates rapidly with distance from the source because of the low-pass nature of the earth's transfer function.

Data Processing

Data shown in Table 1 indicate the type of processing that we have applied to the P-wave reflection data. The processing is very similar to that used in the petroleum industry, except that special care is exercised in muting non-reflected energy.

S-wave processing is similar to P-wave processing, except that an extra step is added to combine two separate data sets that are obtained by our S-wave reflection field procedure (as explained later). The two data sets are differenced (multiply one set by -1 and then add) to enhance S-waves and to cancel P-waves.

ACCOMPLISHMENTS TO DATE

We have succeeded in recording P-wave and S-wave reflections along the same seismic profile near Manhattan, Kansas. A typical field record of P-wave data with no processing is shown in Figure 1. In Figure 2, a 12-fold common depth point (CDP) stack of the P-wave data is shown. Note that the prominent reflector at about 60 msec on the stacked sections (Figure 2) is also visible on the field record of Figure 1. These data were recorded with single 100 Hz geophones using 220 Hz low-cut recording filters and single 180 grain 30.06 rifle bullets fired vertically into the ground. Split spread geometry was used with geophone interval of four feet and shot point to nearest geophone distance of eight feet.

Figure 3 shows a typical field record of the S-wave reflection data. The S-wave survey was done using single 100 Hz horizontal geo-

TABLE 1

TYPICAL COMMON DEPTH POINT PROCESSING FLOW FOR

VERY SHALLOW REFLECTIONS

1) Surface statics and geometry specification

2) Editing

3) Mute first breaks and other linear arrivals

4) Sort into CDP gathers

5) Preliminary velocity analysis

6) Spectral analysis (determine bandpass)

7) Brute stack (preliminary velocity function and filtering)

8) Detailed velocity analysis

9) Determine automatic statics

10) Apply:
    a. Final velocity function,
    b. filter,
    c. correct for normal moveout, and
    d. automatic statics to the sorted data.

11) Residual statics

12) Stacked section

13) Decon. to remove multiples (if necessary)

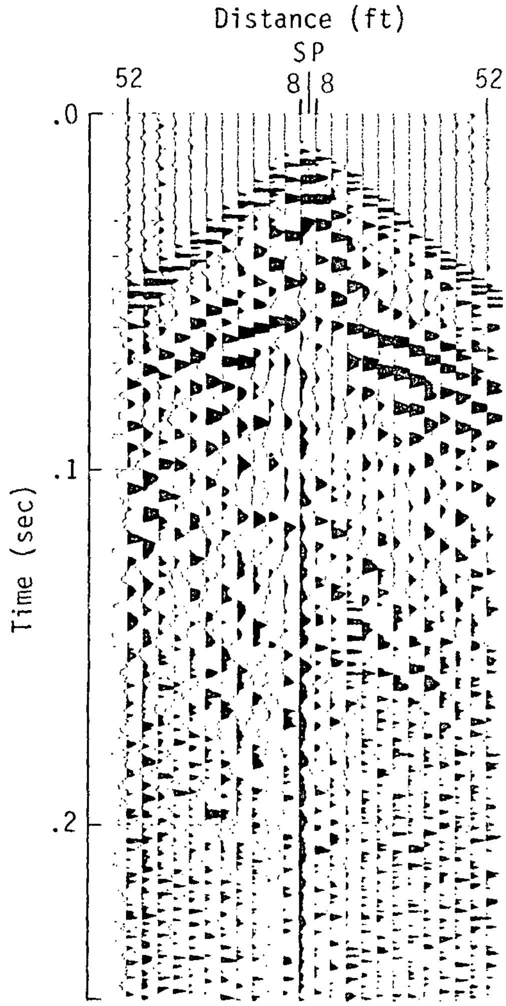

FIGURE 1.--Unprocessed seismic field record showing prominent P-wave reflection at 60 msec.

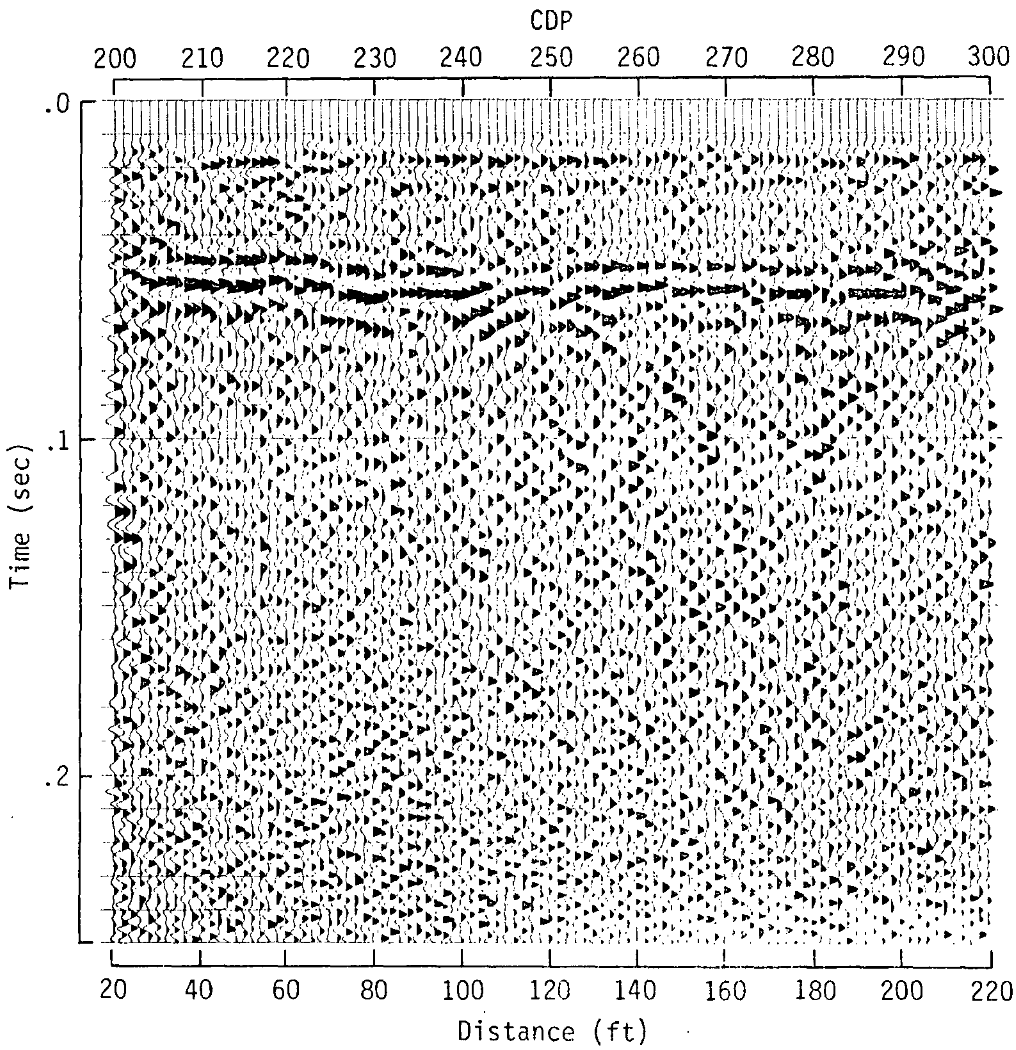

Figure 2.--Processed 12-fold CDP stack in alluvial valley near Manhattan, Kansas. Data from Figure 1 was included in this seismic section. Note prominent reflections in the 50 to 70 msec range and apparent stratigraphic variations. Dominant frequency is 150 to 200 Hz.

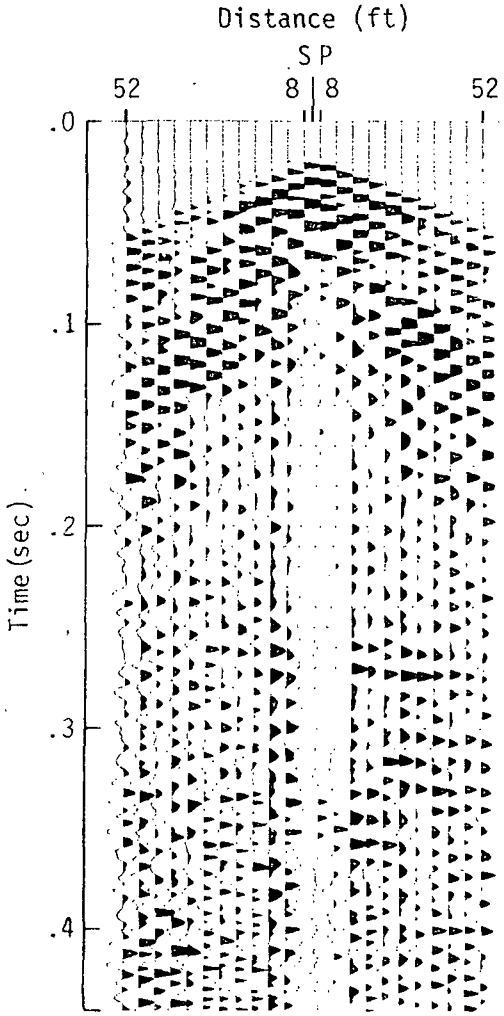

Figure 3.--Unprocessed seismic field record showing prominent S-wave reflection at 270 msec and subtle reflectors at later arrival times.

phones with identical geometry as that discussed in the previous paragraph. Source energy was obtained by firing a single 180 grain 30.06 rifle bullet into the ground at approximately a 45° angle from vertical. Figure 4 shows a 12-fold CDP stacked section of records obtained from the horizontal geophones along the same seismic profile as that shown in Figure 2.

The 100 Hz geophones that we use are omnidirectional in the sense that they are sensitive to motion along their long axis, regardless of their orientation relative to vertical. This allows the phones to be used in either the vertical mode or the horizontal mode, provided they are mounted with their long axes vertical or horizontal, respectively. We have built geophone holders that allow these geophones to be easily changed to horizontal (S-wave) mode in the field.

One might ask why we believe the data in Figure 4 to be primarily S-wave reflections. In addition to the data in Figure 4 that were obtained by shooting the rifle 45° downward pointing north, we repeated the same line shooting 45° downward pointing south (data not shown). This process should reverse polarity of the horizontal component of S-waves, but not of P-waves. The two data sets were then subtracted from one another, trace-for-trace. This procedure should tend to cancel P-waves while tending to enhance S-waves. In Figure 5, the data from this subtraction stack are shown as a "pseudo-24-fold CDP profile." Note that the data in Figure 5 show reflections somewhat better than the data of Figure 4. If the reflection events were primarily P-waves, the subtraction stack would tend to degrade rather than enhance the quality of the reflections. We therefore conclude that a substantial portion of the reflected events shown on Figures 4 and 5 is composed of S-waves.

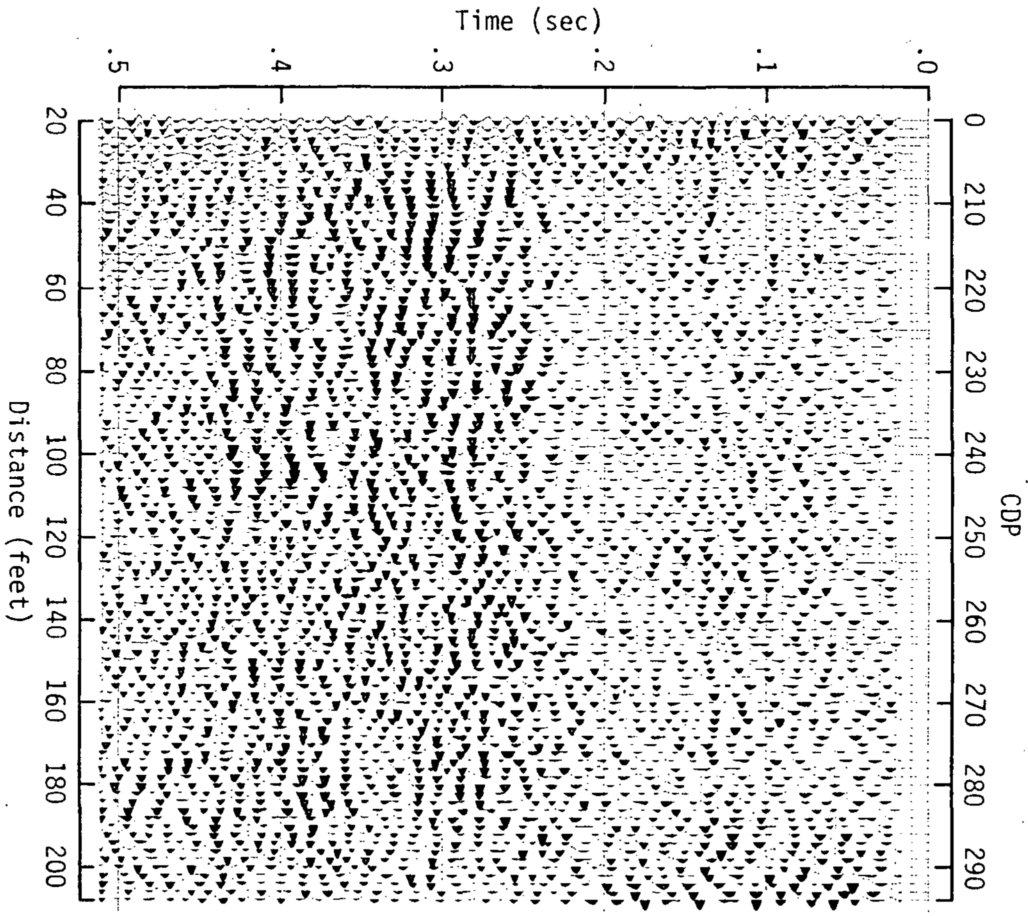

Figure 4.--Processed 12-fold CDP stack of S-wave data at same CDP points as Figure 2.

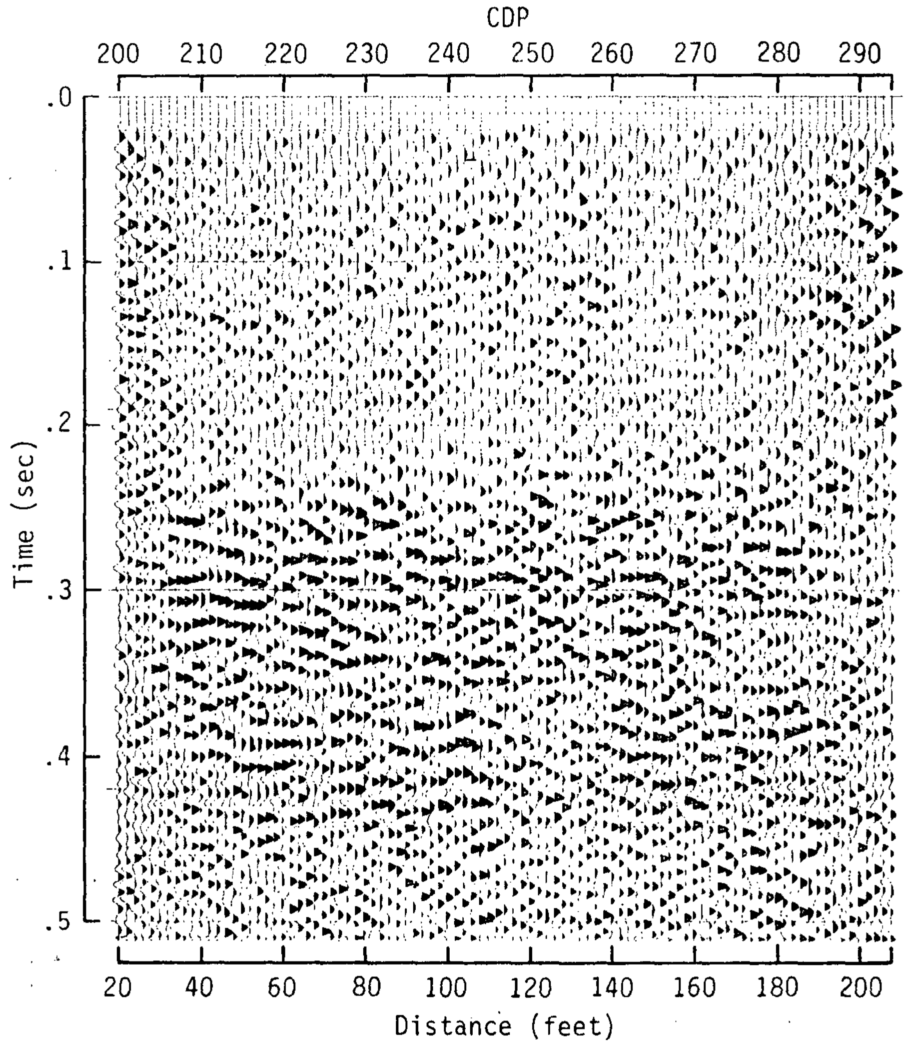

Figure 5.--Processed pseudo 24-fold CDP section obtained by subtraction stack of section in Figure 4 and data obtained at same CDP, with rifle fired in opposite horizontal direction.

Note in comparing Figures 2 and 5 (the P-wave section and the S-wave section, respectively) that the reflections come in at substantially different times (i.e. 60 msec for P vs 260 msec for S).

While the difference between P- and S-wave velocities for solid rock is roughly a factor of 2, it may approach a factor of 7 for unconsolidated materials (Hasbrouck, 1982). If the reflected energy is coming from the same horizons for both P and S, then a factor of 4 difference in P and S velocity is implied. It is not yet clear that we are observing the same horizon, but note a synform structure exists on both Figure 2 and Figure 5 between CDP's 222 and 242. This suggests that the two sections may be observing the same structure, though this conclusion is still speculative.

Field experiments have been conducted at another location in north-central Kansas, but data processing is incomplete at this writing.

RECOMMENDATIONS FOR FURTHER RESEARCH

There are several improvements in technique and additional experiments that need to be performed in order to reach our objective of in situ determination of Poisson's ratio.

1. We need to improve the accuracy of our shot time-break so that high frequency components in the data are not attenuated. This can be done by optical or opto-electronic means. We presently use a geophone attached to the rifle to provide a time-break voltage. The time-break errors of two to three milliseconds are unacceptably large.
2. The 100 Hz horizontal geophones we have been using are perhaps not of low enough frequency to obtain S-waves at some localities.

Experiments should be done with horizontal geophones in the 20 to 50 Hz natural frequency range.

3. Air blast has been a major problem, particularly with the P-wave experiments. We have built an air-blast containment device (ABCD) that eliminates at least 36 dB of air blast noise. Further development and refinement is needed, including improved portability.

4. We need to establish that the P-wave reflections and S-wave reflections are coming from the same horizon. This entails careful choice of a new experimental locality where the geologic section is extremely well known, and/or the performance of experiments such as up-hole checkshot surveys to determine both the P-wave velocity and the S-wave velocity.

5. We need to perform additional experiments to determine the important parameters of bullet selection for S-wave reflection surveys. The use of 150 grain bullets occasionally results in poor energy generation caused by lack of penetration into the earth. The bullets occasionally shatter on impact or ricochet into a steel safety plate. It is likely that the use of 220 grain bullets will alleviate much of this problem.

6. At this writing, the subtraction stack of S-wave reflections must be done in the computer processing. We are in the process of obtaining hardware to reverse polarity in the field during data recording. This will allow more flexibility in recognizing S-wave reflections on the field records.

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EXTENSIONAL AND COMPRESSIONAL PALEOSTRESSES AND THEIR RELATIONSHIP TO PALEOSEISMICITY AND SEISMICITY, CENTRAL SEVIER VALLEY, UTAH

by

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INTRODUCTION

Background: The historic seismic flux along most of the Wasatch fault zone is lower than in many of the adjacent parts of the intermountain seismic belt (Arabasz and others, 1979). It is generally not possible to correlate the sparse diffuse seismicity along the zone with the Wasatch fault (Smith, 1978; Wechsler, 1979; Arabasz and Smith, 1981) thus severely limiting the opportunity to understand the behavior of the fault. In contrast, the seismic flux is relatively high along the south-southwesterly projection of the Wasatch fault zone in the central Sevier Valley region (fig. 1). There the historic earthquake record since 1850 includes nine earthquakes of estimated magnitude 5.0 or greater and the seismicity pattern for the period July 1962-June 1978 shows concentrated activity (Arabasz and others, 1979). Because the seismic flux of the central Sevier Valley region is high relative to that of the Wasatch fault, it has attracted seismicity studies by staff and students from the University of Utah in the hope of improving understanding of earthquakes and earthquake processes in the eastern Great Basin (W. J. Arabasz, oral commun., 1981). In particular, systematic microseismicity studies were conducted intermittently in the region from 1979 through 1982 (McKee and Arabasz, 1982; McKee, 1982; Julander and Arabasz, 1982; Julander, 1983). In the vicinity of the southern termination of the Wasatch fault south of Nephi, Utah, McKee and Arabasz (1982) obtained focal mechanisms by iteratively inverting SV/P amplitude ratios. The mechanisms indicate a

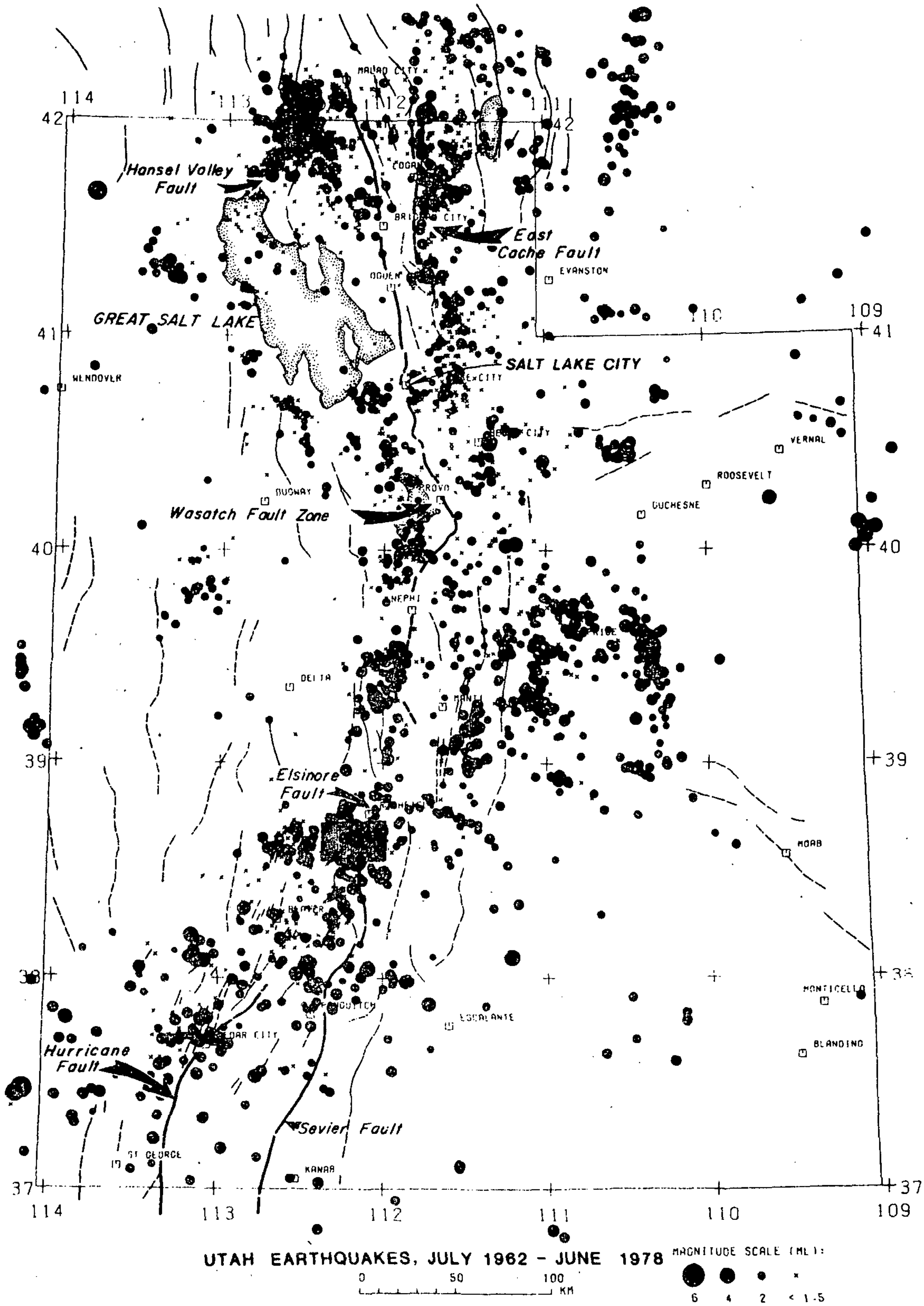

Figure 1.—Location of study area (shaded) and distribution of earthquake epicenters in Utah for the period July 1962–June 1978 (from Arabasz and others, 1979).

mixture of strike slip and normal slip on steep- to moderate-dipping planes. Fault plane solutions from the central Sevier Valley region show that current seismicity in part of the region is dominated by strike-slip (SS) events and includes some oblique-slip (OS) events to depths of 10 km. Epicentral distributions show that some of this seismicity is localized on or near major mapped faults or at places where such faults are intersected by transverse faults. Late Cenozoic SS faults had not been reported for the central Sevier Valley region so no inferences could be made relating the SS seismicity to such faulting (Julander, 1983). Although the microseismicity results do not shed much light on the expected behavior of the Wasatch fault, the occurrence of SS dominated seismicity in a region where conventional wisdom would predict normal faulting seemed worthy of geologic investigation.

Purpose: In June 1983, a systematic search for geologic evidence for SS faulting was begun. The search was successful and it is now clear that the geologic record contains abundant evidence of late Cenozoic SS faulting in the region. The purpose of this report is to present the preliminary findings.

Geologic context: The portion of the central Sevier Valley region from which fault-slip data were collected includes parts of the Pavant Range, Tushar Mountains, Antelope Range, and Sevier Plateau, all of which flank the Sevier River Valley (fig. 2). The study area lies within a zone that is transitional physiographically, structurally, and geophysically from the Basin and Range on the west to the Colorado Plateau on the east (Keller and others, 1975; Smith, 1978; Rowley and others, 1979). It is located on the northern flank of the enormous Marysvale volcanic field, which developed between about 27 and 16 m.y. ago. The faults studied cut rocks of the volcanic field as well as overlying rhyolitic ash-flow tuffs and sedimentary rocks. Fault displacements range from a few centimeters to a few kilometers. Three major

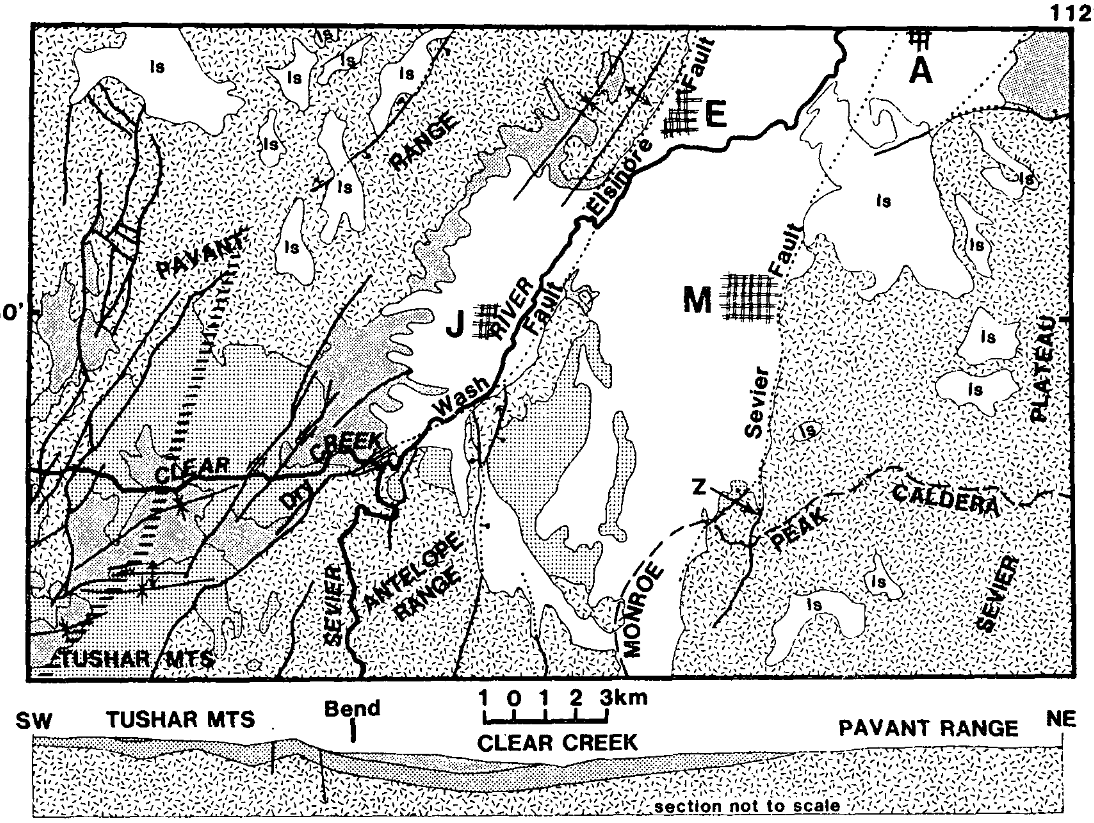

Figure 2.—Geologic map and cross sectional sketch of the central Sevier Valley area, Utah, showing the Joe Lott tuff (stippled) and underlying volcanic rocks (hachured) and overlying basin-fill sedimentary rocks (shaded). Landslide masses are labeled ls and areas of Quaternary alluvium are unpatterned. Faults and folds are shown with standard symbols. Map is generalized from Cunningham and others (1983) and Callaghan and Parker (1962). Line of hachures marks approximate line of cross section. E, Elsinore; M, Monroe; J, Joseph; A, Annabella; Z, exposure of splay of Sevier fault referred to in text.

north- to northeast-trending faults (fig. 2) were previously named and interpreted as normal faults--the Sevier, Dry Wash, and Elsinore (Callaghan and Parker, 1961, 1962; Cunningham and others, 1983). Except for the southern part of the Dry Wash fault, these faults tend to be buried by range-flanking alluvium and their slip characteristics can only be evaluated indirectly by searching for clues on small- and intermediate-scale faults in the adjacent bedrock. The three northeast-trending faults located northwest of and parallel to the Dry Wash fault (fig. 2) were mapped by Callaghan and Parker (1961) and apparently have large displacements. Several previously mapped faults of moderate displacement are also shown on figure 2, but it should be emphasized that most of the slip data on which this report is based come from small unmapped faults with displacements ranging to as much as a few meters.

Methods: In this report faults referred to as small-displacement faults have known or estimated offsets from a few centimeters to a few meters, those referred to as large-displacement faults have known or inferred displacements greater than 30 m, and the remainder are referred to as intermediate-displacement faults. Field procedure for this study consists simply of measuring the orientation of fault surfaces and movement-related striae on those surfaces and determining the slip sense for motions parallel to those striae. The data are classified according to the displacement amount and the certainty with which the sense of slip was determined. Data analysis consists of a preliminary separation into faulting mode with faults whose rake angles exceed 45^{o} separated into a dip-slip mode and those less than 45^{o} into a SS mode. Oblique-slip faults are relatively uncommon so computations can be performed without treating them separately. Paleostress computations utilizing methods similar to those described by Angelier (1979) are performed on data representing each mode; first with all measurements weighted equally and second with a weighting bias given to measurements according to the greater amount of fault displacement. None of the computations reveal significant shifts in the positions of stress axes due to weighting, indicating that the large and small faults behaved similarly during the deformation responsible for the striations. In the absence of evidence to the contrary, the striae are assumed to represent the youngest deformation on a fault. The lack of evidence that fault size influences paleostress orientations provides justification for estimating regional paleostress from fault populations that are dominated by small faults.

Data processing problems have not been fully resolved so the stress-axis orientations are reported without detailed information on their quality. They should be considered as tentative.

RESULTS

For the purpose of discussing the computational results and their relationship to mapped structures the fault-slip data are grouped into four subareas (fig. 2): (1) the west margin of the Sevier Plateau where it trends east-northeast in the Annabella area, (2) the west margin of the Sevier Plateau where it trends northerly south of Monroe, (3) the northernmost Antelope Range, and (4) the Clear Creek area which includes the Dry Wash fault and the area to the northwest of it.

Data distributions for fault strike, dip, and rake as well as for the proportion of SS to DS motion are illustrated for the four subareas in figures 3 through 6. The distributions show that in each subarea there is a mixture of SS and DS motions (figs. 5 and 6) on faults that tend to dip steeply (fig. 4). Faults in the Clear Creek subarea have conspicuously homogeneous steep dips and bimodal rakes as an excellent example of the mixture of faulting modes (figs. 4, 5,). Not only are SS faults in that subarea more numerous

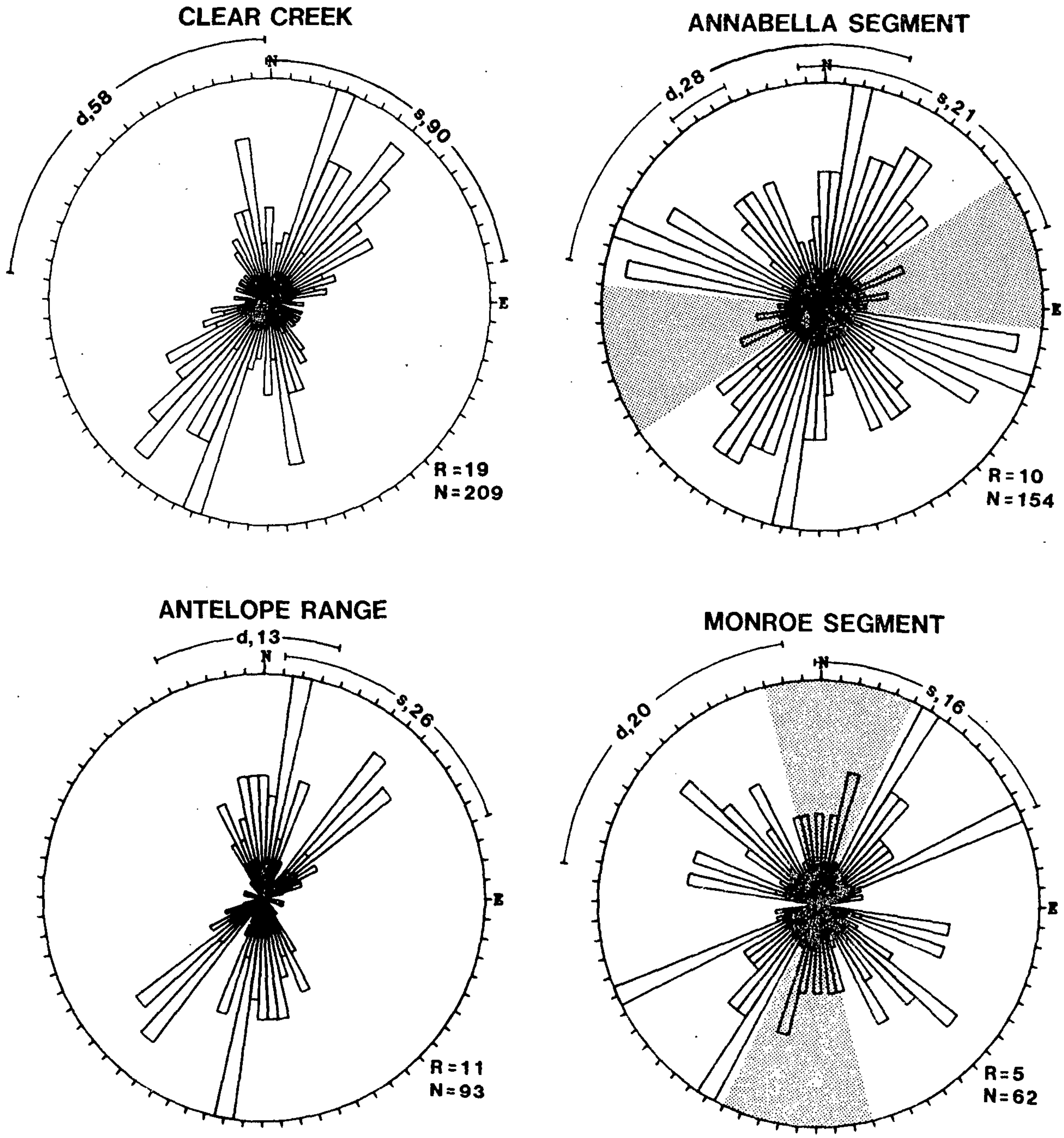

Figure 3.—Azimuthal distribution of strikes of all faults from four separate subareas. N = sample size; R = radius value of plot; d and s and the bars and numbers adjacent to them give the strike range and sample sizes of dextral and sinistral faults, respectively, using 45° as the cut-off limit for rake angles. For the Clear Creek and Monroe subareas there is no overlap in the range of strikes for dextral and sinistral faults. For the Annabella segment subarea there is some overlap and three sinistral faults have strikes well into the range for dextral faults (indicated by short bar). For the Antelope Range subarea the bars only indicate the range of strikes of most sinistral and dextral faults because 26 percent of the dextral faults fall beyond the dextral bar and 17 percent of the sinistral faults fall beyond the sinistral bar. Shaded areas show trend of margin of Sevier Plateau along the Annabella and Monroe segments (plus and minus 20°).

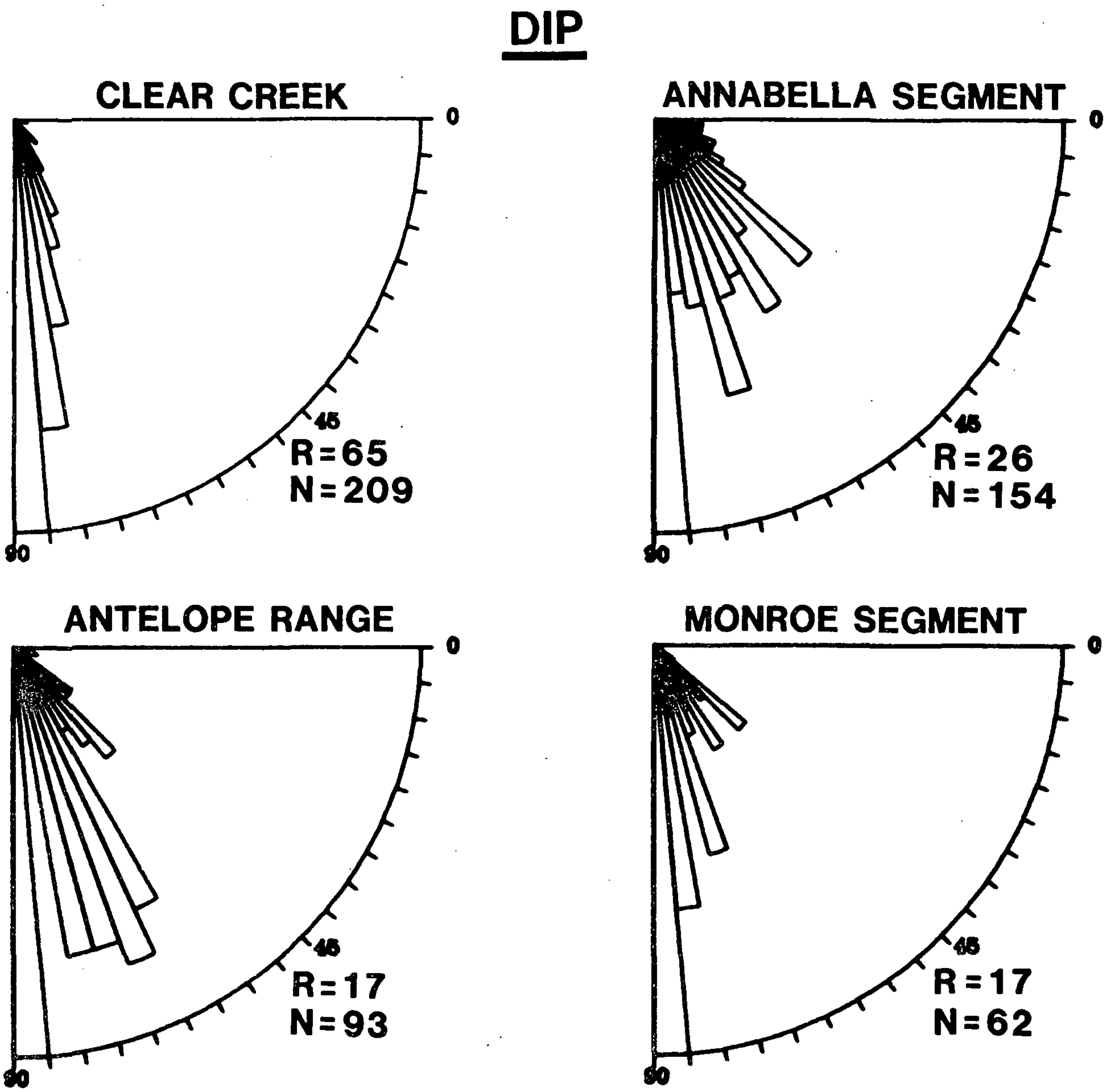

Figure 4.—Distributions of dip angles for all faults from four separate subareas. N = sample size; R = radius value of plot.

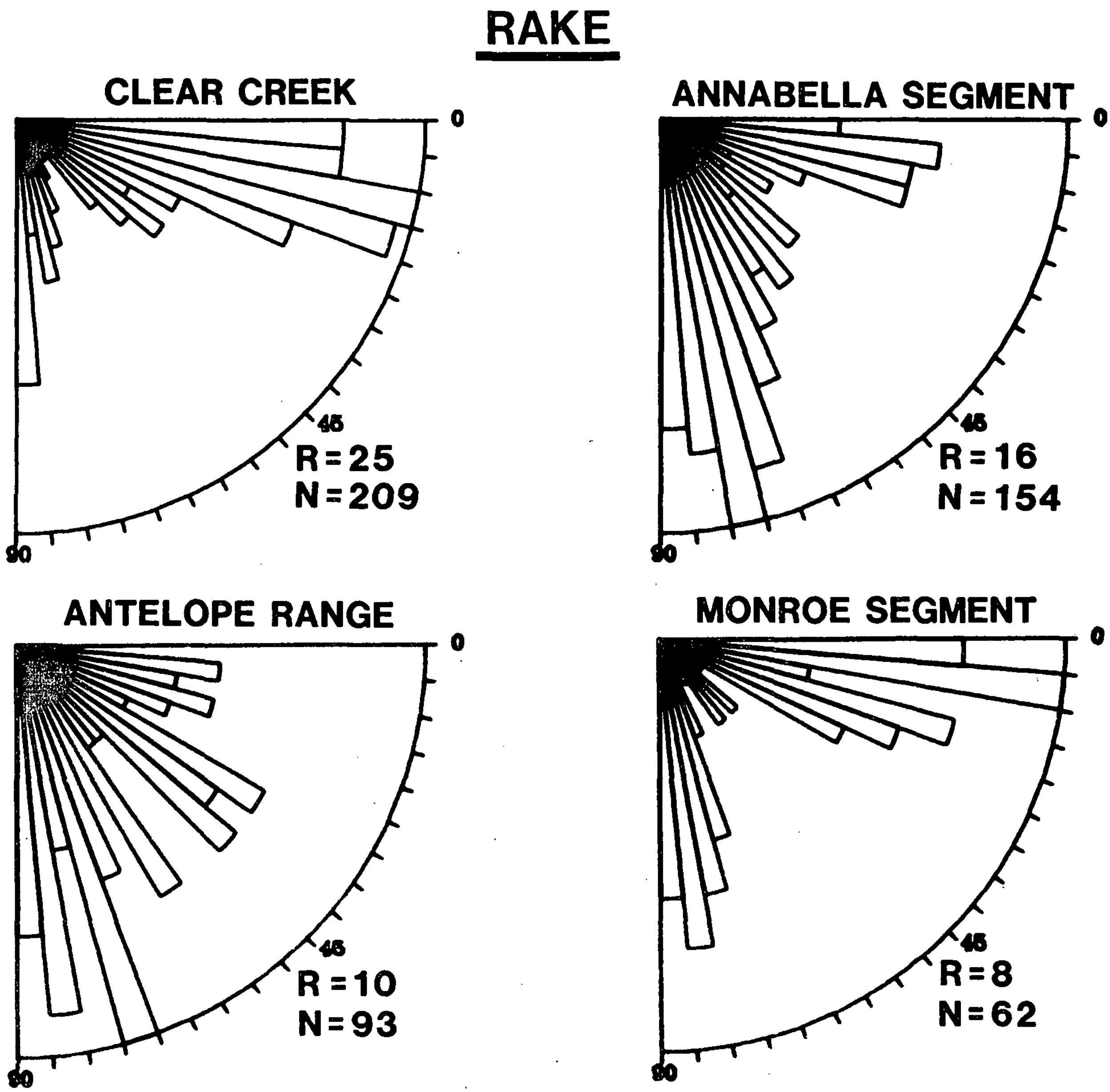

Figure 5.—Distribution of rake angles for all faults from four separate subareas. N = sample size; R = radius value of plot.

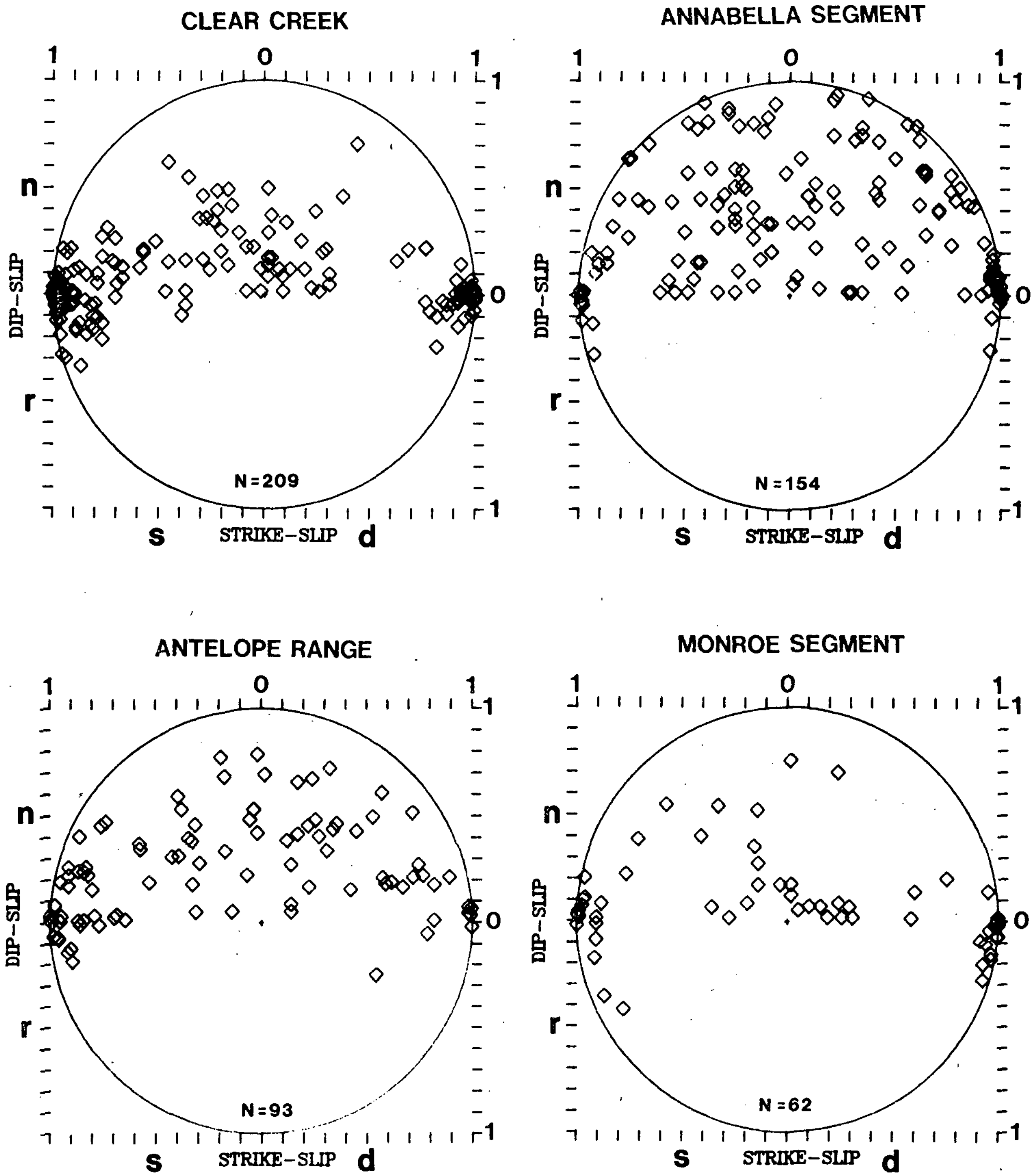

Figure 6.—Plot of SS versus DS components of fault motions for all faults in four separate subareas. Each symbol corresponds to an individual striated fault. Abscissae: ratio of strike separation to net separation (s, sinistral; d, dextral). Ordinates: ratio of horizontal component of dip separation to net separation (n, normal; r, reverse). N = sample size.

than DS faults (fig. 6) they also have larger displacements. Faults that have moderate dips and oblique slip are very sparse in the Clear Creek and Monroe areas and are more numerous in the Annabella and northernmost Antelope Range subareas (figs. 4 and 5). Distributions of fault strikes (fig. 3) show a north-northeast maximum in the azimuthal range 010 to 030 for each subarea, and in each there is a submaximum or node 20°-35° clockwise from the north-northeast maximum. There is a diversity of structural settings represented by the four subareas, so these similarities in fault-strike distributions are unexpected.

Sevier Plateau, Annabella Segment

The location of the trace of the Sevier fault north of Monroe (referred to herein as the Annabella segment) is conjectural. The plateau-margin escarpment bends sharply eastward as it is traced to the north and it is uncertain whether the Sevier fault follows that bend and assumes an east-northeast strike or, as indicated by Callaghan and Parker (1961), strikes N. 35° E. beneath a thick mantle of landslide and alluvial debris to reemerge at the west base of bedrock hills northeast of Annabella. Regardless of the location of the main fault trace, the east-northeast trend of the plateau margin is fault controlled, as shown by Rowley and others (1981). It provides a sharp contrast with the Monroe segment which trends northerly. Volcanic rocks in the upthrown block are mildly faulted with stratal dips that average only about 5°. Bedrock north of the main escarpment dips northward as much as 35° and is downthrown or downbent more than 400 m (Rowley and others, 1981).

Strikes of 154 small-displacement faults along the Annabella segment are very diverse (fig. 3), and 61 have rakes less than 45° and 93 have rakes greater than 45°. The fault-slip data clearly represent a heterogeneous mixture of DS, OS, and SS motions (fig. 5). Because the rake distribution is bimodal it is reasonable to separate the data into DS and SS subsets before performing computations. The strike histogram (fig. 3) shows that few faults parallel the fault-controlled plateau margin along the Annabella segment.

Paleostress axes computed from the DS subset are of good quality because the subset is large enough to perform the computations using a large sample of faults (N=61) with dips between 20° and 80° and rakes greater than 60°. East-west extension is indicated (fig. 7). The SS subset yields paleostress orientations that suggest north-south compression. Because σ_3 for the two faulting modes has a somewhat similar east-west azimuth and there is no indication from the data distributions of the SS and DS subsets (not illustrated here) that DS faulting uses different systems of faults than SS faulting, both faulting modes are assumed to belong to the same tectonic regime.

Sevier Plateau, Monroe Segment

A northerly trending segment of the Sevier fault is well defined, though almost completely buried, south of Monroe where it apparently controls the N. 5° E. trend of the plateau margin for about 6 km. It is referred to herein as the Monroe segment. The fault was seen at only one locality (Z, fig. 2) where its attitude is N. 7° E., 70° W., and it cuts conspicuously intact Oligocene andesite. It is marked by a 1- to 2-m-wide rib of massive secondary silica that has been prospected locally. Striations on and within the silica have a gentle rake to the north. Though neither the sense nor amount of displacement is known, the striations suggest that this segment of the Sevier fault may at times have experienced predominantly SS motion.

Strike distributions of 56 small- and 6 intermediate-displacement faults that cut weakly tilted volcanic rocks in the footwall (eastern) block of the Monroe segment show no tendancy to parallel the plateau margin (fig. 3). Of

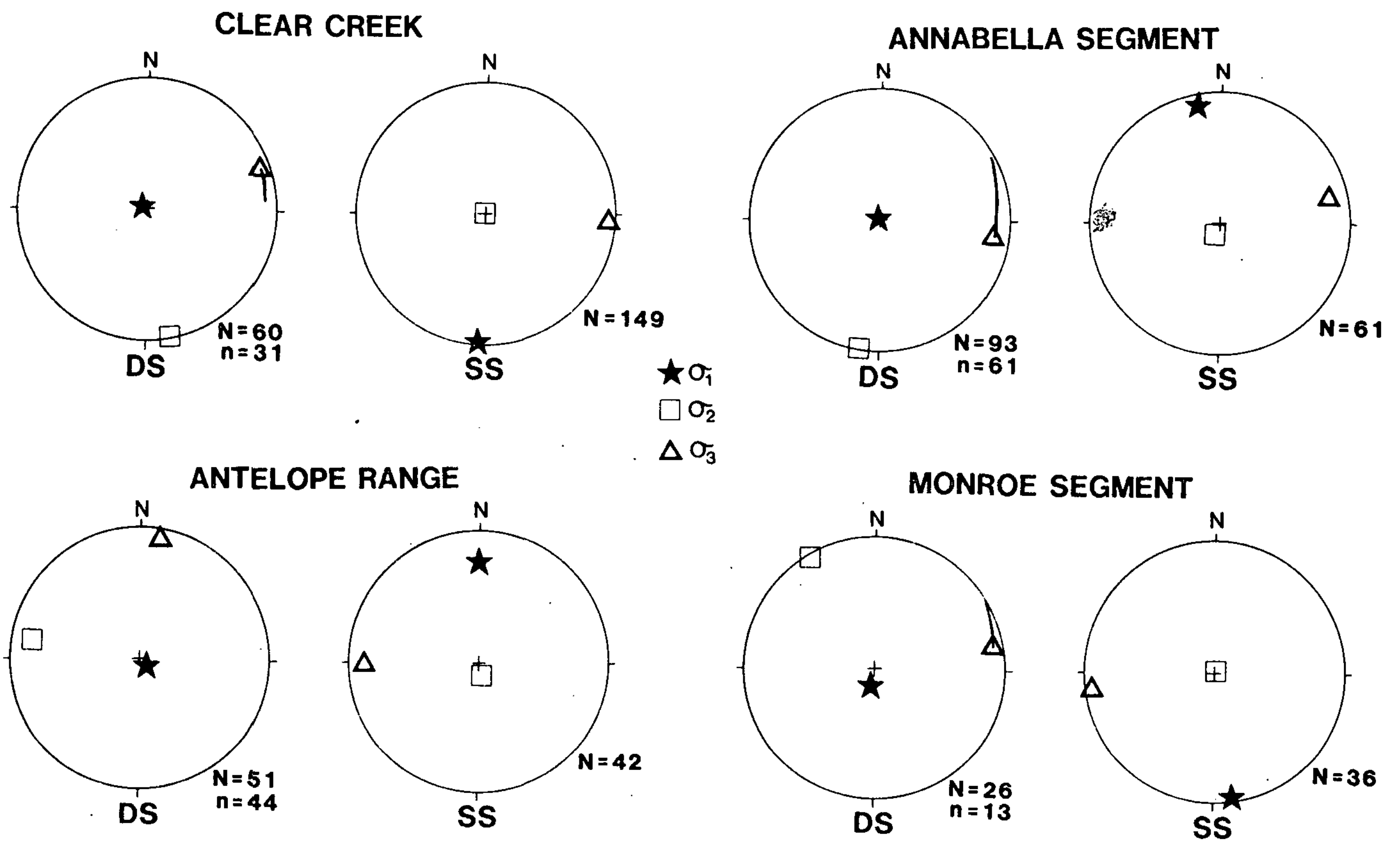

Figure 7.—Paleostress axes computed from SS and DS subsets from the four subareas. All axes are computed from data samples that are not weighted for fault size because weighting does not produce significant changes in axial orientations. All DS axes are computed from samples that have been "cleaned" by eliminating faults with rakes less than 60° or dips greater than 80° and less than 20°. The tie lines extending from the σ_3 axes show the shift produced by "cleaning." The axis for the Antelope Range shows no significant shift and is anomalous when compared with σ_3 axes from the other three subareas. N = sample size before "cleaning"; n = sample size after cleaning.

14 faults whose strikes fall within 20° of the plateau margin, only 3 dip toward the valley and show normal displacement. If the Monroe segment of the Sevier fault is a major range-front normal fault it is clearly not reflected as such in the small to intermediate faults of its footwall block. Of the 62 faults, 36 have rakes less than 45° and 26 have rakes greater than 45°. Their strikes show northwest and northeast maxima. The data suggest heterogeneous slip on faults that bear no obvious relationship to the buried plateau-margin fault.

Stress-axis orientations computed from the small sample of faults are very similar to those computed for the Annabella segment (fig. 7). The similarity, together with the lack of any obvious relationship to the plateau-margin faults in either area, suggests either that the small faults along the Annabella-Monroe segments predate plateau uplift and were not reactivated during uplift or that they represent a complicated uplift-related paleostress history that includes important components of north-south compression. The latter possibility is favored.

Northernmost Antelope Range

The part of the Antelope Range adjacent to the Dry Wash fault consists of a fault-repeated sequence of Oligocene and Miocene flows and tuffs with east to northeast dips ranging from 5° to 45° (Cunningham and others, 1983). Mapped faults strike mostly northwest and northeast, and strikes of those studied are bimodally distributed with northerly and northeasterly maxima (fig. 3). Fault-slip data from the subarea were not combined with data from northwest of the Dry Wash fault because the northernmost Antelope Range consists of a more orderly arrangement of fault-tilted blocks than most other areas in the region and therefore seemed to provide an opportunity to compare computed paleostress with an established structural pattern.

Paleoslip was measured on 83 faults mostly within 2 km southeast of the trace of the Dry Wash fault. Displacement on 74 of them are known or estimated to be less than a meter. Displacement on the remaining nine range from a few meters to more than 100 m. Fault strikes show less scatter than for areas along the margin of the Sevier Plateau (fig. 3). Many of the same faults were activated during SS and DS faulting modes as shown by polyphase striae. Striae with two or more separate orientations were observed on 11 faults and on each the older one has the lowest rake. Many of the youngest striae indicate oblique slip--a feature that is probably responsible for the less conspicuous bimodal distribution of rake angles than is seen for the other subareas (fig. 5). Although data are sparse, the consistency in relative age of striae is not seen in other areas studied. Because it exists in the Antelope Range the low-rake measurements from polyphase surfaces are included in the SS subset and the moderate- to high-rake measurements in the DS subset. The SS subset contains measurements from 42 faults and the DS from 51 faults.

Paleostress axes computed from unweighted subsets are shown in figure 7. The SS subset yields axes suggesting north-south compression and east-west extension similar to the SS subsets from the margin of the Sevier Plateau. The DS subset yields a typically steep σ_1, but, surprisingly, it indicates a north-northeast orientation for σ_3. Such an orientation is inconsistent with the mapped pattern of faulting and tilting from which an approximately east-west σ_3 might be predicted. The 010 azimuth computed for σ_3 is not significantly altered by weighting (as noted above), nor is it significantly altered if axes are computed from a population that contains only faults that dip between 20^o and 80^o and have rakes greater than 60^o. Also, an early computation from part of the data gathered during an early field trip (N=31) shows a similar azimuth for σ_3. These additional computations increase confidence in the validity of the σ_3 azimuth.

Because DS striations are consistently younger than SS ones, a possible explanation for the discrepancy between expected and computed σ_3 for DS motions may be that they are younger than and unrelated to block faulting and tilting. According to such an explanation faults that formed during an early episode of block tilting responding to east-west extension would have been reactivated as SS faults and their striations obliterated in a subsequent stress regime characterized by north-south compression. The compressional event would, in turn, have been superseded by a young mild episode of approximately north-south extension and OS and DS faulting. Alternatively the block tilting could have coincided with the compressional event as an inhomogeneous response to complex permutations of σ_1 and σ_2 (Angelier and others, in press). In either alternative, the 010 orientation of σ_3 is anomalous.

Clear Creek

The Clear Creek area straddles the boundary between the Pavant Range to the north and the Tushar Mountains to the south (fig. 2). It includes data from the Dry Wash fault as well as several other mapped northeast-trending faults.

Callaghan and Parker (1962) considered the southern Pavant Range to be a broad south-plunging anticline as defined by late Tertiary strata. It is separated from the structurally elevated volcanic edifice of the Tushar Mountains to the south by a broad open east-trending synclinal sag with a structural relief of almost 2 km (fig. 2). This sag, named the Clear Creek downwarp by Callaghan and Parker (1962) is the dominant structure in the Clear Creek area. It involves strata as young as the Pliocene Sevier River formation and, according to Rowley and others (1979) defines part of a 150-km-long east-trending structural lineament that has existed for the last 27 m.y. Several upright open east-trending map-scale folds that also involve Pliocene strata are mapped by Callaghan and Parker (1962) on the south flank of the Clear Creek downwarp (fig. 2). These folds have structural relief of about 200 m.

The Clear Creek downwarp and the folds on its southern flank terminate eastward against the Dry Wash fault. The Dry Wash is a major sinistral-slip fault as indicated by common subhorizontal striations and corrugations and the geometry and stratigraphic position of rock slabs that are distributed along it. Net displacement on the Dry Wash could be as much as 8 km on the basis of structural and stratigraphic terminations (Cunningham and others, 1983) and stratigraphic contrasts across it (T. A. Steven, oral commun., 1983). Directly northwest of the Dry Wash fault two additional northeast-trending map-scale faults display abundant evidence of sinistral slip and have net slip of as much as 1 km. These faults also offset strata that were previously folded, although some of their displacement is probably accommodated by the east-trending folds that are located near their southwestern terminations (fig. 2). The folds are cut by many small-displacemnt steep SS faults. Detailed study of 81 of these faults in axial and opposed-limb positions show that they comprise northeast-trending sinistral (33) and northwest-trending dextral (48) sets that (1) offset one another, (2) have broad ranges in strike with no overlap, and (3) contain striations whose rake angles are independent of position on the fold (fig. 8). These relationships indicate that the sinistral and dextral sets are conjugate. Mohr-Coulomb theory (Anderson, 1951) would predict that they formed under conditions of north-south compression. Their relationship to folding suggests that they formed late in

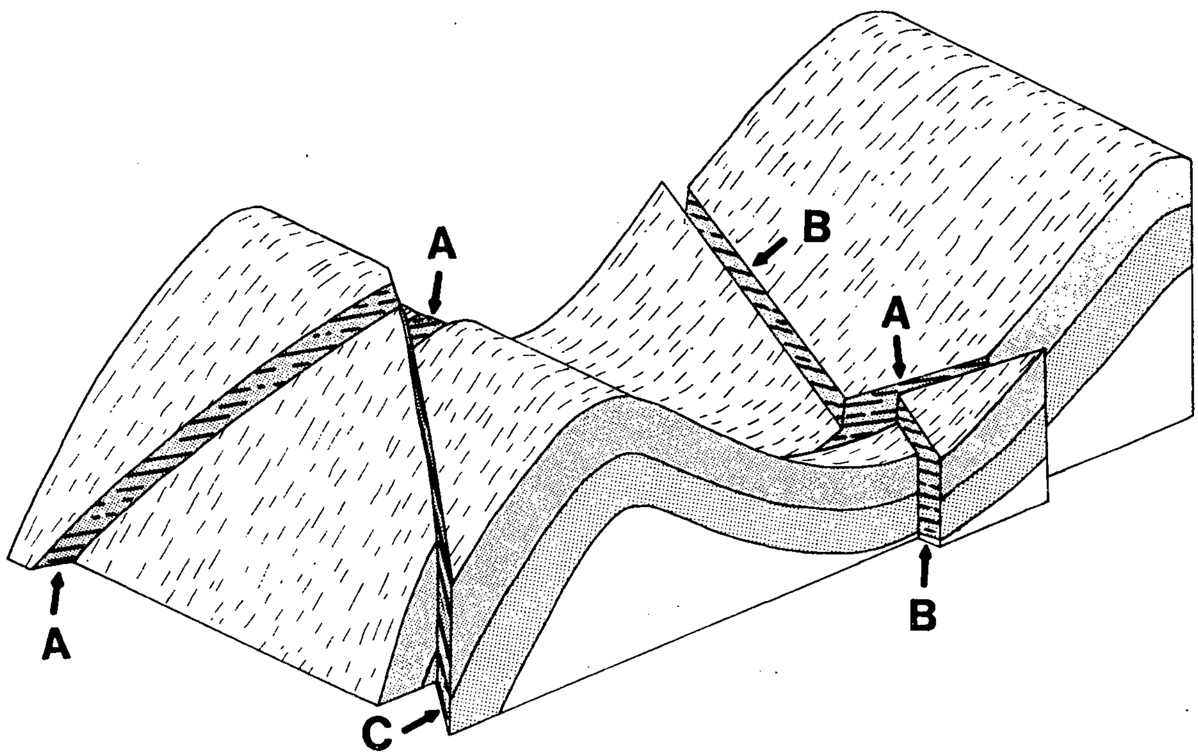

Figure 8.—Schematic block-diagram showing a fold cut by a sinistral fault (A) and two dextral faults (B, C). Heavy lines symbolize striae on fault surfaces. Fault C offsets fault A and fault A offsets fault B as indication of conjugate behavior. Also, rake of striae is independent of position in fold.

the folding history or perhaps after folding, a suggestion that is consistent with the map-scale relationships of sinistral faults to folds noted above.

Dextral faults with small displacements are sparse in the rocks adjoining the Dry Wash fault on the northwest. Though displacements on these faults are very much less than on the adjacent sinistral faults, the two sets are mutually offsetting and their strikes fall into the same range as for the small faults that cut the folds. These small dextral faults were probably active in the same north-south compressional stress field as the large faults, the folds, and the small faults that cut the folds. On this basis all SS data (149 faults) from the Clear Creek area are combined into a single set from which paleostress axes are computed (fig. 7). The axes indicate a north-south maximum compressive stress consistent with that indicated by Mohr-Coulomb mechanics and with orientations computed from SS subsamples from the other three subareas.

Dip-slip striations were measured on 60 faults in the Clear Creek area. Five of these faults show evidence of polydirectional slip. Of those, the dip slip is younger than the strike slip on three and older on two. Thus, no evidence is provided for a temporal separation of SS and DS faulting. Only 31 of the 60 faults have dips between 80° and 20° and rakes greater than 60°. A limited stress tensor computed from those 31 measurements shows σ_3 at azimuth 75° which is within 20° of σ_3 computed from the SS faults (94°). The mapped structures together with the fault-slip data suggest an inhomogeneous late Cenozoic stress history characterized by a permutation of σ_1 and σ_2 in a stress field with σ_3 oriented east-northeast to east-west and dominated by north-south compression.

Other Areas

Fault-slip data from four other areas in or near the central Sevier Valley region provide qualitative indications that the compressional paleostress shown by geologic mapping and fault-slip studies in the four subareas described above is not anomalous. The areas are (1) the southeast margin of the Pavant Range along the Elsinore fault (fig. 2), (2) roadcuts along Interstate 70, 10 km west of the area covered by figure 2 at the latitude of Clear Creek, (3) roadcuts along Interstate 15, 20 km west of the area covered by figure 2 at the latitude of Monroe, and (4) bedrock east of Beaver, Utah, 40 km southwest of the Clear Creek area.

In the vicinity of Elsinore, the structure of the margin of the Pavant Range is dominated by northeast-trending open folds (fig. 2). Strata in the southeasternmost fold limb dip about 50° toward Sevier Valley giving the range-front structure the form of a monocline rather than a fault. The monoclinal form continues 5 km beyond the area covered by figure 2 to the vicinity of Richfield. It has a complex appearance because it involves rocks that were faulted and tilted by earlier deformation and has important down-to-axis faulting associated with it.

Of 59 small- and intermediate-displacement faults observed along the range front between Elsinore and Richfield, only 13 strike within 25° of the N. 35° E. trend of the range front, and, of those, only 3 dip southeast--the dip direction that one would expect if the faults are part of a range-front fault system. Of the three, one shows a sinistral-strike slip, one has polydirectional striae indicating early normal and late sinistral displacements, and one shows normal slip. Thus, only 1 of 59 faults has an orientation and slip sense similar to what would be expected for a range-front normal fault system. As with the Monroe and Annabella segments of the Sevier fault, if the Elsinore fault exists as a range-bounding normal fault it is clearly not reflected as such in the small- to intermediate-displacement faults in its footwall block. Faults that strike northeast dip mostly northwest, and their DS component is down toward the range--a displacement aspect that is common in monoclinal flexures along range fronts. Many faults strike north to northwest and have striae with a bewildering variety of rake angles and polyphase slip. On the basis of the geometry of their intersection with bedding, the dip slip on many of these faults could be related to an early episode of northeast-southwest extension. Though the fault-slip data are too few and heterogeneous to use as a basis for paleostress computations, much of the OS and SS motion on these faults could be related to reactivation of early normal faults in a compressional stress field analogous to the one that controlled late Cenozoic structural development in the Clear Creek area. Neither their formation nor their possible reactivation is likely to be directly related to a range-front normal fault system. If a range-front fault exists in the Elsinore-Richfield area, it is buried beneath the Quaternary alluvium that flanks the range and is probably a continuation of the sinistral-slip Dry Wash fault. The northeast-trending open folds that dominate the structure of this area are considered analagous to those whose axes parallel the trace of late Cenozoic SS faults in the Mercury quadrangle, Nevada Test Site, Nevada (Barnes and others, 1982).

Between the Pavant Range and Tushar Mountains along Interstate 70 several roadcuts provide good exposures of faulted Oligocene and Miocene volcanic and sedimentary rocks in a west-northwest to east-southeast cross-strike distance of about 1.5 km. The rocks dip east to southeast 15°-25° and are cut by numerous steep northeast-trending faults. The area is one in which the stratal repeat patterns and physiography are suggestive of a simple pattern of normal faulting (Cunningham and others, 1983), but the striae tell a much different story. Slip orientations and senses were measured on 20 faults ranging in displacement from about 20 cm to more than 100 m (fig. 9). Eight of the 20 faults have measured or estimated displacements of 10 m or more, and the sense of slip was determined with certainty on 14 of them. The large-displacement faults have gouge zones ranging in width to 50 cm. The gouge has a strong internal shear fabric whose geometry and orientation are consistent with the orientation and sense of displacement measured on the planar walls of the shear zone suggesting an unusually high degree of uniformity of fault motion. One fault strikes north and is dextral. The remaining 19 strike northeast and 17 are certainly or probably sinistral and two are normal (fig. 9). These excellent exposures show that fault deformation in the area is dominated by northeast-trending sinistral faults and that no significant difference exists between the slip on large- and small-displacement faults.

Strongly fractured Oligocene volcanic rocks are exposed in roadcuts along the northbound and southbound lanes of Interstate 15 about 6 km north of the junction with Interstate 70 (fig. 9). The exposures are located a few kilometers west of the boundary between the Basin and Range and faulted transition zone. The strata strike west-northwest and dip gently south-southwest whereas the average strike of faults in the area is 015° (Cunningham and others, 1983). Because the faults strike approximately perpendicular to the strike of the beds, the beds cannot be assumed to be tilted by fault displacements. Displacement amounts on individual faults are not known but are assumed, on the basis of fracture appearances, to range from a few centimeters to a few meters. Unpublished geologic mapping in the area shows at least 200 m of apparent sinistral offset between the exposures along the northbound and southbound lanes. The orientation and sense of slip were

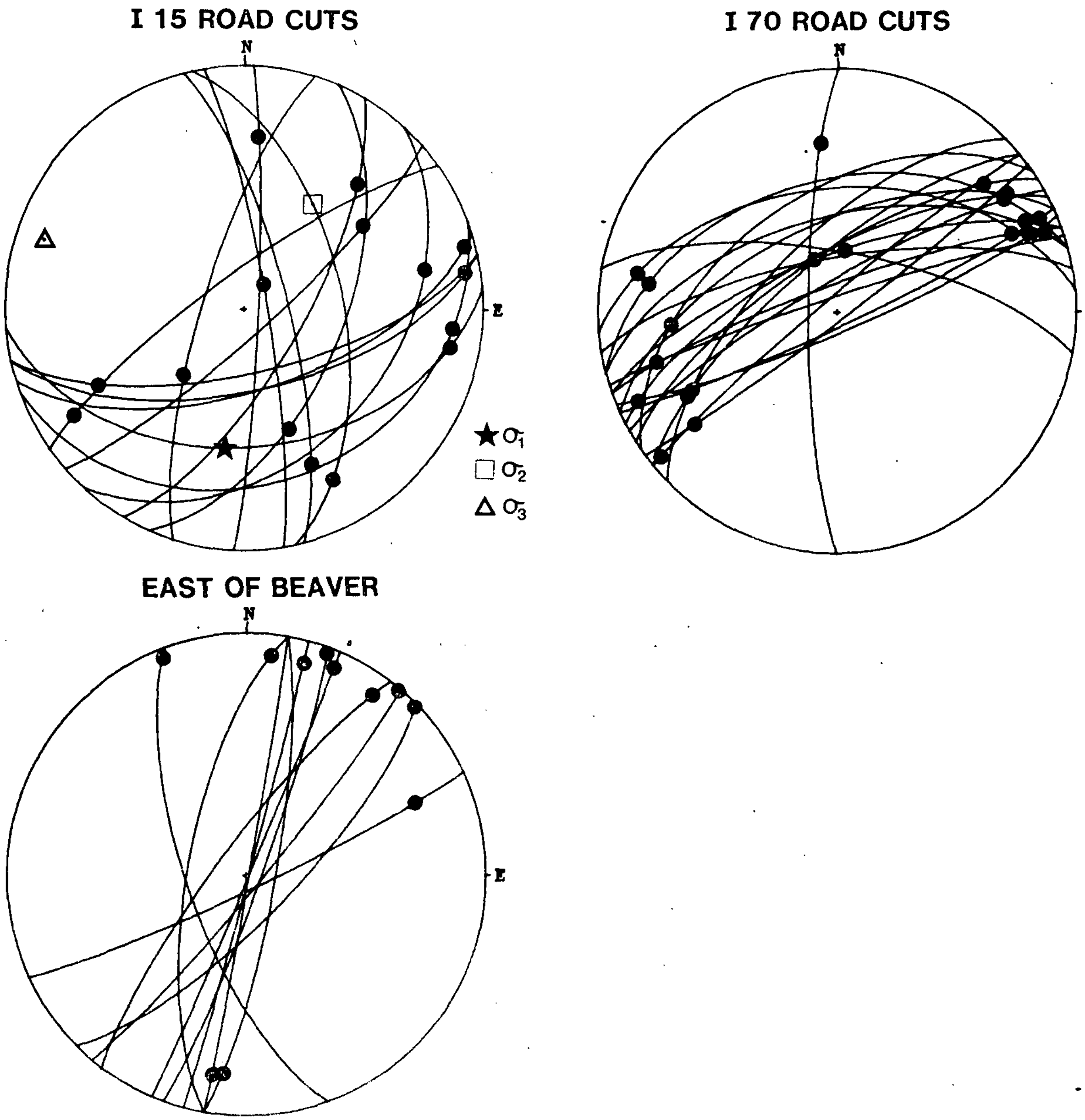

Figure 9.—Lower-hemisphere stereographic plots of faults as great-circle arcs and striae in those faults as dots. Faults at I-70 roadcuts are sinistral except for a north-trending dextral and two DS faults. The faults at the I-15 roadcuts that strike between 015° and 085° are all sinistral. The others are dextral except for the normal fault with a steep rake. The slip sense was not determined for the faults east of Beaver. The computed stress axes for the faults from the I-15 roadcuts are poorly constrained because of the small sample size and predominance of sinistral slip.

measured on six faults in the eastern cut and nine in the western cut. These faults, which range in strike from 345° through 0° to 085° and in dip from 28° to 85°, are probably representative of the range of principal fault orientation in the vicinity of the cuts. Two contrasting slip orientations were measured on 4 of the 15 faults and on each the sense of both motions is similar (all are predominantly sinistral). Of the 15 faults 3 northerly trending ones are predominantly dextral, 7 northeasterly trending ones are predominantly sinistral, and the remainder show a predominance of dip slip (fig. 9). Paleostress axes computed from the 15 faults (using the youngest motions on faults with two orientations) are shown in figure 9. They are poorly constrained because of the small size of the data set.

The fault boundary between the Basin and Range province and the faulted transition to the Colorado Plateau is located about 4 km east of Beaver, Utah. Striations on 10 small- and 1 intermediate-displacement faults that strike north to northeast and cut gently tilted and weakly faulted late Cenozoic bedrock along the Beaver River east of the province-bounding fault indicate predominantly SS motions (fig. 9). The 10 small faults are located in an area of less than 5 km^2 within 2 km east of the province-bounding fault that separates Beaver Valley from the Tushar Mountains. They appear to represent the only fault deformation to which the rocks have been subjected. Late Quaternary fault scarps are abundant in the basin-fill sediments of Beaver Valley (Machette and others, 1981). Conventional wisdom would predict normal DS displacements on those faults as well as on the province-bounding fault. However, the area is located along the southwesterly projection of major faults in the Clear Creek area that are now known to be SS faults. The occurrence of SS faults in bedrock may not be as anomalous as it seems at first.

In summary, not only do striated faults in the four subareas described in this report provide a strong record of SS faulting, but similar faulting is seen in four well-exposed areas in and near the central Sevier Valley area. Together the data show that late Cenozoic SS faulting is common in the region. This is consistent with earlier observations of widespread Neogene SS faulting in southwestern Utah (Anderson, 1980). The data from Interstate 15 roadcuts and the area east of Beaver show that Cenozoic bedrock directly east and west of the Basin and Range province boundary was involved in SS faulting.

AGE OF FAULTING

Rowley and others (1979) conclude that the major faulting in the Clear Creek area took place after 7 m.y. ago and Rowley and others (1981) conclude that the main uplift of the Sevier Plateau (about 1.5 km) took place in less than 2.5 m.y. between 7.6 and 4.8 m.y. ago. Anderson and Bucknam (1979) noted fault scarps of probable late Pleistocene age along the Sevier fault near Annabella and along the Elsinore fault near Elsinore. Callaghan and Parker (1961) noted that Quaternary river terraces northeast of Joseph appear to be tilted eastward by displacement on the Dry Wash fault. Thus, displacements on the major faults in central Sevier Valley probably extend from latest Miocene through Pleistocene. At the I-15 roadcuts the northeast-trending faults from which SS data were gathered are located along the strike projection of northeast-trending faults that cut basaltic lavas of Quaternary age directly south-southwest of the roadcuts (Steven and others, 1979). The simplest interpretation of available data from that area is that the measured striations include a record of Quaternary displacements and that the faults that cut Quaternary basalts are not simple normal faults.

CONCLUSIONS

Listed below are 12 conclusions that can be drawn regarding the late Cenozoic structure of the central Sevier Valley region.

1. The Dry Wash fault and two other northeast-trending, map-scale faults to the northwest of it have major cumulative sinistral displacement that may approach 10 km. They are genetically and mechanically related to abundant small-displacement faults in the Clear Creek area, and, together, they form conjugate sinistral and dextral systems with large dispersion of strikes. On the basis of Mohr-Coulomb mechanics all these faults formed in a late Cenozoic compressional stress field with σ_1 oriented approximately north-south.
2. East-trending folds with amplitudes of 200 m and wavelengths of 1 km formed in the same compressional stress field as the faults of conclusion 1. The fault-fold patterns combine to show that the Pliocene and Pleistocene(?) structural fabric of the Clear Creek area formed predominantly under conditions of horizontal compression and it represents tectonically significant sinistral shear and north-south shortening.
3. Strike-slip faulting is the major and youngest mode of faulting at widespread localities in southwestern Utah showing that the late Cenozoic structural style of central Sevier Valley is not anomalous.
4. Small- and intermediate-displacement faults in bedrock adjacent to Sevier Valley along the Elsinore fault and along the Monroe and Annabella segments of the Sevier fault do not reflect the trend or slip sense of range-front normal faults that have been inferred by previous workers to lie buried beneath range-bounding Quaternary alluvium in those areas.

5. Because the Dry Wash fault is a major SS fault that projects northeast toward the Elsinore fault, and because there is little evidence in the bedrock adjacent to the trace of the buried Elsinore fault that it is a normal fault, the Elsinore fault is probably continuous with the sinistral Dry Wash fault. Sinistral slip on two minor faults near Elsinore support this conclusion. Also, the open folds that parallel the Elsinore fault are probably genetically related to it. This latter suggestion is based on an analogy with similar open folds related to late Cenozoic SS faults in the southern Nevada Test Site.
6. The northerly trending segment of the Sevier fault south of Monroe has probably experienced SS motion.
7. On the basis of observations leading to conclusions 4, 5, and 6, vertical structural differentiation between Sevier Valley and its flanking mountains (Pavant Range and Sevier Plateau) was probably accomplished by a combination of monoclinal flexing and, on the average, OS faulting.
8. Slip data from more than 550 faults (mostly of small displacement but including some of intermediate and large displacement) from the central Sevier Valley area represent a heterogeneous mixture of DS, OS, and SS motions as the youngest slip events on those faults. Rake distributions tend to be strongly bimodal and show that OS faults are relatively uncommon. Such bimodal mixtures of predominantly SS and DS faults are found elsewhere in the Basin and Range. Together with strike and dip distributions, they show that deformation is dominated by two different faulting modes that do not utilize separate and distinct systems of faults in a given mass of rock.
9. Paleostress orientations computed from subsamples of faults with rakes less than 45° are remarkably similar for the four subareas in the central

Sevier Valley area. The orientations suggest subhorizontal north-south maximum compressive stress as part of the late Cenozoic structural history of central Sevier Valley. For the Clear Creek subarea the orientations agree well with paleostress deduced qualitatively from fault-fold patterns. The four subareas have sharply contrasting local structural settings so the occurrence of and consistency in computed and deduced compressional paleostress is unexpected and surprising. The consistency suggests that the orientations have regional significance.

10. Because weighting according to fault size does not significantly influence paleostress orientations, the assumption is made that displacements on the abundant small faults are representative of displacements on the large faults. Because the small structures involve the same rocks as the large ones they are intepreted to be of the same latest Miocene through Pleistocene age as the large faults. Pressure-axis orientations inferred from seismicity studies (Julander, 1983) apparently reflect the superposition of horizontal compression (north-south to northeast-southwest) upon east-west extension (Julander and Arabasz, 1982). The OS and SS faulting modes indicated by focal mechanism solutions derived from microseismicity studies and regional earthquake monitoring in the area are generally consistent with extensional and compressional paleostress states computed from hundreds of faults in the central Sevier Valley region suggesting a temporal continuity between seismicity and paleoseismicity. Deformational models developed to explain the seismicity must be consistent with the youngest part of the geologic record and they must accommodate folding as well as

SS and DS faulting. Also, they should be representative of the full size range of faults and folds--including approximately 2 km of vertical structural relief on the Clear Creek downwarp.

11. The DS and SS faulting modes for three of the four subareas yield separate paleostress axes that suggest permutations of σ_1 and σ_2 consistent with the model of combined lateral and vertical contraction associated with east-west extension deduced from the seismicity data. These relationships suggest that SS and DS faulting belong to the same tectonic regime and that the permutations do not represent major reorganizations of regional stress. For the Clear Creek subarea and the margin of the Pavant Range between Elsinore and Richfield this suggestion is supported by the complex patterns of polyphase slip on numerous faults.

12. Some SS faults in the central Sevier Valley area are as large and as young as the largest and youngest known or inferred normal faults and must therefore be considered to represent a similar level of earthquake hazard. This conclusion is supported by the apparent stress-state correspondence between seismicity and paleoseismicity.

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PRELIMINARY ESTIMATES OF GEOGRAPHIC VARIATION IN RELATIVE GROUND SHAKING IN THE WASATCH FRONT URBAN CORRIDOR

by

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ABSTRACT

This study builds upon the work of several previous studies in the Wasatch Front Urban Area. Hays and King (1982) and King and others (1983) published a study of seismic response based on recorded ground motions at 42 sites in the Wasatch Front region induced by distant explosions and an earthquake. The sites were chosen to sample a variety of geologic conditions. Response spectra and alluvium-to-rock spectral ratios were computed from the horizontal-component data recorded at each location. Generalized descriptions of the lithology underlying each recording site were obtained from R. D. Miller's unpublished maps (1984) of unconsolidated surficial deposits. The lithologic descriptions were categorized into three groups: silt and clay, sand and gravel, and rubble. The log-normal mean of the spectral ratios was then computed for each of the lithologic groups for two period bands (0.2-0.7 s for the short-period band and 0.7-1.0 s for the long-period band). In the short-period band, the mean spectral ratios vary from 2.7 (rubble sites) to 6.2 (silt and clay sites), while in the long-period band, they vary from 3.2 to 7.2, respectively. Ninety-percent confidence intervals about the mean spectral ratios indicate that stations underlain by silt and clay have significantly higher short-period response than those underlain by sand and gravel. There are too few sites underlain by rubble to obtain statistically meaningful results. The results for the long-period data also are not statistically significant using this categorization. Based on this analysis, we have produced maps for the urban areas of Brigham City, Ogden, Salt Lake City, and Provo, showing expected relative ground shaking response for the short-period band.

INTRODUCTION

Several investigators have found that recordings of low-strain measurements of distant nuclear events are highly correlated with geologic conditions underlying the recording sites (Murphy and others, 1970; Borcherdt, 1970; Rogers and others, 1984a). In addition, two direct comparisons have been made between low strain site response from distant nuclear events and site response derived from strong ground motion. In one study, Rogers and others (1984b) compared mean spectral site response from Nevada Test Site nuclear events (strains near 10^{-5}) with mean spectral site response from the 1971 San Fernando earthquake (strains near 10^{-3}). They found that ground response is equivalent for low-strain and high-strain events within the expected variability of the statistics. In another study, Borcherdt and others (1975) found a high correlation between mean spectral amplification determined for sites near San Francisco from Nevada Test Site nuclear events and intensity changes (up to San Francisco Intensity Level 4) observed in the 1906 earthquake. These two studies support the argument that differences between distant low-level sources and strong shaking have only second order significance. These and other studies (Murphy and Hewlett, 1975; Rogers and others, 1979; Hays and Algermissen, 1982; Hays and King, 1982) establish the methodological foundation upon which this study is based.

DATA COLLECTION AND ANALYSIS

King and others (1983) recorded underground nuclear tests at the Nevada Test Site, an earthquake approximately 50 km E of Salt Lake City, Utah, and mining blasts at the Kennecott Mine at Bingham, Utah. Broad-band (3-component, L-7) seismographs were used to record the ground motions from these events. Forty-two sites in the Wasatch Front Urban Area were selected to sample a variety of geologic site conditions. The sites were located in the vicinity of Salt Lake City, Logan, Ogden, Cedar City, and Provo.

The analog-recorded data were digitized and processed to derive 5-percent pseudo-relative velocity spectra (PSRV) (Park and Hays, 1977). The PSRV is approximately equal to a smoothed Fourier amplitude spectra when the damping is small (Jenschke, 1970). Ratios of alluvium-to-rock PSRV spectra were computed as an approximation of the influence of the geologic column underlying each site

(Rogers and others, 1979) on ground motions. This approximation is termed the site transfer function and is computed according to:

$$SFT(T) = \frac{PSRV_A^{r,t}(T)}{PSRV_R^{r,t}(T)}$$

Where r,t refer to radial and transverse components of ground motion, T is the period of the PSRV oscillator and A and R refer to alluvium and rock, respectively.

The mean relative site response was computed from the STF(T) for 2 period bands ranging from 0.2 to 0.7 s (short-period band) and from 0.7 s to 1.0 s (long-period band).

We plotted the location of each of King and others' (1983) sites on R. D. Miller's unpublished map (1984) of unconsolidated surficial déposits in the Wasatch Front Urban Area. The unconsolidated sediments underlying the sites were divided into three categories: silt and clay, sand and gravel, and rubble. Sites mapped as being underlain by sand were classified with sand and gravel, and sites underlain by marsh were classified as silt and clay. A total of 20 sites were located on silt and clay, 18 on sand and gravel, and 4 on rubble. Histograms of the mean spectral ratios for each lithologic category revealed that the site response data have a log-normal distribution. This result is consistent with that observed by Rogers and others (1984a), and, thus, the log-normal mean is used in this study to measure central tendency of the mean spectral ratios. The log-normal mean of the mean spectral ratios was calculated for each lithologic category and for two period bands (0.2-0.7 s and 0.7-1.0 s). The log-normal mean, range, and the 90-percent confidence intervals for the mean-spectral ratios are shown in Figure 1. The mean short-period (long-period) response varies from 6.2 (7.2) at sites underlain by silt and clay to 2.8 (3.2) at sites underlain by rubble. In the short-period band, the 90-percent confidence intervals indicate a statistically significant difference between the ground response of sites underlain by silt and clay compared with sites underlain by sand and gravel. Sites underlain by rubble had lower response than the two other categories. Although the later result is not statistically significant because

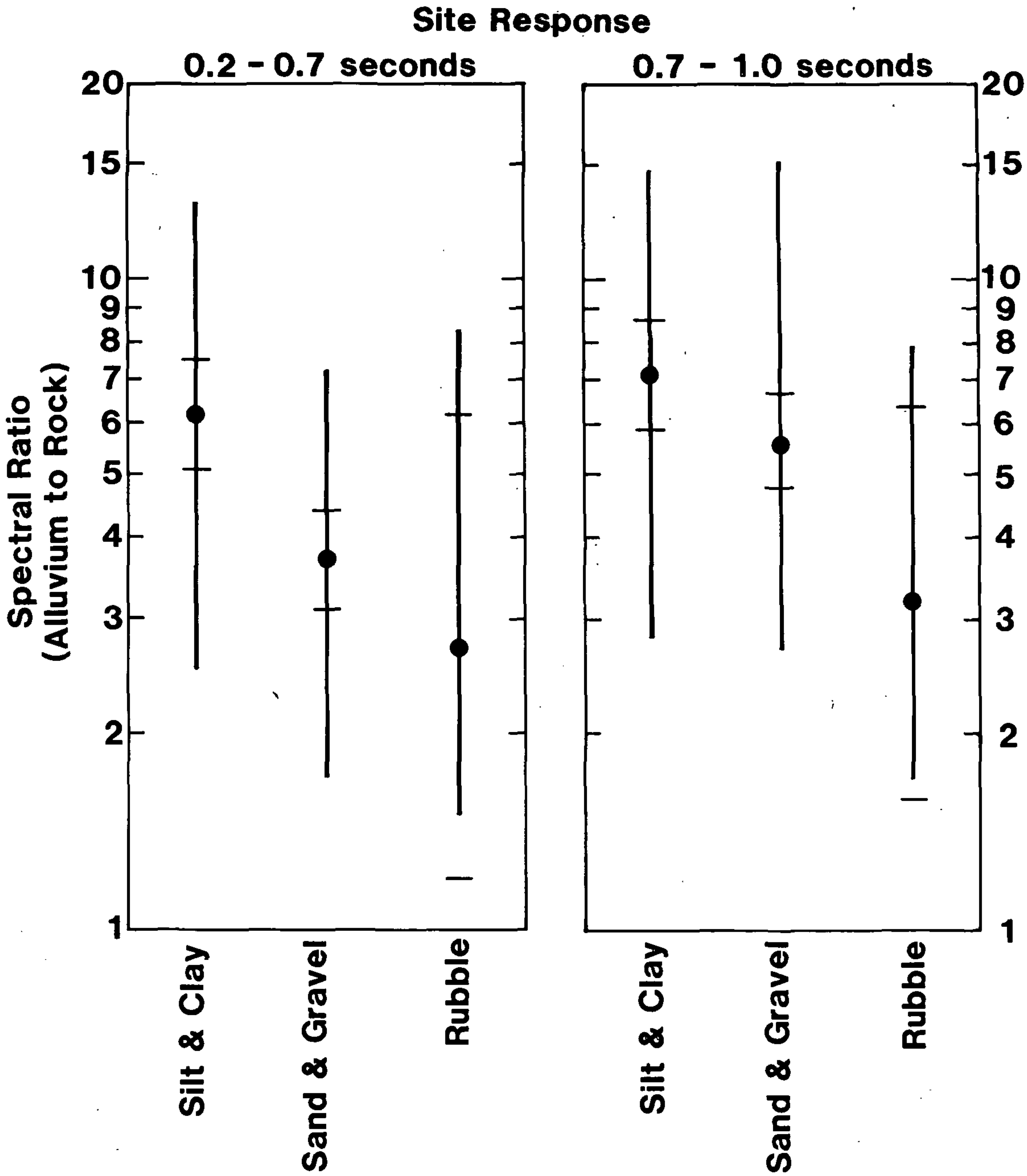

Figure 1.--A graph depicting response relative to bedrock of sites underlain by three categories of surface deposit; silt and clay, sand and gravel, and rubble. The solid dots indicate the log-normal mean of the spectral ratio for each category. The vertical bars indicate the range of individual sites' spectral ratios in the category. The horizontal bars show the 90 percent confidence intervals for each category.

only four sites fall in this category, we accept the physical plausibility of this result. In any case, a very small percentage of the Wasatch Urban Area is underlain by rubble so that an error in estimating the response of these sites will not substantially modify the results presented here.

In the long-period band, the mean-spectral response does not indicate a statistically significant difference using this categorization scheme. This result might be expected based on the work of Rogers and others (1984a) who showed that mean-spectral levels at periods in this range or greater were strongly dependent on deeper structure, such as the thickness of the Quaternary sedimentary deposits and/or the depth to crystalline basement. Development of long-period, mean-spectral response maps will require acquisition of additional data on the three-dimensional structure of sedimentary deposits in the Wasatch Front region.

Although it is known that geological structure can affect the relative level of site response at both long and short periods (Rogers and others, 1984a), in this study we have shown that it is possible to obtain a useful estimate of short-period response based on surficial lithology. This result and generalization of the units used in the maps of the surficial sediment texture by Miller (written commun., 1984) are the basis for the following set of derivative maps (Figures 2, 3, and 4). These figures indicate that for the short-period band areas underlain by silt and clay are expected to experience ground motions roughly six times stronger than bedrock locations; areas underlain by sand and gravel can expect ground motions roughly four times greater than at bedrock sites; while areas underlain by rubble should respond less than sand and gravel, or roughly three times greater than at bedrock sites.

Borcherdt and others found that a factor of two in mean spectral level corresponds to a change of one Modified Mercalli (MM) intensity unit. Relating the geographic variations in ground response predicted by this study to intensity changes, we find that rubble sites are expected to experience MM intensities one to two units higher than the average rock site; sand and gravel sites are expected to experience intensities about two units higher than rock, and silt and clay sites are expected to experience intensities two to three units higher than rock.

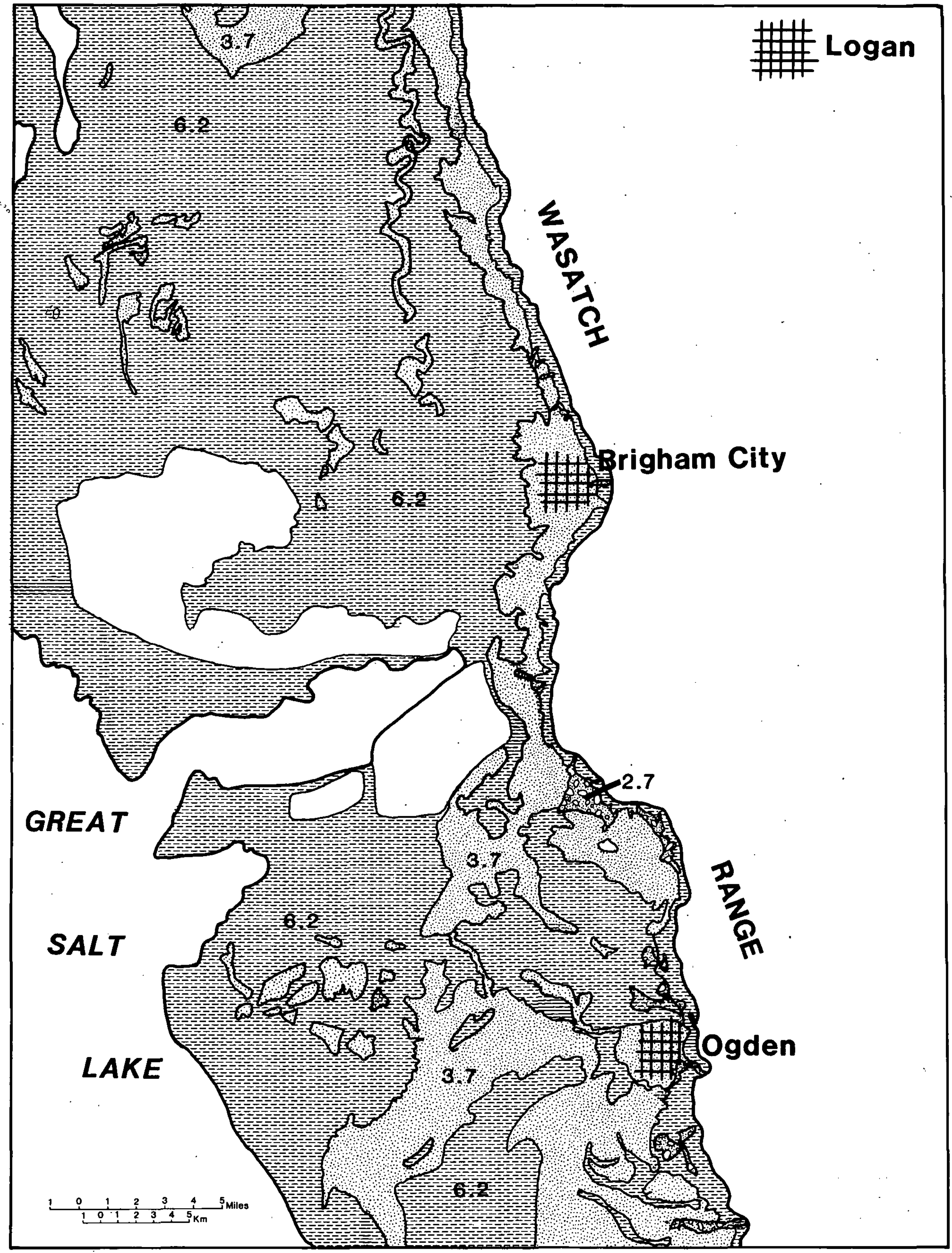

Figure 2.--A map depicting the expected relative ground shaking response in the north part of the Wasatch Front Urban Area. The numbers indicate mean ground response relative to bedrock locations.

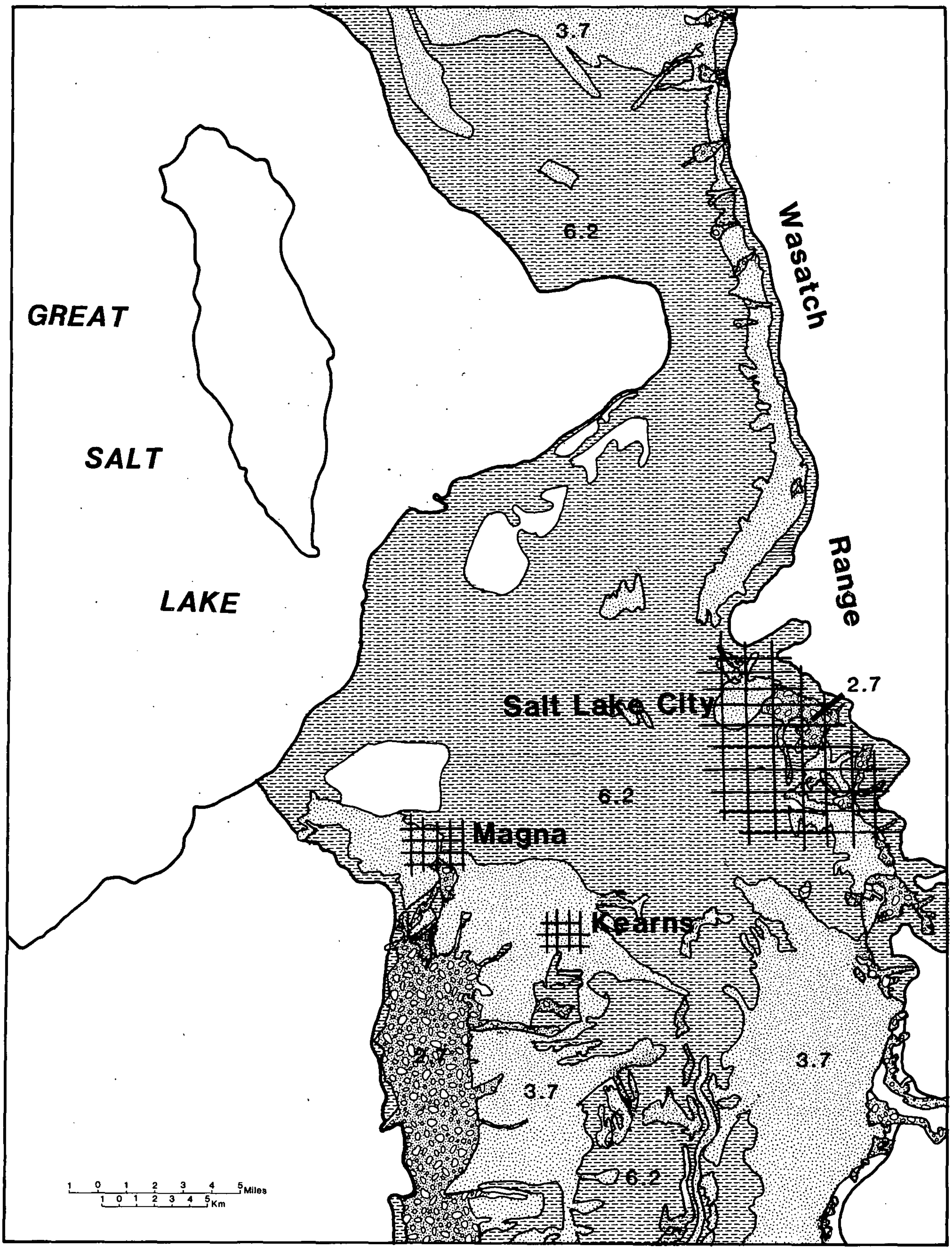

Figure 3.--A map depicting expected relative ground shaking response in the central part of the Wasatch Front Urban Area. The numbers indicate mean ground response relative to bedrock locations.

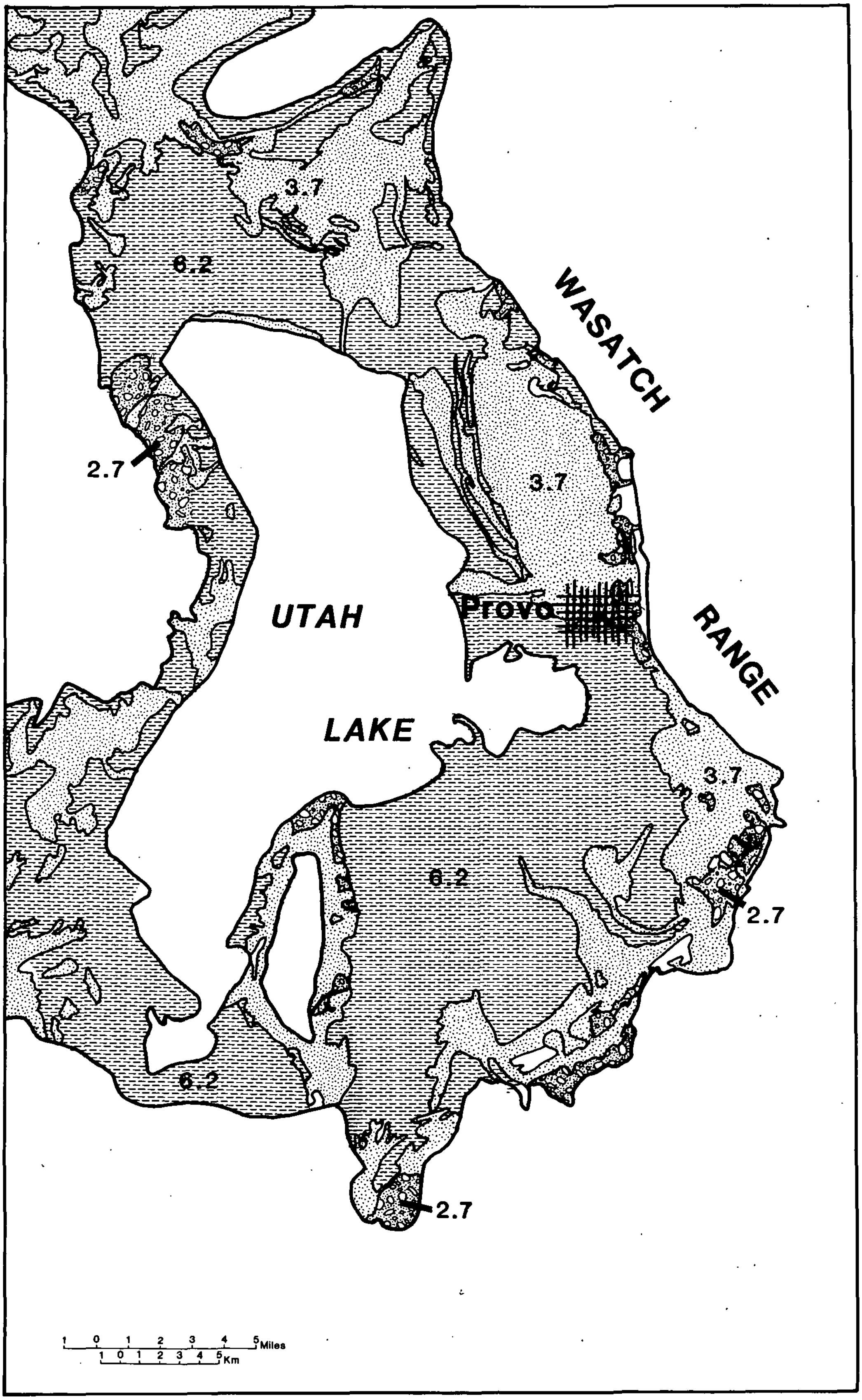

Figure 4.--A map depicting expected relative ground shaking response in the south part of the Wasatch Front Area. The numbers indicate mean ground response relative to bedrock locations.

As noted above, factors other than near-surface lithology can have a bearing on ground motion spectral levels. One example of this may be the two recording sites Hays and King (1982) occupied near the middle of Salt Lake Valley, where mean short-period response values 11 and 13 times greater than bedrock values were observed. Response values this large may be caused by a critical thickness in the surficial layers that produces resonant conditions. Future work in the Wasatch Front Urban Corridor will use more detailed information on geological structure beneath the individual recording sites to improve our site response predictions.

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GROUND FAILURE HAZARDS AND RISKS:

CONSIDERATIONS AND RESEARCH NEEDS APPLICABLE TO UTAH

by

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INTRODUCTION

Presented in this report are comments pertaining to issues of ground failure assessment. The purpose of this report is to provide a general perspective of ground failure hazards and risks with an emphasis on considerations and research needs applicable to Utah.

Ground failure hazards are caused by a variety of processes. Property damage caused by ground failures in the United States amounts to billions of dollars each year (U.S. Geological Survey, 1982, p. 1). Included in the ground failure processes are landslides, subsidence, swelling clays, and construction-induced rock or slope deformations. Over the past 50 years, losses from landslides and subsidence alone are estimated to exceed $1.5 billion per year, and losses from swelling clays alone are estimated to exceed $2 billion per year (U.S. Geological Survey, 1982, p. 1).

Assessment of ground failure hazards is a function of the specific environment being assessed and the variety of natural processes acting on it. Assessment of the risks posed by ground failure hazards is a function of the value and vulnerability of exposed facilities and population.

The following sections of this report consist of a review of ground failure types and processes and a discussion of some salient aspects of risk assessment and research needs.

GROUND FAILURE TYPES AND PROCESSES

Among the most common types of ground failure are those usually called "landslides." The term landslide includes virtually all processes resulting in displacement of earth materials usually on slopes. Five principal types of slope movements have been differentiated by Varnes (1978): 1) falls, 2) topples, 3) slides (including rotational as well as translational), 4) lateral spreads and 5) flows. Many slope failures consist of a complex combination of these five types of movement.

Materials involved in slope failures range from bedrock to unconsolidated, uncemented sediment (soil in the engineering sense). The rates of movement can range from very rapid, as in the case of a rock fall, to very slow, as in the case of an earth slump.

Earthquake shaking can induce slope failure of the types mentioned above. However, earthquakes can also create ground failure in a more fundamental earthquake mode -- fault rupture. In fact, some forms of ground failure do not involve slopes or earthquakes. These forms are related to volume changes resulting from wetting sensitive soils or withdrawing fluids from susceptible formations. The variety of general types of ground failure with some specific examples are presented in Table 1.

Ground failure along fault traces represents a very dramatic example of a damaging geologic process. The ground failure can be abrupt coseismic slip

TABLE 1

VARIETY OF GENERAL GROUND FAILURE TYPES

GENERAL TYPE	SPECIFIC EXAMPLE
Primary Earthquake ground failure	Tectonic rupture along faults: abrupt coseismic slip, gradual aseismic creep.
Secondary Earthquake ground failure	Earthquake-induced failure: falls, topples, slides, spreads, and flows. Also loss of bearing capacity and loss of uplift resistance.
Non-earthquake ground failure	Common failure: falls, topples, slides and flows. Ground failure due to heave of swelling clay or settlement of compressible aquifers or hydrocompactible deposits.
Remote Effects of ground failure	Passage or accumulation of boulders or debris from upslope ground failure

or gradual aseismic creep. No fault rupture in an urban area has occurred in Utah during historic time. However, our understanding of the significance and potential consequence of this type of ground failure is based on a number of damaging earthquake events in which fault rupture occurred in other areas.

Although fault rupture is a dramatic form of ground failure, it affects a very small area when compared to other types of damage, such as strong ground shaking. A secondary effect of earthquake motion includes induced ground failure of any or all five principal types of slope movement. In fact, the two most destructive ground failures of this century and perhaps of all history were induced by earthquake shaking. Rapid soil flows of loess swept through inhabited valleys as a result of the Kansu Province, China earthquake of 16 December 1920 ($M_W = 7.8$), covering several square kilometers of area and killing possibly as many as 100,000 people (Keefer, 1984, p. 418). A slab of rock and ice fell from Nevados Huascaran, the highest peak in Peru, in response to the $M_W = 7.9$ earthquake of 31 May 1970, destroying in a period of approximately 4 minutes the cities of Yungay and Ranrahirca and at least 5 villages, killing over 18,000 people (Keefer, 1984, p. 415).

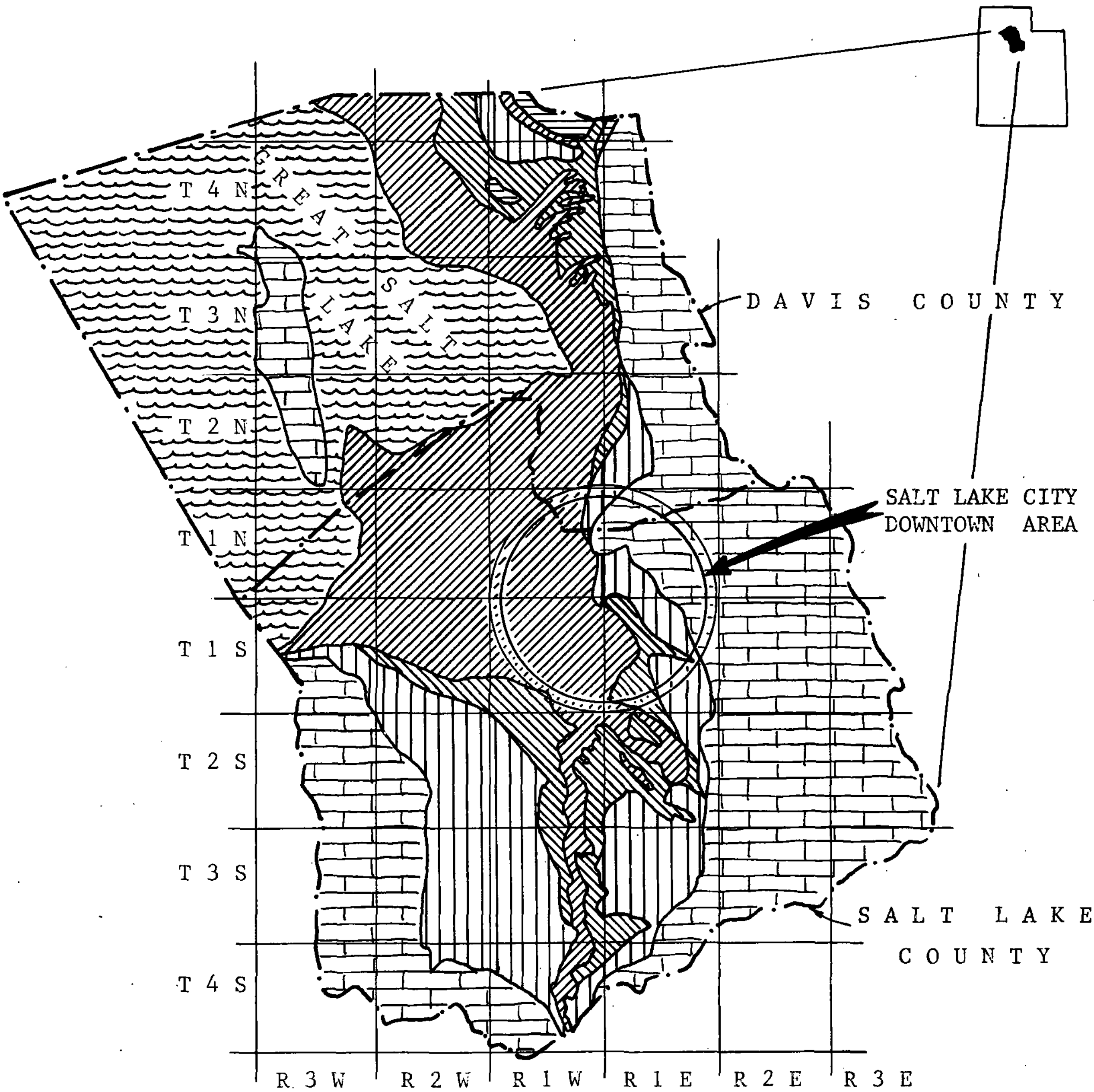
Earthquake-induced liquefaction commonly is represented by lateral spread ground failure which causes extensive disruption of the failed material. This type of ground failure is particularly damaging to buried utilities. But liquefaction can lead to ground failure without involving lateral spread slope movements. On level ground, loss of bearing capacity or loss of uplift resistance can result from liquefaction. Buildings can sink into the foundation material or tip over in response to liquefaction. Similarly, buried light-weight facilities, such as pipelines or tanks, can float to the surface in the "liquid" soil.

The only known occurrence of liquefaction in Utah was associated with the 1934 Hansel Valley earthquake which occurred in an uninhabited remote part of the state. Consequently, no damage to the urbanized zone of Utah has occurred as a result of liquefaction. However, based on an assessment of potential occurrence of ground failure caused by liquefaction, significant parts of the urban corridor of the Wasatch Front of north-central Utah are likely to be damaged during earthquake shaking which has a 50 percent or greater probability of occurrence in a 100-year time period (Anderson and others, 1982). Liquefaction potential zones for Davis and Salt Lake County are shown on Figure 1.

Earthquake-induced "landslides" have affected only relatively remote areas of Utah. Assessment of seismic slope stability in the Wasatch Front area is only now being started (Keaton and Anderson, 1984-85), so the potential impact of this type of ground failure currently cannot be estimated. An alarming conclusion drawn by Keefer (1984, p. 406) is that "few earthquake-induced landslides reactivate older landslides; most are in materials that have not previously failed."

Impacts of non-earthquake ground failure in Utah were dramatically demonstrated during the spring of 1983 (Anderson and others, 1984) and again in 1984. During these two years, landslides combined with flood losses contributed to a total damage estimate of nearly $520 million, including two fatalities in 1984. Slope movements have occurred intermittently in the urban part of Utah since the state was settled.

Ground failure can also be caused by non-earthquake processes other than slope movements. Heave can occur as a result of swelling clays; damage in Utah from this process has been relatively minor compared to other more vulnerable places, such as Colorado and Texas. Settlement can occur as a result of withdrawing fluid from a compressible aquifer or as a result of applying water to hydrocompactible deposits. Ground failure due to compressible aquifers has not been documented in Utah but certainly exists in California and Arizona (Ireland and others, 1984). Collapse of hydrocompactible deposits in Utah has been documented in the Cedar City, Price and Vernal areas and has caused substantial damage (Kaliser, 1982).



EXPLANATION

- High liquefaction potential
- Moderate liquefaction potential
- Low liquefaction potential
- Very low liquefaction potential
- Bedrock materials not susceptible to liquefaction

FIGURE 1
LIQUEFACTION POTENTIAL ZONES
DAVIS AND SALT LAKE COUNTIES

DAMES & MOORE

Reference: Modified from Keaton and others, 1983

Remote effects of ground failure can contribute to damage. For example, ground failure in the form of debris slumps or slides on the mountain slopes above Davis County had sufficient water available to mobilize into debris flows which damaged the communities at the base of the mountains. The actual ground failure occurred 1 to 4 miles away from the locations of the damage. The damage was caused by passage or accumulation of the debris from relatively remote ground failures.

RISK ASSESSMENT AND RESEARCH NEEDS

Ground failure hazard evaluations in Utah generally have been done on a piecemeal basis, concentrating on only one type of ground failure. In the 1970's, the emphasis was on mapping surface traces of the Wasatch fault zone in the Wasatch Front area (Cluff and others, 1970). Thus far in the 1980's, the emphasis has been on differentiating liquefaction potential zones (Anderson and others, 1982). However to achieve the ultimate goal of reducing losses from ground failure hazards, all variety of ground failure types must be considered in "multiple hazard" assessments.

The emphasis on the Wasatch fault zone may give a false sense of security resulting from the attitude that, "If I'm not located on the fault, then I'm earthquake-safe." This attitude is particularly dangerous because, of the variety of ground failure hazards, fault rupture certainly affects the smallest area and probably is one of the easiest to deal with.

Two basic factors need to be coordinated for ground failure loss reduction: 1) the hazard assessments must consider multiple types of ground failure, and 2) the social implications of prudent land use and acceptable risk must be dealt with in a responsible fashion. Consideration of multiple hazards is straightforward and a relatively simple task; one of the difficulties associated with it is acquisition of funding for conducting the assessment. For example, it is difficult for a researcher to justify using Earthquake Hazard Reduction Program funds for assessment of non-earthquake hazards.

Dealing with the social implications is complex and difficult. One of the problems is that the scientists conducting the hazard assessments rarely become involved in assisting the land use planners or public administrators in using or applying the hazard assessments. Once hazard areas are identified, another problem is the distinction in risk between existing facilities and proposed facilities. It is easy to require proposed facilities to avoid hazards or to accommodate them in design. It is practically impossible to reduce the risk of damage to existing facilities in hazardous areas.

Accurate estimates of losses in terms of damage to existing facilities probably would be valuable in demonstrating the extent to which the losses could be reduced. Accurate estimates of losses require quantified probabilities of risk or damage levels. Among the most critical of existing facilities are lifelines.

In the context of assessment of multiple hazards, an important and urgent task is development of a comprehensive model that permits synthesis of characteristics and hazards of the different types of ground failure. Specific ground failure hazards are being assessed on a piecemeal basis; to combine them into a systematic, overall assessment requires consistent hazard evaluation criteria, data formats, and map scales.

Research needs for ground failure hazard and risk assessment can be summarized in the following six specific tasks:

Task 1. Probabilistic methodologies for ground failure assessment should be improved. Among the most important issues for this task are liquefaction-induced failures and seismically-induced slope failures

Task 2. A basis needs to be developed for estimating how much movement is likely to result from liquefaction-induced ground failure and from seismically-induced slope failure.

Task 3. Many of the soils in the Wasatch Front area were deposited in Lake Bonneville and consist of thinly-bedded fine sand and silty clay. The fine sand layers are susceptible to liquefaction while the silty clay layers are not. A unique characteristic of these soils is that the liquefiable sand layers are very thin, actually thinner than can be detected by conventional investigation techniques. The implications of the unique characteristics of the local soils with respect to liquefaction potential and to ground failure needs to be assessed.

Task 4. Tectonic subsidence and ground tilting have accompanied earthquake events in the Basin and Range region. A preliminary analysis of the consequence of tectonic subsidence of the same magnitude or that which accompanied the 1959 Hebgen Lake, MT. earthquake was performed by R. B. Smith for the urban area north of downtown Salt Lake City. As he reports in this volume, substantial "permanent" flood inundation would occur at the margin of the Great Salt Lake. He found a similar result at the margin of Utah Lake. The hazard from tectonic subsidence in the Wasatch Front area must be assessed systematically and combined with other hazard assessments.

Task 5. During the Winter and Spring months, thousands of visitors as well as local residents enjoy skiing on famous Utah snow. An earthquake occurring between mid-December and mid-May could create a substantial problem by inducing major snow avalanches in the mountainous terrain where the ski resorts are located. Additional avalanches could impact the transportation corridors leading from the Wasatch Front communities toward the east, all of which pass through the Wasatch Range. A systematic assessment of the hazard from earthquake-induced snow avalanches should be made.

Task 6. Damage estimates for post-earthquake reconstruction and loss reduction are being developed chiefly by planners and public safety and emergency management personnel. Scientists developing ground failure hazard assessments should assist in developing realistic estimates of damage based on the results of their studies. Lifeline damage estimates are particularly important because of the large number of people who could be potentially impacted by loss of lifelines.

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APPLICATION OF GROUND FAILURE MAPS TO EARTHQUAKE HAZARD REDUCTION

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INTRODUCTION

The National Program for Earthquake Hazards Reduction stipulates that regional earthquake hazards assessments be conducted in urban areas "identified as having moderate to high risk, including analyses of potential ground shaking and ground failure on a regional scale and the demonstration of specific hazard assessment techniques unique to each region. (This does not include block-by-block analyses (microzoning), which are more properly performed at the State and local level.)" In response to this requirement, techniques have been developed for compiling maps of liquefaction and ground failure potential on a regional scale, and maps for several regions have been completed. Methods for applying these maps by state and local governments, financial, insurance, and other private groups to reduce earthquake hazards, however, are still largely in the developmental state. The purpose of this paper is to examine some applications and benefits that are presently being derived form these maps.

AVAILABILITY OF LIQUEFACTION AND GROUND FAILURE MAPS FOR UTAH

Utah State University and Dames and Moore Consulting Engineers (Anderson, this volume) are preparing a series of liquefaction potential maps for several counties in the State under sponsorship of the U.S. Geological Survey. A map for Davis County has been completed and maps are in preparation for Salt Lake and Utah Counties. Contracts are being prepared for compilation of liquefaction potential maps for additional counties in the northern part of the state and also for evaluation of regional landslide hazards along the steep Wasatch Mountain front. These maps are regional in scale and are more valid for comparing the relative hazard in one area or zone versus another than for making decisions about the hazard at a particular site. Site specific geotechnical studies are required to make the latter determination.

APPLICATION OF LIQUEFACTION AND GROUND FAILURE MAPS

Considerable progress has been made in compiling maps showing areas subject to liquefaction; application of these maps, however, to reduce or mitigate liquefaction hazards is still in a developmental-experimental state. There are three general areas where effort is being made to use these maps - land use planning, building code provisions, and bases for insurance rate and other financial decisions.

Land use planning.--The broadest attempt to date in this country to mitigate earthquake hazards through land use planning is the required inclusion of a seismic safety element in the general plan of each county and community in the state of California. Each seismic safety element considers liquefaction and ground failure along with other earthquake hazards. With respect to liquefaction and ground failure, the elements generally define the processes and associated hazards, give general information on areas in the community where susceptible materials might lie, state general plan requirements for potentially hazardous areas, and suggest zoning and engineering measures to mitigate the hazard. A statement from the Fremont, California Seismic Safety Element is given here as an example:

> The areas subject to general ground failure presently have General Plan designations of industrial use, public open space use, medimum density residential use, and transportation facilities, including portions of the Fremont Airport. These areas are located in the westernmost portion of the Northern Plain, in the Baylands, and in the industrial area. The most westerly of these lands are classified by the U.S. Soil Conservation Service as Land Capability Class VIII. Such lands will be designated Open Space when the Baylands Area plan is amended to implement the Open Space Element of the General Plan. The remainder of the soils in this area have a Land Capability Classification of III and would not be disignated Open Space. Development need not be totally prohibited in either of these areas. However, thorough testing of the liquefaction potential of any proposed development site should be required. In gereral, these areas will be more appropriate for light, low structures and for low intensity uses than for tall structures and intensive uses.

Seismic Safety Elements are being used as a valuable aid to California communities for understanding their earthquake hazards and for implementing planning and regulatory measures to mitigate the consequences. Examples of planning measures that have been implemented based on information produced for the elements are set-backs from active faults and improved building code provisions. Additional benefits and more concious use of the available information will likely develop as more experience is gained.

Building codes.--The influence of soil conditions on the response of buildings to earthquake shaking has long been recognized and criteria incorporated into some building codes to account, at least in part, for that influence. Code provisions to consider the effects of liquefaction and ground failure, however, are only now being developed. A pioneering effort in this area is occuring in the City of San Diego, California. A tentative code element has been drafted and approved by several key committees and final inclusion in the city building code and city approval is expected (oral communciation, Andrew Dawson, Woodward-Clyde Consultants, March 1984). The San Diego element (see appendix to this paper) primarily requires specific engineering investigation for various classes of construction where these developments are to be located in potential liquefaction areas as delineated in the Seismic Safety Element of the General Plan. In this instance, the Building Code and the Seismic Safety Element are complimentary. This element might serve a as model for other communities, including those in Utah with potential liquefaction problems. If adopted and implemented, this element should significantly reduce the risk of damage from liquefaction to major new construction in San Diego, while allowing wavers for relatively low-cost, low-occupancy construction, such as residential housing, where the owner is willing to accept the risk rather than pay for the expense of an engineering investigation.

Financial and Insurance Considerations

Although liquefaction and ground failure potential maps appear to be well suited for use by insurance companies to set rates based on risk and by other financial companies as a factor in the decision making processes, this writer knows of very little application in these areas. Possible incentives from favorable financial decisions and insurance rates and financial requirements for safe siting of constructed works could have considerable beneficial impact for earthquake hazard mitigation. Such measures could also provide means for local property owners and communities to repair or reconstruct damaged facilities with out calling for emergency help from state and federal governments.

Appendix - Code Element on Liquefaction

Tentatively Approved For San Diego, California Building Code

(condensed and slightly reworded by the author)

Soil Liquefaction: These requirements are applicable to "potential liquefaction" areas as identified in the Seismic Safety Element of the General Plan for the City of San Diego.

Exception: An evaluation of the liquefaction potential and mitigation measures if necessary are required for any site, regardless of lacation, if an essential facility is to be lacated at the site (see item 1.A., below).

1. Investigations: An investigation conforming to Section 2905 shall be made of subsurface soils to evaluate their susceptibility to liquefaction from earthquake-induced ground shaking for the following structure or occupancy categories.

A. Essential facilities.

Essential facilities are those structures or buildings which must be safe and usable for emergency purposes after an earthquake in order to preserve the health and safety of the general public. Such facilities shall include but not be limited to:

1. Hospitals and other medical facilities having surgery or emergency treatment areas.
2. Fire and police stations.
3. Municipal government disaster operation and communication centers deemed to be vital in emergencies.

B. Buildings with an importance factor greater than 1.0 as specified in the tabulation below:

Type of Occupancy	Importance Factor
Essential facilities	1.5
Any building where the primary occupancy is assembly of more than 300 persons (in one room)	1.25
All others	1.0

C. All buildings over two stories in height.

D. All buildings containing the following occupancies:

1. Any building with an assembly room and a stage or with an assembly room with an occupant load of 300 or more without a stage, including such buildings used for educational purposes.

2. Any building used for educational purposes through the 12th grade by 50 or more persons for more tha 12 hours per week or four hours in any one day.

3. a. Buildings for storage, handling, use, or sale of hazardous and higly flamable or explosive materials other than flamable liquids. b. Buildings for storage, handling, use, or sale of Classes I, II, and III-A liquids (includes dry cleaning plants, paint stores with bulk handling, paint shops, spray-painting rooms and shops).

4. a. Nurseries for the full-time care of children under the age of six accomodating more than five persons.

   b. Hospitals, sanitariums, nursing homes with nonambulatory patients and similar buildings (each accomodating more than five persons).

   c. Mental hospitals, mental sanitariums, jails, prisons, reformatories and buildings where personal liberties of inmates are similarly restrained.

E. All buildings with an occupant load of more than 300 (as determined from Table 33-A of the building code).

F. Tanks of more than 20,000 gallons capacity intended for storage of toxic, hazardous or flammable contents.

G. Tanks over 35 feet high.

H. Towers over 35 feet high.

I. Other structures not included in categories A through H, except construction of a minor nature as determined by the Building Official, must either have an investigation made to evaluate if hazards are posed by the effects of liquefaction, and if so, to incorporate measures to mitigate the hazards or obtain a waiver from the Building Official. The waiver, which shall be executed by the legal owner, approved by the Building Official and recorded by the County Recorder, shall state the applicalble facts relative to potential liquefaction and shall attest to the legal owners's knowldege thereof.

A PLAN FOR EVALUATING HYPOTHESIZED SEGMENTATION OF THE WASATCH FAULT

by

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ABSTRACT

Swan and others (1980) and Schwartz and Coppersmith (1984) hypothesized that seismogenic structure along the Wasatch fault zone is segmented, and that segments tend to rupture completely and independently in earthquakes of characteristic sizes. If true, that would affect hazard evaluation along the Wasatch Front urban corridor. This report proposes ways to evaluate the hypothesis of segmentation. The most direct evaluation would come from more trenching of the Wasatch fault, but probability calculations suggest that that could require several times as many sites as have been trenched thus far. Methods of tectonic geomorphology may also be used to evaluate segmentation. So may statistical evaluation of spatial associations of structural and geophysical anomalies with proposed segment boundaries, and specialized structural studies of proposed boundaries.

INTRODUCTION

Schwartz and Coppersmith (1984) hypothesized two things that, if true, would have much impact on evaluation of seismic hazard for the Wasatch Front urban corridor. First, they proposed that the Wasatch fault comprises six segments that are mostly or wholly independent of each other structurally and seismogenically. Second, they proposed that seismic release of energy in a given segment occurs mostly as earthquakes of a size that is characteristic of that segment. These characteristic earthquakes tend to rupture the whole segment but tend not to rupture across segment boundaries into adjacent segments.

Neither hypothesis implies the other, but if the fault is not segmented then earthquakes of various sizes may be regarded as occurring more or less randomly along the fault. The fault as a whole and any portion of it would be likely to exhibit the standard behavior that is characterized by a constant slope (b value) on a recurrence plot. Of the two hypotheses, segmentation is the more fundamental for understanding behavior of the Wasatch fault. This report outlines a plan for evaluating the segmentation hypothesis.

IMPORTANCE

If segments rupture individually and independently, and usually in earthquakes of a characteristic size, there would be several consequences. First, there would be more large earthquakes than expected from a linear extrapolation of a recurrence relationship that is derived from historical and instrumental earthquakes (Schwartz and Coppersmith, 1984). Such a departure from constant slope of a recurrence plot could reconcile the discrepancy between low observed frequencies of small earthquakes and geologic observations of abundant fault scarps. The scarp observations indicate a frequency of large earthquakes along the Wasatch Front that is about 10 to 30 times that inferred from extrapolation of observed small earthquakes (Schwartz and Coppersmith, 1984, their fig. 13).

Second, Schwartz and Coppersmith (1984, their table 2) suggested that scarp forming events in the past 8,000 years have been concentrated in the four central and most heavily populated segments. Indeed, compared to frequencies expected if scarp forming events were distributed uniformly along the Wasatch fault zone, their data imply that segmentation could nearly double the frequency of large events in the Salt Lake City and Nephi segments. That increase in frequency would be in addition to the tenfold to thirtyfold increase inferred from scarp abundances.

Third, production of probabilistic maps of seismic hazard uses estimates of three parameters: the magnitude of the largest expected earthquake, the recurrence interval of earthquakes of that size, and the geographic zone over which those two values are expected to apply (Algermissen and others, 1982; Thenhaus, 1983). Segmentation of the Wasatch fault would change estimates of all three parameters, and thus would alter the calculated hazard. If the characteristic earthquake hypothesis is also true, it might not further affect the zones, but would greatly change estimates of maximum magnitudes and recurrence intervals in each zone.

Thus the segmentation hypothesis, particularly with addition of the characteristic earthquake hypothesis, poses questions whose answers will greatly affect hazard evaluation along the Wasatch Front, and particularly in the population centers of the central portions of the front.

STRATEGY

Design of an investigation of segmentation is governed by consideration of pertinent time scales, and of the significance of spatial associations. The portion of the future about which hazard evaluation attempts to draw conclusions is the next decades, centuries, and millennia. Periods extending successively further into the future are of interest for emergency planning, for design of critical structures, and for storage of radioactive or toxic wastes. For example, the probabilistic hazard maps of Algermissen and others (1982) are calculated for the next 10, 50, and 250 years. Thus geological and other data are pertinent to the evaluation of segmentation for hazard purposes only to the degree that those data apply to the coming decades to millennia.

The Wasatch Front lies in an extensional tectonic regime. So does northeastern China (Molnar and Tapponier, 1975, 1977; Zhang and others, 1984). For northeastern China, McGuire (1979) and McGuire and Barnhard (1981) found that seismicity of a 50-year period is best characterized by that of the preceding 50 years. However seismicity of a 200-year period is poorly characterized by that of the preceding 200 years, because Chinese seismicity exhibits an apparent cycle with a period of about 300 years. Implications of those findings for the Wasatch Front, for which Schwartz and Coppersmith (1984) estimated a recurrence interval for scarp forming events of about 444 years, are that useful geologic records will most probably be those that formed during, or can be shown to bear on, the Holocene and late Pleistocene, a length of time over which any such cyclicity is likely to be averaged out.

To identify segment boundaries and to demonstrate their existence and control on Holocene and late Pleistocene evolution of the Wasatch fault zone, Schwartz and Coppersmith (1984) sought spatial coincidences of proposed segment boundaries with anomalies in several types of geological and geophysical data along the front. For instance, they examined breaks and shape changes in the mapped trace of the Wasatch fault, differences in ages of the most recent scarp-forming events, saddles in the Bouguer gravity field over the valleys that border the front on the west, changes in crestal elevation of the Wasatch Range, and changes in morphology of young fault scarps. No one kind of data clearly reveals or convincingly documents segments or their boundaries. However, the argument is that (1) spatial coincidence of anomalies of several kinds is good enough that it cannot be attributed to chance, but must reflect some common underlying cause of the various kinds of anomalies, and (2) each type of anomaly occurs in data of a sort that is likely to reflect structures that are probably responsible for

Holocene seismicity, so that the inferred common cause of the anomalies may also affect that seismicity.

This is a fundamentally statistical argument, so the subjective perception of spatial coincidence, and its evaluation as being better than would be expected from chance, can be tested objectively. That is fortunate, because there are few enough anomalies of few enough kinds that another observer might form the opinion that the coincidence is a result of chance, and that there is no underlying common cause. Such a disagreement between two subjective perceptions is usually difficult to settle without either a properly designed statistical test, or more data. The first alternative is usually quicker and cheaper.

Thus the strategy will be to seek answers to two questions. First, do segments exist along the Wasatch Front, or are they artifacts of perception and a small sample, indistinguishable from patterns arising from chance? Second, if segments exist, have they affected uplift and seismicity along the Wasatch fault both in the Holocene and far enough back in time that they can be expected to continue those effects for the next decades, centuries, and millennia?

INVESTIGATIONS

Several lines of investigation are proposed below. Limits on personnel and funding make it unlikely that all can be pursued to completion by the end of fiscal year 1986. However, all are described here in the hope that other workers may wish to follow one or more of them. A following section gives preliminary results from some of the investigations.

Paleoseismicity and Tectonic Geomorphology

The most direct way to evaluate the hypotheses of segmentation and of characteristic earthquakes together would be to examine the record of Holocene and late Pleistocene faulting and uplift, as expressed in landforms and in alluvial and colluvial stratigraphy. For example, the most direct evidence for segmentation of the Wasatch fault comes from the trenches described by Swan and others (1980) and Schwartz and Coppersmith (1984), and comprises differences, from segment to segment, in the ages of and intervals between scarp-forming events. However, there is only one trench site per segment, with as many as three trenches per site, so the present trench data cannot determine whether the differences between segments exceed the variability within segments. More trench sites would solve that problem but would be expensive and would require careful preparation. Because of that high cost, decisions about the need for additional trenching of the Wasatch fault and identification of optimal locations for additional trenches might best await results of continuing mapping of late Cenozoic deposits along the Wasatch Front (for example, see M. N. Machette, this volume).

Currey (1982) measured elevations of Bonneville, Provo, and other shorelines throughout the Lake Bonneville basin of Utah, Idaho, and Nevada. Elevations near the Wasatch Front are few, but D. R. Currey (oral and written communs., 1984) estimates that many more could be obtained on both hanging and footwalls of the Wasatch fault. Then perhaps one could determine whether, say, footwall elevations of the Bonneville shoreline differ significantly from one segment to another, or whether pairs of elevations that span the fault demonstrate differing amounts of post-Bonneville dip slip in adjacent segments.

Mayer and Wentworth (1983) demonstrated that statistical analysis of stream-gradient indices can detect the existence and sense of recent dip slip across an inferred fault. Similar analysis, controlled for the effects of lithology of the bedrock and other factors, may be able to detect differences in uplift rates between segments, and compare such differences to variability within segments (L. Mayer, 1983, and written communs., 1983).

Other numerical or descriptive characterizations of landforms that record uplift may also be able to detect differences between proposed segments that exceed variability within segments. These include elevations of ridge crests atop faceted spurs (Hamblin, 1976; Hamblin and Best, 1980), steepness of the range front (Hamblin and Best, 1980), and determinations of which wall of the Wasatch fault remained stationary while the other wall moved up or down relative to it (Hamblin, 1984).

Spatial Associations

It should be straightforward to design and perform a statistical evaluation of the suggested spatial association of geological and geophysical anomalies with the inferred segment boundaries. The goal would be to determine whether the proposed segment boundaries occur at the same places along the Wasatch Front as do anomalies in structural and geophysical data of types that are available along most or all of the front. For each kind of data used, it must be shown that the kinds of anomalies selected are those that would reflect structures that could localize segment boundaries. Examples include gravity and magnetic data, geometry of thrust sheets along the front, and large features that trend across the front such as the Little Cottonwood stock and the edges of the Uinta aulacogen.

If the proposed segment boundaries as a group are significantly associated with structures that predate the Wasatch fault, then those older structures can be interpreted as having caused segmentation of the fault (Zoback, 1983). If the association is not significant, then either the proposed segment boundaries do not exist, or they exist but represent distortions in the late Quaternary evolution of the Wasatch fault that are randomly distributed along the front, or the boundaries exist and are long-lasting features of the fault but have not been localized by older structures. Any of those three interpretations would cast doubt on the segmentation hypothesis, the hypothesis of characteristic earthquakes, or both.

Bedrock Structure

Whether or not the proposed boundaries as a group can be shown to be significantly associated with older structures, and interpreted as caused by them, specialized geologic mapping and structural studies of small, selected areas may be able to demonstrate segmentation, control by older structures, or both for a single segment boundary.

Structure maps.--Thrust sheets of the Sevier orogeny reached the Wasatch Front from the west in Cretaceous time (Armstrong, 1968). There, the complex of thrust sheets is interpreted from well, seismic reflection, and stratigraphic data to be 5 to 10 km thick (Standlee, 1982; Smith and Bruhn, 1984). The Wasatch fault cuts that complex. Abrupt, along-strike changes in the geometry of the thrust sheets could have caused interruptions, bends, or en echelon steps in the Wasatch fault zone. If that happened, the result would be segmentation of the fault.

Figure 1 illustrates a way in which the shape and internal structure of a thrust sheet could cause segmentation of a zone of normal faults that cuts it. Figure 1a shows the footwall of an east directed thrust sheet. On the flats the sheet rides on bedding-plane faults. At the longitudinal ramps the thrust fault cuts up section as a reverse fault. Common in thrust complexes are transverse ramps (buried tear faults), where the ramp locally has a different strike and experiences oblique or strike slip. Atop the longitudinal ramps, units that are cut by the ramps are duplicated structurally. This duplication and related processes form hanging-wall anticlines (fig. 1b). Because little or no duplication occurs above the transverse ramp, and because the longitudinal ramps do not aline, the anticlines plunge past each other (fig. 1c).

If instead the two longitudinal ramps of figure 1a represent two thrust faults that lose displacement past each others' tips (fig. 1d), then no transverse ramp need form. The result is a transfer zone (Jones, 1971), in which slip is transferred en echelon from one fault to another, so that all east-west sections through figure 1d experience the same net shortening. Transfer zones and transverse ramps can occur together, and complexities abound in natural examples (Boyer and Elliott, 1982; Harris, 1970).

The portion of the thrust sheet above transverse ramps and transfer zones is structurally disrupted. Where several transverse ramps or transfer zones occur in rough alignment across strike, and are not yet exposed by erosion, their expression in the overlying thrust sheet is a CSD (cross-strike structural discontinuity) (Wheeler, 1980; Wheeler and others, 1979). The rocks exposed in CSD's of the Appalachians differ in various ways from rocks of the same units that are exposed along strike, outside the CSD's (Wheeler and others, 1979). The various structural, geophysical, geomorphic, stratigraphic, hydrologic, and metallogenic anomalies that can be distributed along a CSD allow its recognition, and can be interpreted in terms of underlying, concealed transfer zones and transverse ramps. Some CSD's can be inferred to have formed above causative basement faults, but generally that inference cannot be tested because the rocks that contain the CSD have usually been thrust away from whatever portion of the basement they might originally have overlain (Wheeler, in press).

(a)

(b)

(c)

(d)

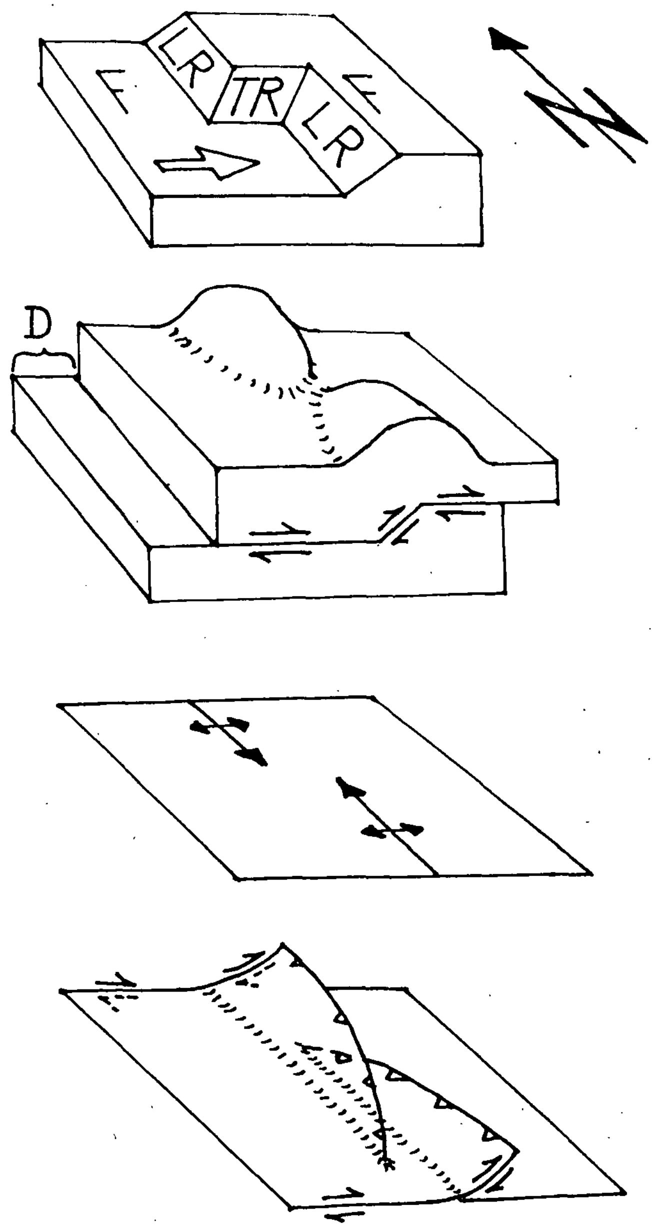

Figure 1.--Sketches showing geometries of structures that may occur in or under CSD's in thrust complexes. (a) Block diagram of footwall of a thrust fault. Open arrow shows direction of transport of hanging wall (not shown) over footwall. F shows flats, LR shows longitudinal ramps, and TR shows transverse ramp. (b) Block shown in (a), with addition of hanging wall block. Transport over distance D, in direction shown by arrows on front faces of blocks, produces hanging wall anticlines shown on top surface of block. (c) Geologic map of top surface of block shown in (b), with arrows showing trends of hanging wall anticlines and plunges of their noses. (d) Shape of bottom surface of a hanging wall block that has been cut by two thrust faults whose tips overlap and which die out past each other, en echelon. Sawteeth identify leading edges of both faults.

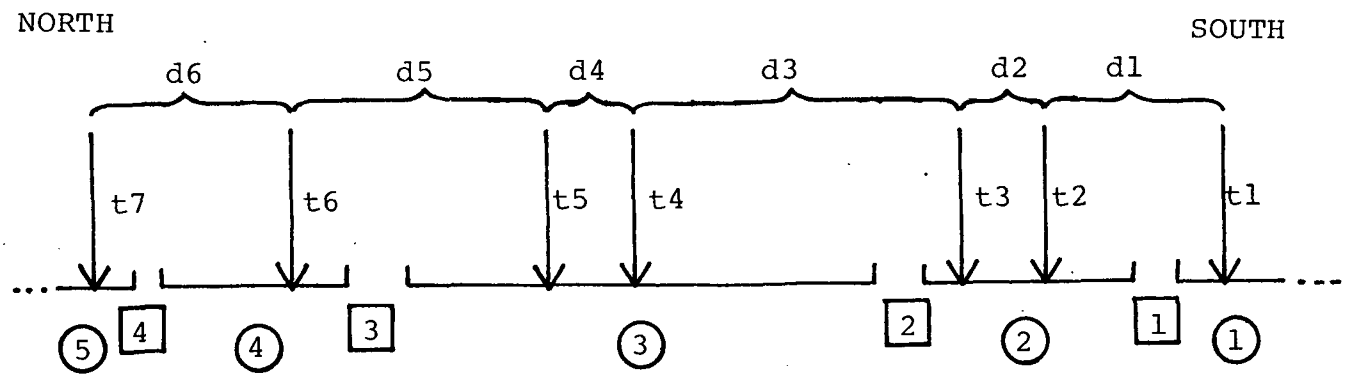

Figure 2.--Schematic diagram of hypothetical example for one value of t per site (see text). View is to east. Long horizontal brackets identify segments, from north to south along Wasatch Front. Circles enclose segment numbers, and squares enclose boundary numbers. Arrows point to locations of trench sites, at which t values are obtained. Here, in notation defined in text, s = 7, b = 4, and d(i) = t(i+1)-t(i).

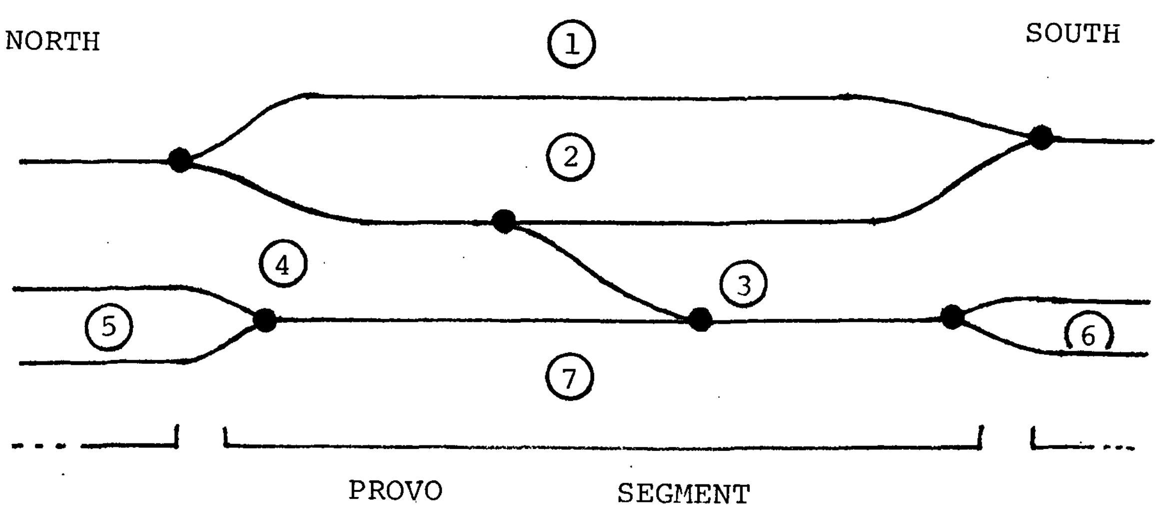

Figure 3.--Schematic diagram representing view eastward toward range front in Provo segment and adjacent ends of adjoining segments. Horizontal lines represent pediment surfaces. Dots on them represent branch points. Slopes between pediment surfaces represent periods of uplift, ranked approximately from youngest (circled 7) to oldest (circled 1).

If a thrust complex, complete with transverse ramps, transfer zones, and perhaps overlying CSD's, such as the Sevier thrust complex (Smith and Bruhn, 1984), is extended in a direction roughly similar to the older direction of thrust transport, normal faults that nucleate between CSD's will propagate along strike and encounter a CSD. If the propagating normal fault stops, bends, splits, changes to strike slip, or is replaced en echelon by another, it is most likely to do so in the weakened, disrupted rock of a CSD, other things being equal. Thus CSD's may partly decouple portions of the extending mass from each other, resulting in segmentation.

Prospecting for CSD's can be time consuming, so fieldwork will be confined to the area at and around the boundary between the Provo and Nephi segments, near Payson. There, structure and stratigraphy are simpler than at other segment boundaries. Maps useful in detecting and defining CSD's include strike-line maps, maps of contours of values of bed dip, and structure contour maps (Wheeler, 1980; LaCaze and Wheeler, 1980; Wheeler and others, 1979, and references cited there). Most data needed for production of such maps have been obtained from compilations being prepared by I. J. Witkind and B. H. Bryant (oral and written communs., 1983-84), and from bed orientations plotted on numerous published and unpublished maps, mostly M.S. theses from Brigham Young University.

Geologic mapping.--Inspection of the geologic and structural compilations just mentioned reveals several small areas where detailed remapping may aid evaluation of the proposed boundary between the Provo and Nephi segments. All are in or near the Payson Lakes quadrangle (fig. 4). In and adjacent to the northwestern portion of that quadrangle, the Wasatch fault of the Nephi segment extends northeastward along the west edge of Dry Mountain. East of Dry Mountain, the fault of the Provo segment extends southwestward; its

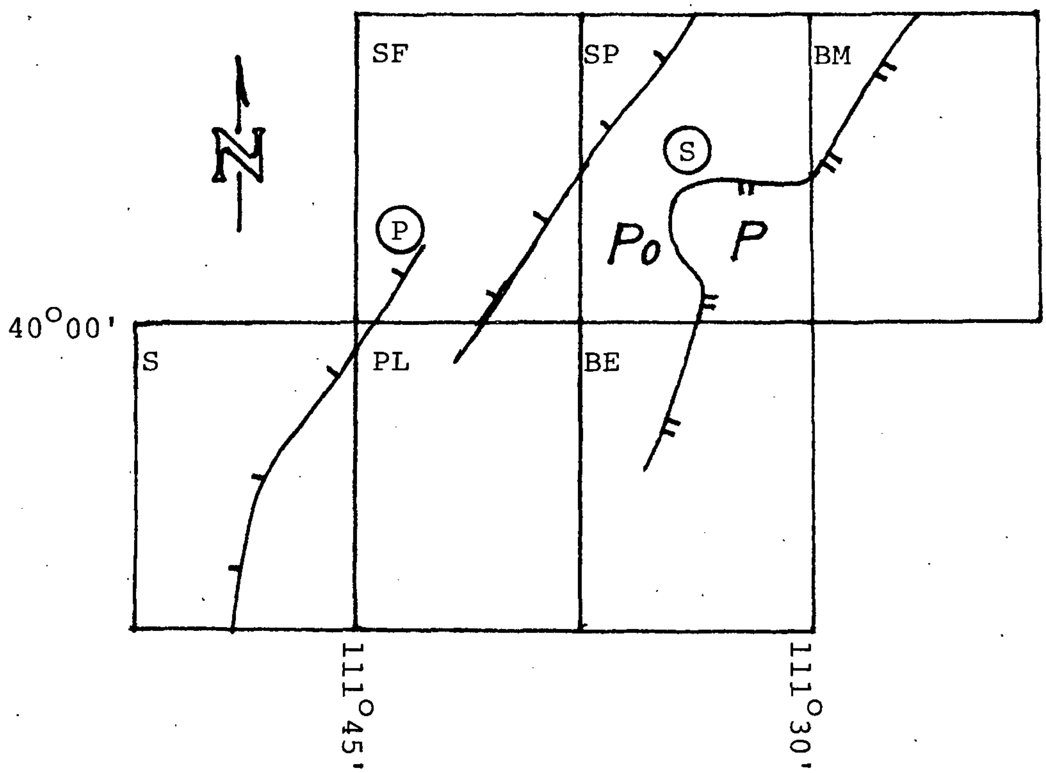

Figure 4.-- Sketch map summarizing preliminary evidence for a CSD at or near the segment boundary at Payson (circled P). 7.5 minute quadrangles shown are Spanish Fork (SF), Spanish Fork Peak (SP), Billies Mountain (BM), Santaquin (S), Payson Lakes (PL), and Birdseye (BE). Line with single hachures represents approximate locations of portions of the Wasatch fault that enter SP from the north, as the Provo segment, and S from the south, as the Nephi segment (after Davis, 1983). West sides are down. Line with double hachures represents the contact between the Oquirrh Formation and older rocks (Po) with overlying Permian and younger units (P), all upright and dipping southeasterly (after Davis, 1983). Double hachures show generalized directions of bed dips at and west of that contact. In BE, elevation of contact is mostly above 8000 feet, and in eastern SP and BM, mostly below 7000 feet. Numerous bed orientations (not shown) in SP, PL, and BE are from Harris (1954), Metter (1955), Rawson (1957), Hintze (1962), Baker (1972), and Davis (1983).

Circled S in center of SP shows location of road cuts of Oquirrh Formation in Spanish Fork Canyon, where systematic joints have been analyzed (see text).

southwestern tip overlaps the northeastern tip of the fault of the Nephi segment (fig. 4). Between the two fault tips, Dry Mountain exposes Precambrian to upper Paleozoic rocks. Mapping of young faults between those two fault tips should aid in evaluating the proposed segment boundary.

In the north-central portion of the Payson Lakes quadrangle, Metter (1955) mapped exposures of Flagstaff Limestone throughout about one-fourth of a square kilometer. The Flagstaff Limestone is Eocene in age (MacLachlan, 1982), and Metter mapped the Bear Canyon thrust fault at its southeastern contact. The thrust fault is probably a splay within the Charleston-Nebo thrust complex. If remapping verifies that it cuts the Flagstaff Limestone, then some thrusting continued as late as Eocene.

In the central portion of the Payson Lakes quadrangle are two basins defined by concentric belts of outcrops of several Tertiary units. In the centers of the basins occur exposures of volcanic and sedimentary rocks of late Eocene to Oligocene age (Davis, 1983). The few available bed orientations from the basins, together with basin orientations and positions, are consistent with the hypothesis that the basins represent synclines separated by an anticline, all formed above a blind thrust that is part of the Charleston-Nebo thrust system. If remapping verifies that hypothesis, the basins would constitute further evidence of small amounts of thrusting as late as middle Tertiary time.

Demonstration of middle Tertiary thrusting would be pertinent to evaluating segmentation if the same Tertiary units are also exposed northeast of the Payson Lakes quadrangle, on the other side of the proposed segment boundary and about on strike with the exposures just described. If such rocks can be found, and if they are not folded, that would demonstrate at least partial decoupling of the thrust complex across the segment boundary, and would support the inference of a CSD at the location of the segment boundary.

Jointing history and intensity.--Joint fabrics of thrust sheets can change into and across CSD's. Dixon (1979), Wheeler and Dixon (1980), and LaCaze and Wheeler (1980) found that systematic joints are more closely spaced inside Appalachian CSD's than outside them. Both greater size and greater abundance of joints produce smaller spacings (Wheeler and Dixon, 1980). If a CSD and its causative structures partly decoupled adjacent portions of a thrust complex during one or more episodes of joint formation, then jointing history may also change into or across a CSD, and so may help to detect and define it. Jointing history can be worked out by using joint shapes, fillings, and abutting relations, and delicate structures on joint faces such as plumose structures. Interpretation of such joint features to elucidate the evolution of single joints and of intersecting joints follows the principles of fractography, which were developed by ceramicists and applied to rocks in the field by Kulander and others (1979), Barton (1983), Verbeek and Grout (1983), Grout and Verbeek (1983), and R. L. Wheeler (unpub. data, 1978-84).

Examination of jointing history and intensity will be concentrated at and near the inferred boundary between the Provo and Nephi segments, near Payson. There, the most widely exposed rocks are the interbedded sandstones with some shales and limestones of the Oquirrh Formation of Pennsylvanian and Permian age. Synorogenic clastic units of Cretaceous age and postorogenic lacustrine and volcanic sedimentary units of Tertiary age are exposed locally. Thus, outcrop abundance and distribution require that the proposed jointing studies begin with the Oquirrh Formation, but application to inferred segmentation of Cenozoic structures requires that results be carried into the Cretaceous and Tertiary units. Rocks of the Oquirrh Formation have a long and complex structural history. At least their older joint sets may predate Cretaceous thrusting or at least Tertiary extension, and so may be useful only for identifying widespread joint sets and CSD's. Only joints in Tertiary rocks are likely to bear directly on evolution of the Wasatch fault.

PRELIMINARY RESULTS

The sections of this chapter are organized to match those of the preceding chapter on investigations.

Paleoseismicity and Tectonic Geomorphology

How many trench sites?--The impact of the results of Swan and others (1980) and Schwartz and Coppersmith (1984) demonstrates the value of data obtained from trenches across fault scarps along the Wasatch Front. The importance and cost of such data make it worthwhile to estimate the number of trench sites that would be necessary to test the existence of segments. The following hypothetical examples illustrate that such a test would require more sites than presently exist. The examples also illustrate considerations and calculations that may be useful in optimizing future trenching operations.

Swan, Schwartz and coworkers actually trenched only the four central segments of the Wasatch Front, but surface observations in the two end segments allowed them to obtain information similar to that which could have been obtained there by trenching. Because they obtained most of the effect of six trench sites, the following discussion is phrased in terms of six sites.

The question to be answered is whether the recurrence intervals of scarp-forming events differ more between segments than they vary within segments. We will consider trench sites like the six of Schwartz and Coppersmith (1984), noting that a single site may contain more than one trench. For each example below, we use the randomization test (Conover, 1971, p. 357-364; Mosteller and Rourke, 1973, p. 12-15; Siegel, 1956, p. 152-157). In that test the P-value, or descriptive level of significance P, is the ratio of the number of ways in which the observations can be arranged to give a result at least as extreme as the one observed, to the total number of ways in which the observations can be arranged. Let s be the number of trench sites, b be the number of segment boundaries, t be the recurrence interval in years that is determined for scarp-forming events at a given trench site, and d be the difference between t values obtained from two adjacent sites. For example, for the data of Schwartz and Coppersmith (1984), s = 6 and b = 5.

In each of the following examples, we calculate the smallest value of s for which it is possible to detect segmentation at the conventional significance level of 0.05. We cannot guarantee that having more sites than the minimum number will detect segmentation if it does not exist or is very subtly expressed, but we can be certain that having fewer sites will preclude detecting any segmentation that might be there.

Suppose we obtain only one value of t per site. That might occur because the structural and stratigraphic relationships and the amount of carbon recovered for that site allow only one value of t to be determined. It might also occur because we obtain several t values from a site but wish to average them in order to decrease variability. Figure 2 illustrates this example. We could then investigate whether the average of the values of t obtained for several sites in one segment differs significantly from the average from several sites in an adjacent segment. However sites suitable for trenching might not be concentrated within two adjacent segments. It would be safer to assume that suitable sites will be found in several different segments. Accordingly we examine values of d, not t, and ask whether the values of d that span segment boundaries are significantly larger than those that occur within individual segments. For figure 2, we would ask whether d1, d3, d5, and d6 are significantly larger than d2 and d4.

In the most clear cut case, the b segment boundaries will be spanned by the b largest values of d. How many trench sites are needed for it to be possible to achieve significance at 0.05? In terms of the randomization test, P = 1/C(s-1,b), and we wish to solve for the smallest value of s for which P does not exceed 0.05. For the segments of Schwartz and Coppersmith (1984), b = 5 so s must be at least 8.

If some of the boundary spanning values of d are small, they will overlap some of the d values that do not cross boundaries. Then the result is less clear and more sites are needed to test significance. For example, suppose that the boundary spanning values of d are not the b largest in the set of s-1 numbers, but are only among the 2b largest. Then we calculate s such that 0.05 equals or exceeds P = C(2b,b)/C(s-1,b). We find that we need at least 19 sites.

Note several things about these examples. The t values will have uncertainties, and we would need to consider these uncertainties when comparing values of t and d. Correlating scarp-forming events between sites is not necessary for the calculation, but if it can be done it would aid in evaluating the uncertainties of the t values, and in determining which of any two values of d is the larger.

Also, if we obtain several t values at a site and average them to decrease variability, the averages will be more stable and reliable estimates of t than are the individual values, but our sample size will be smaller. Stabler estimates increase our ability to detect significant differences between segments, but smaller sample sizes decrease that ability. It is not clear which effect will dominate the other, so the analysis should be performed both with and without averaging. If we averaged all t values from a site, then probably we would have few enough sites in each segment that we would have to work with d values, as described above. If we did not average t values at a site, then we might have enough t values that we could work directly with them. In that case, we could ask whether the several t values in one segment differ significantly from those in an adjacent segment. The better approach of the two will be the one that gives the smaller P-value.

The upshot of these calculations is that evaluating the segmentation hypothesis with more trench sites might be done with only a few more sites than have already been obtained by Swan and others (1980) and Schwartz and Coppersmith (1984), perhaps as few as eight in all. However, evaluation could require several times that many, for example at least 19.

Crestal elevations of the Wasatch Range.--Schwartz and Coppersmith (1984, their fig. 10) note that elevation of the crest of the Wasatch Range appears to change between segments, with some large changes occurring across segment boundaries. They suggest that those changes support the notion that the range is segmented, and that the segments have been uplifted independently. That suggestion can be tested as follows. For both tests below, we use the Kruskal-Wallis test (Siegel, 1956) because the calculations for the randomization test become long and tedious for all but very small samples or special cases. Figure 10 of Schwartz and Coppersmith (1984) shows crestal elevations at 39 points along the range.

First we ask whether the largest changes in crestal elevation, as measured between two adjacent points, span segment boundaries. They do not: the five elevation changes that span boundaries exceed the other 33 changes only at $P = 0.36$. A histogram of the two groups of numbers shows no obvious difference between the two groups.

Next we ask whether adjacent segments differ significantly in elevation. The northernmost (Collinston) segment is significantly lower than the adjacent Ogden segment, with P = 0.01. However, no other pair of adjacent segments differs significantly in elevation: the other four P-values exceed 0.10.

Thus for the Wasatch Front as a whole, and for the populous central segments, these crestal elevation data are consistent with the segmentation hypothesis, but can neither support nor deny it. However, there are only about six elevations per segment, and crestal elevation at single points may be affected by lithology and structure. Other measures that could yield more values, or that could average over larger areas might detect differential uplift between segments. For instance, more values could be obtained by determining median elevations of squares measuring 10 km on a side, over the entire range. Larger areas could be averaged by estimating total rock volume that lies above, say, 6,000 ft, within strips 10 km wide and spanning the range.

Pediments atop faceted spurs.--Hamblin (1976) and Anderson (1977) mapped and correlated pediment surfaces along the western face of the Wasatch Range in and near the Provo segment, from the Traverse Mountains southward to Payson Canyon. Can the pediment data of Anderson (1977) address the segmentation question? Several assumptions are needed for the following analysis. First, we accept Anderson's (1977) identification and morphologic correlations of pediment surfaces between ridges and across canyons. Second, we assume that pediment surfaces represent periods of little or no uplift, and that the slopes between pediments represent periods of comparatively rapid uplift (Hamblin and Best, 1980).

The slope between two vertically adjacent pediments cannot represent a scarp formed by a single event, because the slopes are typically 200 to 300 m high (Hamblin, 1976). Schwartz and Coppersmith (1984) estimate typical rates for uplift produced by scarp-forming events along the Wasatch Front at about 1 mm/yr, and typical scarp heights for single events at about 2 m. Given those estimates and the range of data about them, each intrapediment slope may represent tens to hundreds of scarp-forming events that occurred over a few hundred thousand to a few million years. Thus if pediments reflect segmentation in any way, that segmentation would act on time scales much longer than the Holocene. Such segmentation would be likely to continue for the next few millennia, the time period of most interest here.

If a single pediment is followed north or south along the range front, it may branch into two pediments that continue at different elevations (Anderson, 1977; fig. 3). Branch points can be interpreted as the ends of portions of the range that underwent periods of uplift more or less as coherent blocks. If segments and their boundaries controlled that uplift and defined those blocks, then branch points should concentrate near segment boundaries.

Branches do not open preferentially to either north or south ($P = 0.26$ by the binomial test), so we seek departure from a uniform distribution of branch points along the Wasatch Front, rather than from a uniform northward or southward increase in numbers of branch points.

Anderson (1977) mapped 29 branch points in 590 linear kilometers of pediment, along 76 km of the range front. Pediment preservation, pediment detection, and range height vary along the front, so we normalize the number of branch points by kilometers of measured pediment length. Because branch points are few, and because locations and widths of segment boundaries are uncertain, we divide Anderson's (1977) 76 km traverse roughly into northern and southern quarters and central half. We ask whether the number of branch points in the two end quarters, taken together, significantly exceeds the number in the central half, normalized for the fraction of the 590 km of pediment length that falls into each of the two parts of the traverse.

The binomial test gives a value for P between 0.4 and 0.5. We conclude that either Anderson's (1977) mapped branch points contain no evidence that segmentation operated at the time scale of pediment formation, or we have interpreted the pediments and branch points incorrectly, or both.

Spatial Associations

No work has been done on this topic yet, beyond considering which types of data to use, and collecting maps of such data.

Bedrock Structure

Structure maps.--Preliminary interpretation of partly compiled data suggests that a CSD may exist at or near the inferred boundary between the Provo and Nephi segments, east of Payson (fig. 4). The structure defined by the contact between Permian rocks and the underlying Oquirrh Formation, and the distribution of bed orientations in the outcrop area of the Oquirrh Formation, are consistent with the existence of a transverse ramp under the central portion of the Spanish Fork Peak quadrangle, and a flattening of southeastward dips in areas northeast of there. Southeast dips and upright orientations throughout the area sketched in figure 4 indicate that the area lies on the front limb of a large hanging wall anticline, the Nebo anticline of earlier workers (for example, Eardley, 1934). The lower elevations of the base of the Permian units to the northeast of the inferred transverse ramp suggest that the ramp may dip north (fig. 5).

Geologic mapping.--No work has been done yet, beyond collecting and compiling available maps and structural data.

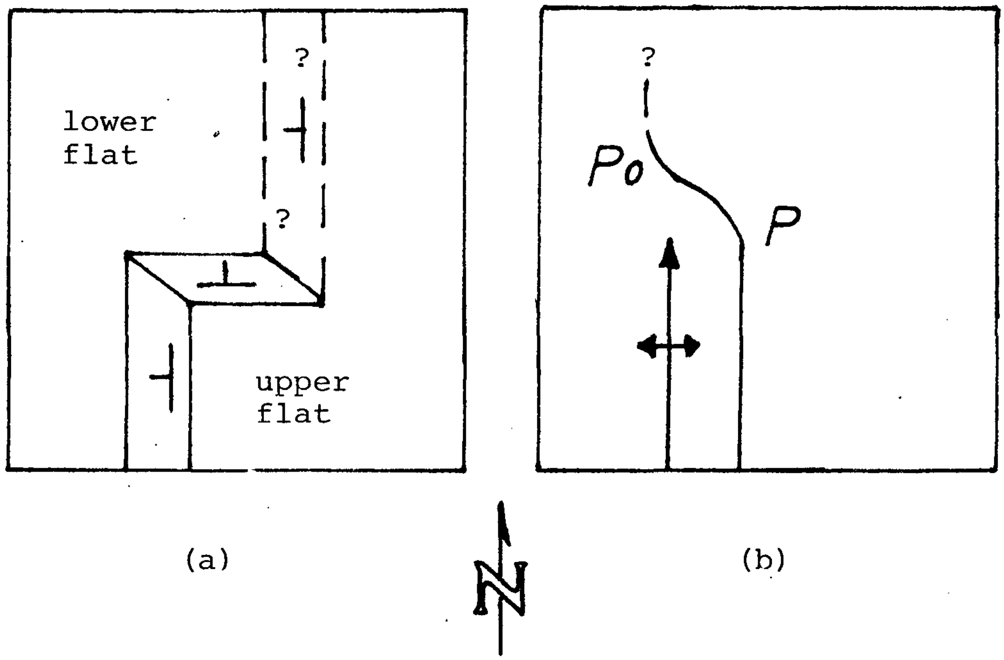

Figure 5.--Sketch maps showing inferred structure of buried footwall block (a) and exposed hanging wall block (b) in area surrounding Spanish Fork Peak quadrangle of figure 5. In (a), strike and dip symbols show dip directions of inferred longitudinal and transverse ramps. In (b), Po denotes exposed upper portion of Oquirrh Formation and older rocks, and P denotes exposed Permian and younger rocks. Hanging wall anticline in (b) overlies the southern of the two longitudinal ramps in (a). Structure in northern portion of area shown is speculative, as indicated by dashed lines and question marks.

Jointing history and intensity.--Two large roadcuts about 3 km apart in Spanish Fork Canyon expose sandstone beds of the Oquirrh Formation (circled S in fig. 5; Baker, 1972). There, four sets of calcite-filled systematic joints exhibit abutting and other relationships that define the order in which they formed; crystallization of joint fillings need not have occurred at the same time or in the same order as did jointing itself. Scattered observations elsewhere in the southern Wasatch Range indicate that this jointing history may be recognizable elsewhere in exposures of the Oquirrh Formation. Planar joints, many filled with calcite, occur in some roadcuts exposing synorogenic clastic units of Cretaceous age, and in natural exposures of the Flagstaff Limestone of Eocene age. Thus it may be feasible to develop jointing histories for those rocks. In and around the Payson Lakes quadrangle appears to be the best area to do that, and to attempt to relate jointing histories of younger rocks with that of the widely distributed and well-exposed Oquirrh Formation. Then jointing history and intensity could be compared across and into the segment boundary that is inferred to occur near Payson.

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SPECIAL SESSION -- INTRODUCTION

by

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Producers of earth-science information at the Utah Geological and Mineral Survey (UGMS) and the United States Geological Survey (USGS) believe that this information must be translated for and disseminated to nontechnical users in order to ensure its use for planning and decisionmaking. This special session was designed specifically to provide an opportunity for users of earth-science information to communicate their needs to the UGMS, USGS, and others who produce such information.

The need for a dialogue between producers and users of earth-science information is clear. It has been recommended, or its lack has been identified as an obstacle, by A. D. Little, Inc. (1975), the Council of State Governments (1976), Wissel and others (1976), Downing (1978), Kockelman (1975, 1976, 1979), the U.S. Office of Science and Technology Policy (1978), and Bates (1979). In their recent book, **In Search of Excellence**, Peters and

Waterman (1982) observe: "Finally, and most important, is the user connection .... we will simply say that much of the excellent companies' experimentation occurs in conjunction with a lead user."

Both the UGMS and the USGS have attempted to stimulate user-producer dialogues. For example, they have incorporated an implementation task (Component 5) into the workplan of the "Regional and Urban Earthquake Hazards Evaluation; Wasatch Front, Utah." Furthermore, they have sponsored or supported the "Governor's Conference on Geologic Hazards" (Utah Geological and Mineral Survey, 1983) and convened this special session on user needs.

The purpose of the special session (convened and moderated by the authors of this paper) was to carry on a dialogue in order to determine user needs for earth-science information and to identify any obstacles to its use. Five elements of the special session are of particular significance: the panelists, speakers, invitees, briefing materials, and the unrestricted discussion of needs presented by the panelists and other attendees.

Six panelists representing important city, county, State, or private planning and decisionmaking agencies and activities graciously consented to participate. The panelists were selected on the basis of their experience in the use of earth-science information and on their need to have scientific information translated, disseminated, and used. The panelists were:

Mr. Jerrold Barnes -- Planner, Salt Lake County

Mr. Darrel Crawford -- Engineering Coordinator,
Mountain Fuel Supply Company

Mr. G. Allen Fawcett -- Director, Richfield Community Planning and Economic Development

Hon. Don LeBaron -- Member, Utah State House of Representatives

Mr. George Shaw -- Planner, Sandy City

Hon. Harold Tippetts -- Commissioner, Davis County

Seven speakers experienced in determining or meeting user needs, made presentations that were prepared specifically for this session. Their individual papers are presented here in the proceedings of the workshop. The speakers' collective experience included conducting studies of user-needs, translating scientific materials for nontechnical users, communicating information to non-technical users, or using earth-science information to reduce hazards. The speakers were:

Dr. Robert Alexander -- Research Geographer, USGS

Dr. Patricia Bolton -- Social Scientist, Batelle Research Center

Mr. Wesley Dewsnup -- Manager, Utah State Multi-Hazards Project

Dr. Steven French -- Researcher, Earthquake Planning Needs

Mr. Clark Meek -- Emergency Planner, State of Idaho

Ms. Jeanne Perkins -- Planner-Geologist, San Francisco Bay Region

Dr. Merrill Ridd -- Professor of Geography, University of Utah

Invitations to participate in this session (as well as the workshop) were sent to over 70 city, county, and State officials, planners, engineers, and university researchers and educators. Representatives of the Utah League of Cities, League of Women Voters, American Planning Association (Utah Chapter), Wasatch Front Regional Council, **The Western Planner**, and the Southeastern Utah Association of Governments also were invited.

Besides the panelists and speakers, the following individuals participated in the special session:

Jerold Barnes -- Salt Lake County Planning
Barry Burton -- Davis Company Planning
Gar Elison -- Utah Department of Health
Phillip Emmi -- University of Utah
Deborah Epps -- Wyoming Disaster and Civil Defense
Terry Feldman -- Federal Emergency Management Agency
Ralph Findlay -- Utah Department of Comprehensive Emergency Management
Dave Florence -- American Red Cross
Paula Gori -- U.S. Geological Survey
Walter Hays -- U.S. Geological Survey
Patrick Johnson -- Utah Department of Health
Bruce Kaliser -- Utah Geological and Mineral Survey
Donald LeBaron -- Legislature
Anne Mathews -- Salt Lake City Tribune
Loren Nielsen -- Utah Department of Natural Resources
Richard Olson -- Arizona State University
Loren Rausher -- Utah Department of Transportation
Chirstopher Schaefer -- Davis Company Planning
George Shaw -- Sandy City Planning
James Slosson -- USGS--Boise State University
Laverne Snow -- Utah Department of Health
Jerry Solson -- Federal Emergency Management Agency
Craig Taylor -- J. H. Wiggins Company
Brent Taylor -- Bureau of Reclamation
Charles Thiel -- Consulting Engineering
Harold Tippetts -- Davis County Commission
Bruce Vandro -- U.S. Department of Agriculture--Forest Service
Delbert Ward -- Structural Facilities, Salt Lake City
Spenser Wood -- USGS--Boise State University

During the workshop that preceded the special session, the panelists, speakers, and other attendees heard talks on: (1) important research findings concerning the Wasatch Front, (2) the vulnerability of city lifelines, (3) preparedness planning, (4) specific actions to reduce potential losses, (5) some of the public liability issues, and (6) the draft work plan for evaluation of earthquake hazards along the Wasatch Front. Papers covering these subjects are included in the proceedings.

Briefing materials emphasizing the needs of users were provided to each panelist and speaker before the session and were made available to other attendees at the session. The materials were carefully selected to complement the knowledge and experience of the panelists, speakers, and other attendees. The briefing materials included excerpts from publications relating to the following topics:

- Needs of Real-Estate Brokers (Mathewson and Ruckman, 1974)
- Dissemination of Earthquake-Hazards Information (Greene and Gori, 1982)
- Natural Hazards into the Planning Curricula (Havlick and Harris, 1983)
- Management of Flood Hazards (Burby and Cigler, 1983)
- Environmental Resource Data (Council of State Governments, 1978)
- Recommendations to Meet Needs (Council of State Governments, 1976)
- Factors For and Against Microzonation (Olson and Nilson, 1982)
- Political Economy of Life Safety (Olson, 1983)
- Information Needs of County Government (Alexander, 1983)

- Is Salt Lake Planning for Disaster?
  (League of Women Voters, 1983)
- Use of Earth-Science Information by Regional Agencies
  (Kockelman, 1979)
- Transferring Information to Decisionmakers (Bates, 1979)

We have included in the **References** other reports that identify user needs: Atkisson and Petak (1981), Burby (in press), Cornwell (1981, 1982), Council of State Governments (1974), Environmental Systems Research Institute (1983), French and Harmon (1982), Heikkala and Green (1984), University of Wisconsin Center for Geophysical Analysis (1975). In addition, we provided the panelists and speakers with lists of hazard information disseminators, typical communication techniques, potential users, and typical hazard-reduction techniques.

The speakers, panelists, and other attendees were most cooperative in providing cogent, informative remarks while adhering to a tight presentation schedule and a single-purpose topic. Special thanks are owed William Brown III for taking notes during the session.

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LAND USE PLANNING TOOLS: INFORMATION NEEDS FOR ASSESSING IMPLEMENTATION FEASIBILITY

by

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INTRODUCTION

Provo, Utah, is a moderate-sized community located between Utah Lake and the Wasatch Mountains. Its inhabitants make up a portion of the 90% of the state's population which lives in the zone of active faults known as the Intermountain Seismic Belt. Because of its earthquake hazard, Provo was selected as a site in which to test the application of a framework for guiding local planning decisions for earthquake hazard mitigation (Note 1). While general statements have been made about how land use planning tools can be applied to earthquake mitigation, the framework discussed here goes further in providing decision makers with an approach to assessing land use planning tools with respect to appropriateness to a specific local situation.

LAND USE PLANNING TOOLS

Many land use planning tools exist which lend themselves to the purpose of reducing losses and damage from earthquakes and associated hazards. These include:

- zoning ordinance
- subdivision ordinance
- sensitive lands ordinance
- special use or critical facility permits
- building codes related to specific locations
- hazardous building abatement ordinance
- real estate disclosure
- tax credits
- property acquisition
- environmental impact statement

In the approach used in Provo, several tools were selected as most likely to be appropriate for that community, based on an assessment of:

- the potential availability of various types of information on the seismic hazard which would enable a specific tool to be applied;

- the utility of the application of a specific tool in view of the current and future development patterns for the locale.

Two of the four tools considered the most appropriate for Provo will be discussed here. These two tools will be discussed in terms of what type of information is needed to assess whether or not the development and adoption of a particular tool are feasible in the community. The relative costs and effectiveness of tools also are important considerations in the decision-making framework (Note 2), but implementation feasibility is considered to be of crucial importance for policymakers.

IMPLEMENTATION FEASIBILITY

An obvious information need when comparing land use planning tools is that of technical information. Decision makers must ask, "Can the nature and location of the hazard be identified well enough for use in land planning?" It should be noted that the study team identified a pool of hazard information in Provo applicable to land use planning. However, this information is in scattered locations, not generally familiar to local government officials, and seldom applied to development decision making. This can be a reflection of a variety of problems, such as inadequate attempts to translate this information into terms meaningful to planners and decison makers, or a general political disinclination to place conditions on development to reduce seismic risks because possible future earthquakes are perceived as low probability events.

Thus, it must be acknowledged that the existence of preliminary or even excellent technical information won't assure that land use planning tools will be adopted or that they will function to reduce future damage from seismic or related hazards. Ultimately, the effectiveness of a land use planning tool depends on the extent to which it can be fully implemented. Considerable emphasis has been placed on obtaining hazard mapping and other kinds of geological information, but much less emphasis has been put on how likely the possession of that information is to lead to the reduction of damage in a particular community. The question must be asked, "What kinds of earthquake mitigation actions will be most administratively possible to adopt and politically acceptable in the community?"

To assess the potential of a particular tool to be put in place and to work as intended, information needs to be gathered which will indicate how likely that tool is to be adopted, complied with, and enforced. In general these questions are as follows:

- Can requirements be met which enable officials to institute the tool?
- Is this type of approach likely to be acceptable to various interests in the area?
- How likely are affected parties to comply with the tool?
- How difficult will it be to enforce the tool?
- How compatible is the tool with other local objectives?

This type of information can help to sort out tools in terms of their potential effectiveness compared to other tools. Also, it can help to identify potential obstacles to be negotiated around if a particular tool has been selected for adoption.

THE PROVO EXAMPLE

By way of illustrating the type of information needed to assess implementation feasibility, a summary follows of the specific questions addressed in the assessment of two types of tools considered applicable to Provo. One of the tools used in the example is aimed at existing development and the fact that many buildings in use in the area, and in particular in downtown Provo, are not likely to survive a major earthquake. This suggested Hazardous Building Abatement Ordinance would require that buildings specified by the city's building inspection staff be reinforced to a predetermined standard, with the costs borne by the building owner.

The other tool is designed for making future development less vulnerable to the seismic and related hazards in the area. The analysis suggested that an existing Sensitive Land Development Ordinance could be modified so as to apply to areas subject to such consequences as sliding, slumping, liquefaction, or flooding in the event of an earthquake. Development proposals for areas designated as sensitive because of the risks would be reviewed by the city to assure that the risk on the site is understood and that measures are taken by the developer to mitigate the hazard.

Table 1 displays the considerations for adoption, compliance, and enforcement of a Hazardous Building Ordinance in Provo, and Table 2 displays these considerations for a strengthened Sensitive Land Development Ordinance for Provo. The information for addressing these questions was gathered in December, 1983, from relevant government and agency personnel, including the Utah Geological and Mineral Survey, Utah Division of Comprehensive Emergency Management, Utah County Planning Office, and Provo city departments of Community Development, Building Inspection, Engineering, and Police. Data also were collected from the Geology Department at Brigham Young University. The information was used to make a "test" application of the decision-making framework being developed by the research team. The results which are summarized in Tables 1 and 2 are the product of an overview analysis rather than a more in-depth analysis, such as would be possible for local planners to undertake. However, the level and scope of the detail provided in the following tables are adequate to provide an illustration of the types of information which are needed to assess the implementation feasibility of a mitigation tool under consideration at the local level.

NOTES

1. Marjorie Greene and Susan Heikkala are the co-principal investigators for the research effort reported on in this paper, and are the authors of the Provo case study report from which the information for this paper is drawn. The framework referred to in the text is to be the basis for a handbook which can be used to guide local planners in the use of land use planning tools for earthquake damage reduction. The research forming the basis of this paper was conducted pursuant to a grant from the National Science Foundation. The statements are those of the grantees and do not necessarily reflect the views of the U.S. Government in general, or the National Science Foundation in particular.

2. The assessment of relative cost considerations and a comparison of the relative effectiveness of four selected tools are reported, as well as the assessment of implementation feasibility, in a report provided to the Provo participants in the initial information-gathering phase. This report is titled "Earthquake Hazard Mitigation: Guiding Local Land Use Planning Decisions, The Provo Case Study." Similar test applications were made in Bellingham, Washington, and Santa Rosa, California.

ACKNOWLEDGMENTS

The project team would like to acknowledge the willing and constructive participation in this project of the various governmental and university respondents in Provo who provided the information needed to test the framework being developed in the project.

Table 1

Hazardous Building Abatement Ordinance--Assessing Implementation Feasibility in Provo, Utah

Can a Hazardous Building Abatement Ordinance be adopted?

1. How easily can these hazardous buildings be identified?	• Potentially hazardous buildings must be precisely identified. They would likely include all buildings built before seismic standards were first included in the body of the UBC as well as all unreinforced masonry buildings. No inventory of these buildings presently exists but the ordinance envisions that this would be developed in a phased process following adoption. Fairly general criteria can be used to select buildings to be inventoried. Most would be located in the small downtown area.
2. How feasible are the development and application of retrofitting standards?	• The ordinance will specify buildings be brought up to something less than current UBC standards. The specific retrofitting actions needed to make a particular building meet these standards would be determined on a case-by-case basis. The Building Inspector would first determine that retrofitting would be necessary. Then, the owner would be responsible for retaining a structural engineer to specify specific actions. The Chief Building Official would verify the plans prior to issuing permits. The Building Section does not presently have the in-house expertise to undertake the building inventories or the plan certification.

How likely are owners to comply with such an ordinance?

1. What is the economic or other incentive for property owners to comply?	• The owner's potential legal liability should they not mitigate a known hazard is the major compliance incentive. Lower insurance rates following retrofitting may add to this.

Table 1 (continued)

2. What are the size and value of buildings affected?	• The ordinance would probably affect a 40-block area in the heart of Provo's business district plus some additional high density housing and scattered public facilities. Most buildings are less than five stories. Numerous businesses on Center Street appear to be economically marginal.
3. Is there a mix of private/public building ownership in affected areas?	• Most of the buildings likely to be subject to the ordinance are privately owned; however, more information on the actual ownership mix of buildings is needed. The retrofitting of public buildings would demonstrate the city's commitment to the program. If most of the buildings are private, the city has less leverage and will have greater difficulty in showing the benefits of the program.

How difficult is <u>enforcement</u> likely to be?

1. How difficult will it be to assess property owner conformance with retrofitting requirements?	• The first check would be at the plan review stage. Following would be several on-site reviews as work progressed. The Building Section does not now have sufficient structural engineering expertise to perform this function. Initially this would necessitate a staff addition or having someone on retainer. The volume of work would determine how much help would be required.
2. How likely is there to be willingness to reduce retrofitting requirements for specific buildings?	• It is likely the city would be somewhat flexible on retrofitting requirements. Provo has a negative attitude towards regulation generally. Strong political pressure for exemptions or reductions can be expected. Moreover, many of the businesses in the old masonry buildings appear

Table 1 (continued)

	economically marginal. Rather than force people out of business, requirement reduction is likely.
3. What is the economic value to the city of buildings and/or uses subject to retrofitting requirements?	• Unknown at this time. An accurate response requires an inventory of potentially hazardous buildings. The higher the building value, the more likely the owner can afford the retrofitting cost.

Are there <u>other considerations</u> which would affect implementation?

1. How compatible are the retrofitting requirements with other community objectives (e.g., historic preservation)?	• There may be a conflict with Provo City's objectives to maintain structures with economic and historic value.
2. What is the likelihood that building officials and elected officials will endorse such an ordinance?	• The Provo City government has generally avoided development regulations. In particular, there is likely to be limited public support for requiring retrofitting existing buildings unless and until a severe earthquake causes extensive damage.

Table 2

Strengthened Sensitive Land Development Ordinance--
Assessing Implementation Feasibility in Provo, Utah

Can a strengthened Sensitive Land Development Ordinance be adopted?

1. How easily can these areas be delineated?	• The current ordinance already covers steep slopes and high water table areas. This could be expanded to include areas of known or suspected faulting using the results of the engineering study now underway. Maps of these areas are not presently available, but could be readily generated.
2. How easy is it to identify and evaluate the types of reports to be required for different developments?	• The reporting requirements can be defined generally--e.g., an engineering report prepared by a licensed structural engineer must accompany each development proposal that falls within a sensitive area, addressing the nature of the identified hazard and appropriate mitigation measures. This approach is likely to yield more relevant information than uniformly specifying report contents in the ordinance. However, this then requires sufficient staff expertise to evaluate the contents of the report and adequacy of proposed remedies.
3. How feasible are the development and application of performance standards?	• It is technically possible. Mitigation actions would be established on a case-by-case basis, based upon the findings of the site report. This would ensure that remedying actions are tailored to the existing site problems and nature of the development. The current ordinance does not give the city the authority to deny or condition a permit as long as an engineer certifies the report. This severely limits the effectiveness of the ordinance. The city needs the authority and expertise to

Table 2 (continued)

	independently review these reports and the ability to specify appropriate development standards.
4. To what undeveloped areas would this apply?	• Provo City continues to grow and expand into some of the more hazardous areas in the city, e.g., the area around Heritage Mountain and other scenic foothills locations, and the low-lying areas near Utah Lake (also valued for their agricultural development potential). A more precise assessment of how much land this might affect would require projections of growth and development rates and the amount of potentially available land.

How likely are developers to <u>comply</u> with such an ordinance?

1. How much existing development is there in the potential sensitive areas?	• A moderate but increasing amount. Residential developments are located in the foothills, and additional development is planned there. Agricultural and some residential developments are located in the lowlands near Utah Lake. It has been estimated that half the city's 1983 development took place in areas which would be considered sensitive. The fact that development has taken place in these locations may make it impossible to prohibit future development; but it may be reasonable to require studies and mitigative construction techniques.
2. What is the economic incentive to comply?	• There is a limited economic incentive to comply in the absence of enforcement as this would represent an additional cost to the applicant. Potential liability is not likely to be an incentive since most of the affected development will be residential.

3. Are there alternative development sites available?	• There are alternative sites available, but the most hazardous areas are also some of the most desirable development sites because of their superb views across the valley. The ordinance is not likely to preclude development here, rather it will lead to design or structural modifications. The more valuable a development site, the more likely the purchaser would be able to afford more thorough planning and preparatory site work.
How difficult is <u>enforcement</u> likely to be?	
1. How possible is it to assess the adequacy of special site reports and prepare development standards or mitigation requirements on a case-by-case basis?	• It would be possible only to a limited degree given present staffing--lack of structural engineering expertise and an inadequate number of inspectors. The study that is presently underway by the Engineering Department may help define some appropriate review standards. However, the implementation of the ordinance would require additional professional help--either a structural engineer or engineering geologist--on retainer or brought on staff. Depending on the volume of development affected by the ordinance, more than one individual may be needed over time.
2. How much would enforcement affect the economic value of future developments in the city, in terms of tax revenues?	• This is difficult to predict without making detailed growth projections. However, the proposed Heritage Mountain development is a $160 million project that is expected to generate numerous jobs. Any regulation that would jeopardize such a development would face strong political opposition.

Table 2 (continued)

3. Primarily who will be affected by such an ordinance?	• Private developers of residential subdivisions, but it will likely impact some small-scale commercial/retail, *industrial and multi-family* developments, particularly those associated with Heritage Mountain.
4. What is the willingness to reduce development standards for particular projects?	• The willingness to negotiate standards will depend on a variety of factors including the perceived economic importance of the project, the knowledge and commitment of the city staff and the strength of the ordinance itself. Although the city presently suffers a staffing shortage, there has been a greater commitment to enforcing development regulations in the past 10 years. Nonetheless, officials would probably want to avoid placing an undue burden on developers, particularly if it would make an economically valuable and desirable project infeasible.
5. How possible is it to detect non-conformance with specific project requirements?	• There are multiple checks, the most important check being the plan changes required to obtain the initial building permit. Additional checks can be incorporated into the site inspection process during the course of development. However, the inspection staff is presently overworked (see next point).
6. How likely is there to be follow-through on implementation?	• The city is seen as playing a more active role in permit enforcement than in the past. The city staff perceives their orders to be generally obeyed. However, the inspection staff time is already overcommitted. More staff would be needed--the number to be determined by project development volume.

Table 2 (continued)

Are there other considerations which may affect implementation feasibility?	
1. How compatible is the sensitive land development ordinance with other goals?	• This represents only a modification/strengthening of an existing ordinance. Modifications to the ordinance based upon the findings of the soon-to-be completed Engineering Department study already are being considered. Nevertheless, natural hazard mitigation has never been a high political priority and the city has already rejected a stronger version of this same ordinance.
2. How likely is there to be political support for this ordinance change?	• Support is more likely now than ever before due to the recent flood losses. Moreover, if seismic hazards are included in a comprehensive approach to hazard management the chance for implementation success is greater. This only calls for a modification of an existing ordinance, but a countervailing force, such as a "big ticket" project like Heritage Mountain, might bring on increased opposition to any increased regulation. (At this point, Heritage Mountain has apparently satisfactorily addressed the city's earthquake hazard concerns.)

USER NEEDS AS IDENTIFIED BY THE UTAH MULTIHAZARDS PROJECT

by

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The concept of a multihazards mitigation program is not only viable, it is critical if actual mitigation is ever going to be achieved. The process of single purpose planning (e.g., earthquake mitigation plans or flood mitigation plans) is much easier to manage and thus perhaps more attractive to local governments with limited resources. However, natural events do not always occur as single events in the real world, therefore, a multihazards approach to mitigation is the only approach that will be successful both in the short and long term.

The multihazard approach does not by itself provide answers or solutions to problems. What it does do is formalize a consistent method for the collection of tools for problem solving, analysis of individual areas and guidelines for selecting feasible alternatives. The process can be equally applied to all jurisdictional levels of government for identifying hazards and analyzing alternative mitigation actions to determine the appropriate level of action.

Regardless of what type of mitigation alternative is selected it is essential that they be coupled with an adequate response plan that is developed in light of the information generated by the multihazard approach, thus ensuring greater survivability of existing populations and critical facilities.

The application of this process in the Ogden, Utah, area has revealed both anticipated and unanticipated strengths and weaknesses. First and perhaps foremost of the strengths of the Project is the level of involvement of the local officials. Rather than proposing a predesigned set of guidelines and standards to be met, the Project provides for local determination of what can be done given the local political, economic and social climate. The Project provides for local officials, a method for evaluating the problem and potential solutions and resources necessary for actual mitigation. It is this ability of the local government to determine their own destiny that appeals so strongly to them.

Closely related to local involvement and of critical importance to the success of the Project is the fact that the efforts of all levels of government have been synthesized. They now have an opportunity to make policies and decisions in a nonemergency environment where a wide range of alternatives can be addressed.

The tools that are provided to local officials identify specific areas of concern, provide a range of alternatives to consider and help identify various ways to defray costs of data collection and program implementation.

The weaknesses that have become apparent were not necessarily weaknesses of the Project, however; they must be addressed if there is to be overall success. First, the "best available information" is at present inadequate. It does, however, provide enough background information on which to base appropriate questions and supports the need for more detailed investigations. Where adequate information did exist, it was presented in such a variety of scales and levels of translation that it was of marginal benefit. Many of the reports were "in-house" or "unpublished" reports that contained valuable information but were unavailable as resource documents.

A large void in the study has resulted from a lack of available economic information, both in terms of how costly a disaster would be, and in developing cost and benefit figures for the various mitigation alternatives.

The Project methodology to evaluate probabilistic risk has only evaluated the worst-case events and the 100 year events. In order to more fully understand the potential for damaging events, more than these two return frequencies must be analyzed.

In order to overcome some of the weaknesses the following information is needed: a ground response spectrum analyasis; a low level aerial photo inventory of the area; a probabilistic hydrologic analysis; fragility curves for earthquake damage, flood damage and landslide damage; model cost/benefit analysis; a user oriented document to perform probabilistic risk assessments; guidelines to implement this probabilistic methodology, including the level of effort required, that data requirements and the application in the decision making process of local governments; simplified guidelines to assist planners and local officials in interpreting the technical studies; and an automate risk analysis program as an on-line management tool.

To ensure continued efforts in hazard mitigation it is imperative that local governments be assisted in acquiring adequate information concerning the existence of the hazards in their community, what risks those hazards pose to life and property, the economic impact of both the disaster and the mitigation programs, what the technically feasible mitigation options are, information on how to relate the above information to a concerned public without generating unnecessary levels of either anxiety or apathy and information on where funding may be available to implement mitigation programs.

THE NEED FOR

INTEGRATED MULTI-HAZARD ANALYSIS AND MAPPING

by

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INTRODUCTION

Considerable geotechnical information is available from multiple sources resulting from decades of research. To the planner and decisionmaker, this array of eclectic information is basically inaccessible, for two reasons: 1) it is scattered in the scientific and technical literature, and 2) it is rarely presented in a usable language and format. The objective of this brief paper is to make a case for integrated multi-hazard analysis and mapping, and to present the technical information in a language and format that promotes its acceptance and implementation into the decision stream.

Although the topic of this conference focuses on earthquake hazards, the thesis of this presentation is that hazard mitigation can never be accomplished without integrating seismic risks with all other geotechnical and biophysical risks. Natural systems are interfunctional; adequate safeguards and planning must likewise be.

Furthermore, man's activities at and near the earth's surface often alter the direction and/or rate of those interrelated events. Thus, human structures and alterations of the landscape must be part of the analysis of hazards.

HAZARDS ALONG THE WASATCH FRONT

Among the natural hazards occurring along the Wasatch Front are the following, arranged basically in order of decreasing frequency of occurrance, yet generally increasing impact per event:

EROSION and DEPOSITION

Especially from disturbed slopes

GROUND WATER ALTERATION

a. interception (especially from perched water tables)
b. alteration of recharge, quantity and quality

SOIL INSTABILITY

a. expansive soils
b. collapsible soils

FLOODING (Snowmelt and Cloudburst)

a. from natural slopes and channels
b. induced by development

SLOPE FAILURE (mass movement)

a. rock fall
b. surficial sliding
c. bedrock failure

SEISMICITY

a. ground shaking
b. surface rupture
c. slope failure

There is, in addition, a set of biologically related losses resulting from human activity along the Front:

DETERIORATION OF WILDLIFE AND FISH HABITAT
DETERIORATION OF VISUAL QUALITY
INCREASE IN FIRE HAZARD

All of these potential risks and losses are interrelated in various ways. Proper management of one factor may help to mitigate losses in another. Conversely, failure to mitigate against one may increase the risk of other hazardous events.

OBJECTIVE

The objective of hazard analysis and mapping for mitigation against potential risk should be three-fold: 1) to assemble and integrate existing geotechnical and biophysical data and augment it with new, improved data where possible, 2) to present the data in such a way as to bridge the language gap between the technical specialists and the planner/decisionmaker, 3) to establish a "living document" of such information as to allow and encourage subsequent information to provide a constant update. On this basis, model ordinances can be prepared to implement the knowledge into hazard-mitigating controls or guidelines.

APPROACH

The basic approach to the above is through identification of terrain units. Inasmuch as the landscape is perceived, managed, zoned, and built upon as units of land, and inasmuch as carefully identified terrain units can be expected to behave in particular ways under environmental stress, a carefully chosen set of terrain units is the logical foundation for both the technical investigation and the planning process. Such land units might be called geomorphic "process-form" units, to reflect their dynamic origin and behavior.

The basic premise is that geomorphology is the integrating science of the earth's surface form and development. The on-going processes of geologic, hydrologic, pedogenic, biotic, and climatic forces tht created the landscape features continue to shape them. By identifying the distinctive land units so formed, such as alluvial fans, beaches, and channels, we may predict their future behavior under certain conditions. Once the terrain units are identified and mapped, they become the foundation for decision-making, including ordinance preparation.

Since man can alter landscape conditions, both natural and man-induced hazards must be identified. Both can be identified, within reason, on a geomorphic terrain unit basis. Mitigating measures may also be best defined within the context of these homogeneous landform features. The geomorphic terrain unit, then, becomes the basic structure for an integrated, multihazard mapping, assessment, and mitigation program.

EARTHQUAKE PROGRAMS OF PRIVATE BUSINESSES AND INDUSTRIES

by

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On a recent series of interviews of company officials throughout California, the Association of Bay Area Government (ABAG) staff gained important insights on the earthquake preparedness programs of businesses and industries. These insights include: a) what the companies are currently doing in earthquake preparedness; b) what are their motives for acting to reduce the earthquake hazards; and, c) what the company officials feel is needed to encourage business and industry to do more for earthquake preparedness.

This research was conducted as part of a project on the liability of private businesses and industries for earthquake hazards and losses, funded by the National Science Foundation.

CURRENT PROGRAMS FOR EARTHQUAKE PREPAREDNESS

Those company officials interviewed expressed a pride in their safety programs. The extent of these programs tends to be broader and more complete than imagined by the local government officials in the areas ABAG visited. The emphasis of these earthquake preparedness programs tends to vary by the type of business or industry. Earthquake safety programs of mining, construction material, chemical, manufacturing, high technology, and agricultural industries tend to emphasize worker safety, evacuation plans and drills, emergency medical capabilities, and fire control. Types of safety programs of smaller business offices emphasize third party safety, insurance, and redundancy of record keeping. Businesses in highrise office buildings, however, often had evacuation plans and drills, emergency medical capabilities (often including in-house employees certified to teach first aid and CPR), and personnel training in fire control. Larger companies, regardless of type of company, that could afford to have at least one person whose primary responsibility was safety or disaster preparedness, tend to have programs which are more comprehensive, more formal, and well documented. Retail service businesses also tend to have relatively comprehensive programs because of their concerns with both worker safety and third party customers or visitors. The companies interviewed having the most comprehensive programs were those that were most highly regulated and included hospitals, utilities, and companies handling large amounts of hazardous or nuclear materials.

On the interviews, ABAG staff asked two questions related to the use of geologic, soils, and structural engineering information by companies: a) is such data used when siting and designing new facilities? b) is such data evaluated prior to the acquisition of new land or facilities?

Although a relatively large number of the companies interviewed routinely made use of geologic and engineering information for new facilities, the use of such information prior to acquisition is relatively rare. However, many of the larger financial institutions, that is, the banks, savings and loans, and insurance companies, routinely require their acceptance of a geologic and engineering report as a condition to purchasing property. These companies, except, perhaps, for the very largest, make use of outside consultants for gathering and interpreting this geologic and engineering data.

MOTIVATIONS FOR EARTHQUAKE PREPAREDNESS

The company officials were frank about motives for acting to mitigate hazards, providing the following ideas.

1. THE NEED TO COMPLY WITH REGULATIONS. Such requirements included those of the Occupational Safety and Health Administration, the Uniform Building Code, and the Alquist-Priolo Special Studies Zones Act for fault surface rupture.

2. CONCERN FOR WORKER SAFETY. Company officials regarded their fellow workers as friends and close associates. They had a genuine concern for not wanting to see them injured or killed.

3. EMPLOYEE MORALE. Company officials noted improvements in employee morale and productivity, as well as in union-management relations, when safety programs were jointly handled by management and employees with strong management leadership.

4. CONCERN FOR PUBLIC SAFETY. This concern for visitors, customers and by-standers was noted more by the service businesses than by the industrial companies.

5. GOOD BUSINESS PRACTICE OR WISE FINANCIAL MANAGEMENT. This motivation was two-sided. First, the company officials wanted to minimize damage to the company's investment in buildings and equipment. Worker safety was even included in this category by some company officials. As they put it, the time and money required to recruit and train qualified personnel was substantial. Second, the officials noted the financial need to continue in business or continue to provide a service, thereby enabling them to collect their fees.

6. PUBLIC RELATIONS. The aspects of acting, or not acting, responsibly and subsequent media attention was a primary concern, especially for large or visible companies.

7. MEDIA PUBLICITY ON PREPAREDNESS. Newspapers, TV, and radio stations have been doing an excellent job of bringing up the needs for better earthquake preparedness whenever an earthquake occurs. This coverage has kept company officials, and their employees, more aware of the need for preparedness.

8. AGRESSIVE PROGRAMS OF INSURANCE CARRIERS OR LOCAL GOVERNMENT FIRE DEPARTMENTS. Insurance carrier or fire department inspectors, if knowledgeable in earthquake preparedness, can have an active role in making constructive suggestions to companies or improving their programs.

9. LEADERSHIP. Key company officials who are personally committed to earthquake or disaster preparedness can provide needed leadership. Two primary reasons for such commitment that were cited in the interviews

were: a) participation on the board of directors or previous employment with companies which had strong disaster programs, and b) having close friends or relatives who had been killed or injured due to a lack of strong safety and disaster programs.

10. LIABILITY. Potential liability was believed to be a deterrent to negligence, that is, a means of encouraging reasonable behavior.

WAYS TO ENCOURAGE MORE PREPAREDNESS ACTIVITIES

The company officials interviewed had many ideas on ways to encourage preparedness.

1. EDUCATE ON HAZARDS AND MITIGATION. The officials believed that guidelines should be available on potential deaths and injuries for certain hazards, available means to better prepare for earthquakes, and cost information on mitigating hazards or implementing earthquake safety programs.

2. UPGRADE BUILDING CODES AND ORDINANCES. Candidates for retrofitting included older tilt-up concrete buildings, unreinforced masonry buildings, and mobile home foundations. Candidates for fastening included mechanical and electrical equipment, utilities (largely water and power lines), and furnishings (especially if large and heavy).

3. USE FINANCIAL INCENTIVES. Emergency preparedness activities might be tied to tax cuts, interst free loans, or cuts in insurance premiums. One interesting rationale for government spending the money for such incentives was that industry would be reducing the amount that government agencies would ultimately be spending on emergency preparedness and disaster recovery programs.

4. WORK WITH BUSINESS AND PROFESSIONAL GROUPS. Such groups might include local Chambers of Commerce, manufacturers associations, savings and loan organizations, insurance organizations, and civil, structural and geotechnical engineering professional associations.

5. USE INSPECTIONS. More inspections by insurance and local government staff trained in earthquake safety would be useful, especially if coupled with seminars on how to fix the problems and promote safety. Some suggested that any changes should be voluntary.

6. FOCUS ON EMERGENCY TRAINING AND EXTENSIVE DRILLS.

7. WORK FOR BETTER PUBLIC/PRIVATE COOPERATION. These officials saw a lack of understanding of the business community and unfounded expectations on the part of government agencies on appropriate disaster preparedness activities. They also saw a lack of governmental leadership in this area.

8. REQUIRE EARTHQUAKE INSURANCE. Some officials were impressed by the safety programs required by their insurance carriers.

9. WORK WITH THE MEDIA. Although working with the news media to promote continued awareness of earthquake hazards was only mentioned once in the direct context of recommended strategies, several company officials, especially in southern California, pointed to the role of the media in maintaining earthquake awareness.

10. EDUCATE ON LIABILITY. In spite of the reluctance to use liability rules as a means of promoting earthquake hazard reduction, many of the officials interviewed expressed an interest in more education on liability for hazards.

A LESSON LEARNED FROM THE IDAHO EARTHQUAKE HAZARD MITIGATION EFFORT: THE NEED FOR EARTHQUAKE PLANNING SCENARIOS AND THE NEEDED INFORMATION THEY COULD PROVIDE

by

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INTRODUCTION

Idaho experienced a major earthquake of magnitude 7.3 on October 28, 1983, in the vicinity of Mackay and Challis, Idaho. Subsequently, on November 18, 1983, Custer County, which contains the small towns of Challis and Mackay, was declared to be a major disaster area by the President of the United States. Under the provisions of Public Law 93-288, Disaster Relief Act of 1974, recipients of disaster aid, which are primarily State and local governments, are obligated to develop and implement appropriate hazard mitigation measures as they relate to that disaster in order to be eligible for Federal Disaster financial aid. Besides being a qualifying requirement for aid for this disaster, it also can be a prerequisite for receipt of future Federal assistance, should a major earthquake occur again in this county.

Because of this mandate, the moral obligation of government to preserve life and property and the probability of the need for future Federal Disaster aid, Idaho has moved into a new era of emergency planning with respect to serious earthquake hazard reduction planning and implementation. Unfortunately, this put the State in a situation of learning about hazard mitigation while doing it. What compounded the problem further was that there was a shortage of usable support information or it could not be obtained in a timely manner. This prevented many suggested (perhaps reasonable) mitigation measures from being considered or analyzed in depth because a supporting case could not be built.

To help preclude this problem in the future, it is proposed that earthquake planning scenarios be prepared. The development of these scenarios can be a vehicle which can generate the informational support base that could be used to develop, analyze and assess practical hazard reduction strategies and measures.

INFORMATION SHORTFALL

Idaho in many respects has a very fortunate situation in its earthquake hazard reduction activities. Yet there are some very serious limiting factors because of these sets of circumstances. Of course, the major factor is that Idaho, up to this point in time, has not had a predicted catastrophic event within its boundaries nor did the Borah Peak event produce the damage the experts expected which in both cases is not a bad situation to be in. On the one hand, hopefully, there is time to develop an earthquake hazard reduction program in some orderly and organized fashion without a lot of false starts. On the other hand, because of the lack of pressure, relevant, translated, scientific information is in short supply and has a resulting low priority in development, warranted or not. However, a very discouraging observation was that this translated information has not been significantly developed elsewhere, where there is an unquestionable priority.

Regardless of the priority though, policymakers, decision makers, planners or whomever are involved in earthquake hazard reduction in States such as California, Utah, Washington, Alaska, and even Idaho need similar kinds of data. There is voluminous scientific information that has been provided by earth scientists, engineers and other disciplines on the subject of earthquakes in general, as well as area specific. Most of this, in its current form, though interesting, important, pertinent, and a prerequisite, generally does not adequately support mitigation efforts. The problem with most of the information available which is being used for hazard mitigation is that it shows what has happened, and not what could happen in the future. What policymakers and planners are looking for is a best estimate forecast of an event(s) in terms of location, magnitude, intensities, recurrence intervals, multihazards, identification and mapping, physical effects, areas of impact, damage estimates, projected losses, probability ranges of occurrences, degree of severity, confident levels, physical damage, nonphysical damage, and quantitative impacts on critical facilities.

PLANNING VEHICLE

As with any planning effort, there must be a focal point for all those involved in the research, scientific transfer, the multidiscipline exchange, strategy development, measure identification, policy development and decision making, as well as the overall planning process. Hazard mitigation planning requires a multidiscipline approach and an extensive information exchange between those disciplines. In many cases, it is a close one-on-one dialogue between disciplines. With the inducement of a focal point, these disciplines can gain a sense of direction and unity toward a common goal. Because of this need, it is proposed that earthquake planning scenarios be used to achieve that end.

Earthquake planning scenarios are intended to portray the effects and dynamics of future major or near major earthquakes in selected areas in terms that all users can understand. The scenario will be in quantitative and graphic terms that will provide the means to access the impact of major earthquakes. It is essentially a tool which serves as a basis for emergency planning only and should not be considered as an actual prediction of an event. For planning purposes, it shows dynamics of the problem to be solved and should serve as a basis to attack those problems. The earthquake planning scenario for a magnitude 8.3 earthquake on the San Andreas Fault in Southern California provided by the California Department of Conservation, Division of Mines and Geology, is an example of this type of scenario.

SCENARIO DEVELOPMENT

It has been suggested that in developing an earthquake scenario, decision makers and planners need to assemble a variety of competent authorities. At least in Idaho's small mitigation effort, it was an issue that surfaced frequently when dealing in scientific and technical areas. The competent authorities would likely include earth scientists (geologists, seismologists, hydrologists, geophysicists, e.g.), the engineering community (structural, civil, mechanical, electrical, e.g.), Federal, State, local government and private users (policymakers, planners, elected officials, educators, private sector leaders, e.g.) and eventually followed by a host of other professionals (economists, sociologists, psychologists, financers, e.g.). The basic task of this group is to translate scientific data into forecast data which quantifies expected losses to the multihazards associated with earthquakes in a particular area. This would be followed by taking the developed ranges of expected quantified losses, the highest probabilities points in those ranges and build a planning scenario around those estimates. The scenario would tend to be developed on the pessimistic side. In any case, the scenario should be a reasonable facsimile of the best realistic prediction available. Ideally, it should expose a wide berth of problems that could be expected with a major earthquake. This process would likely include the development of at least four products before a scenario is scoped out. These four products would be a hazard analysis, vulnerability analysis, expected economic loss, and expected noneconomic loss.

The hazard analysis should be made up of maps and quantitative displays which indicate the nature and probability of occurrence or recurrence interval of potentially damaging events at various levels of magnitude and intensity in the area of concern. Also, it would depict the area of multihazards such as shaking, liquefaction, subsidence, rupture, land slides, flooding, etc., and their potential effects.

The vulnerability analysis should be made up of maps and graphic displays showing the physical and nonphysical damage at a large number of locations, particularly critical facilities in the area of concern should that event occur. This would all be based on the results of the previous hazard analysis.

Expected economic loss analysis translates the damage assessment to economic terms by depicting the various previously determined risk levels in combination with the damage and combining the effects of all hazards to display the total economic loss.

The expected noneconomic loss analysis would focus on quantifying the projected risk of life, loss of life, injuries and other health-related impacts; social and psychological impacts on the inhabitants; impacts on the basic necessities for day-to-day living, impact of the financial and health care system and any other destabilizing noneconomic impacts as appropriate.

Once this ground work has been essentially completed, the development of the planning scenario can proceed. The question might arise at this point as to why a scenario should be developed when the preceding process has been essentially completed. First, the preceding process must examine a considerable number of possibilities. Secondly, the planning effort cannot cover all of the contingencies that might arise because of the limited predictability of earthquakes and the markedly different pattern of damage they are known to produce. Besides, it would not be economically feasible to cover all of the varying possibilities, as well as involving a hugh consumption of planning time. The planning effort needs to focus on something that is manageable, realistic, and a reasonable estimate of what could occur. It does not make sense to plan for a 7.3 earthquake if the experts say that one would not occur probably in another 1,000 years. What scenario developers are likely looking at is an event which could occur within the next 20 to 50 years. It should be emphasized that the hazard and vulnerability analysis should provide the basis for determining the hypothetical earthquake and its effects.

CONCLUSION

Successful development and implementation of mitigation requires that the public and their officials perceive the hazard as real and a threat to them. This in turn requires cohesive and strong support of conventional researchers, scientists, design professionals and engineers, as well as the local construction industry, realtors, land developers, financial institutions, insurers, labor and politicians to name a few. To achieve this end, there must be a planning focus and a target that involved parties understand. The scenario is that vehicle and it inherently provides the target in which the strategies and measures can be based.

Without the scenario, the identification of the measures for reducing the expected losses and the selection and implementation of sound mitigation strategies will be severely hampered. This then will result in policymakers and planners becoming highly frustrated and disenchanted with the effort.

EARTH SCIENCE INFORMATION NEEDS OF PLANNERS AND POLICYMAKERS IN LARIMER COUNTY, COLORADO

by

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INTRODUCTION

Larimer County, Colorado, was the site of a study of information transfer from Federal to local levels of government. Five departments of County government evaluated information on geology, soils, topography, hydrology, and land use that was supplied by the U.S. Geological Survey (USGS) and the U.S. Soil Conservation Service (SCS).

Results of the Larimer County investigation are potentially applicable to the Wasatch Front earthquake hazard reduction program in two ways: (1) methods used to promote two-way communication among information producing and consuming agencies apply in the rapidly growing urban area of both Colorado and Utah; and (2) to a large extent, the kinds of information needed for earthquake hazard reduction are also needed for the regular and continuing functions of local government. This report presents a summary of the methodology and results of the Larimer County study, which is reported more fully elsewhere (Alexander, 1983). Following that is a brief summary of recent interagency cooperation in the Colorado Front Range region, that grew out of the Larimer County study. Finally are some comments on applications to earthquake hazard mitigation in the Wasatch Front region.

METHODOLOGY AND RESULTS OF THE LARIMER COUNTY STUDY

Earth Science Information Transfer and Use

The Larimer County study benefitted from a number of earlier studies designed to demonstrate the applications of its products to land use planning and decisionmaking in urban areas, summarized by Bates (1979). An in-house USGS effort designed to assist in long-range planning identified ten areas of special need for products of interdisciplinary studies involving Geologic, Water Resources, and Mapping Divisions (figure 1). Figure 1 depicts (not in priority order) five Central Region areas of energy resource development, two of special interest for water resources development, and three urbanized areas where rapid growth is taking place in the face of potential geologic and hydrologic problems. Larimer County was chosen to typify the information needs in the rapidly growing Colorado Front Range region.

Cooperative Approach

The study was carried out through a cooperative Memorandum of Understanding among the U.S. Geological Survey, the U.S. Soil Conservation Service, and the government of Larimer County, with each agency contributing in-kind resources and no exchange of funding. A key connection was established between the legislative body (County Commissioners) and the career professionals in five County departments: Assessor, Engineer, Health, Planning, and Sheriff. The County Commissioners authorized the study in the beginning, and reviewed and approved its results at the end.

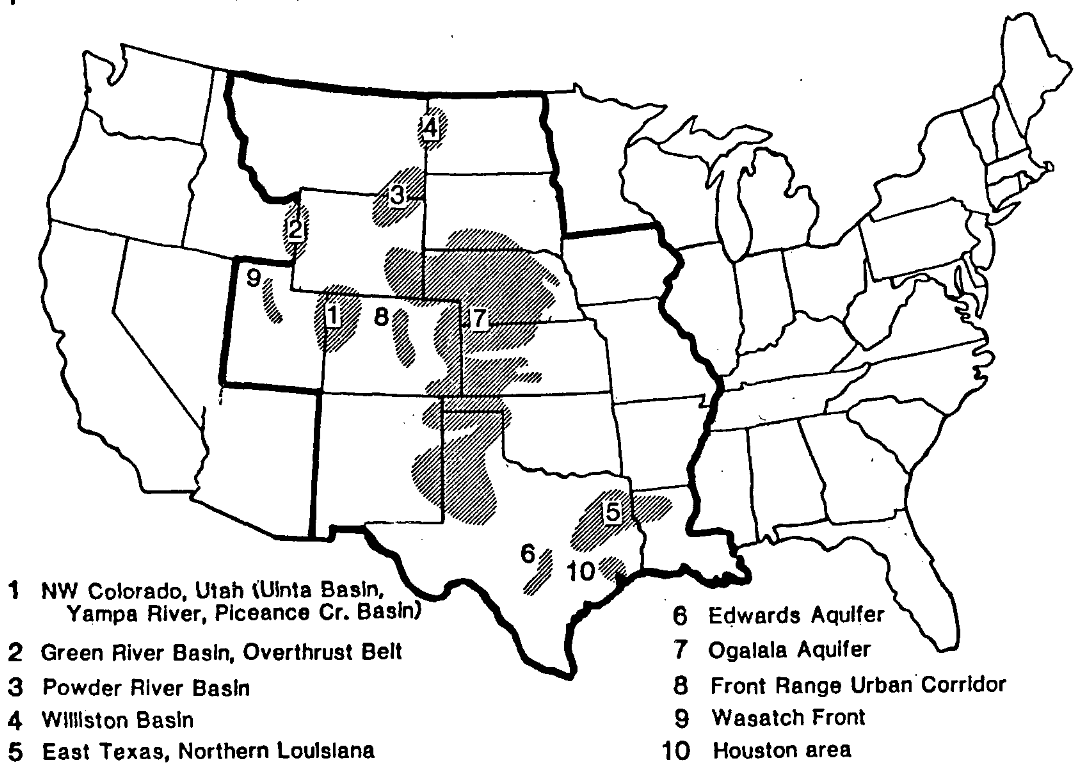

Figure 1: USGS Central Region -- Areas of need for USGS interdisciplinary studies to assist in mitigation of energy, water, and urban growth problems

(from Bates and others, written communication, 1982).

Information Exchange

The first step was a meeting among all cooperating parties to determine the scope of the study. Then the two Federal agencies presented to Larimer County officials all information pertaining to any part of the County's area -- scientific reports, maps, bibliographies, and indexes to other available information. Then, through a series of interviews, each of the five County agencies responded to the information presented in terms of: (1) adequacy of the information for current needs; (2) anticipated future needs for earth science and soil science information; and (3) driving forces behind the information needs. Among the latter factors operating in Larimer County were pertinent laws and regulations the set up the requirements for information, expertise of local government career professionals, and citizen pressure.

Summary of Findings and Recommendations

1. Some available information is usable -- for example, soil surveys, surficial geologic maps, hydrologic data, topographic maps, and aerial-photo-based products -- but in some cases the existence of such information is not known to the potential user.

2. Much vitally needed information -- particularly geologic and land use maps at scales of 1:24,000 or larger -- is not available from Federal sources, or from other sources, at costs which County government can afford. Some County officials are trained to use earth science information products in the form originally produced by the earth scientists; others require interpreted or translated information which can be used by non-scientist officials, who often have to make rapid decisions in favor of or against proposed new developments.

3. A consequence of the above is that many decisions are being made with inadequate information.

4. Larimer County is developing a County-wide mapping program, designed to take advantage of technological improvements in the handling of

map data developing at all levels of government. Coordination of the automated mapping systems is poor, both within local government and among local, State, and Federal systems.

5. Based on the above findings, the study made a number of recommendations for improved availability and use of earth acience information in County government: Continued interagency cooperation and expansion to include other Federal and State agencies; improved bibliographies and indexes to available information from Federal, State, and local agencies and from universities; improved interpretation of earth science information products for non-scientist users; and a new cooperative program in land use data collection and mapping, taking advantage of technological developments in computer mapping and geographic information systems.

FOLLOW-ON DEVELOPMENTS IN THE COLORADO FRONT RANGE REGION

The two cooperating Federal agencies reviewed the results and recommendations of the Larimer County study. The SCS responded by speeding up publication of the Larimer County Soil Survey, which was more useful to County officials as a published booklet than in the previous format. Many of the County's needs for geologic, hydrologic, and land use information were too detailed to be supplied by USGS programs, at least in the next few years when need will remain acute. The County has contracted with private consulting firms to fulfill needs for interpreted geologic hazard maps at a scale of 1:24,000. Only a few such maps for high-priority areas under pressure for rapid development had been completed at the time of the study.

A USGS follow-up effort did take place, however, resulting from the recommendation to pursue further cooperation in land use mapping. This mapping was inadequate and out of date for the County's needs to track recent growth and perform a variety of other local government functions. USGS has a program for providing land use maps and digital data bases nationwide. The most recent coverage from that program for Larimer County and the northern Colorado Front Range region is for 1976, and no funds are available for update. Therefore a study was launched to determine feasibility of obtaining more recent land use data through cooperative means.

In this follow-up study Larimer County was joined by two counties to the south, Boulder and Jefferson. By a process of negotiation and technical information exchange, in a series of small-group meetings, the three Counties' planning departments agreed upon a land use classification scheme to satisfy the needs of each county, and also be compatible with the standard USGS classification scheme (Anderson and others, 1976). Such agreement is necessary if the potential of digital map data technology is to be realized for application to common data bases crossing jurisdictional boundaries. Other necessary agreements, such as on technical standards for digital cartographic data structures and formats, await future cooperative efforts.

Using the experimental three-county land use classification scheme, USGS geographers and cartographers prepared maps of a 186-square-mile test site, in both manually drafted and digital forms. Those maps were submitted to a wider selection of potential users, including Federal, State, and local government agencies, as well as private industry, academic, and professional-society representatives, for evaluation in a day-long workshop on May 15, 1984. Data on industries in the test region, and geologic data classified in accordance with expected hazards to future development, were also included.

Evaluation of the test site data is incomplete at this writing. The workshop participants, however, concluded unanimously that a process of coordination and information exchange on digital data bases, geographic information systems, and their many applications in the entire Front Range region (figure 2) is urgently needed to make more efficient use of the new technology and reduce the costly duplication of efforts existing at present.

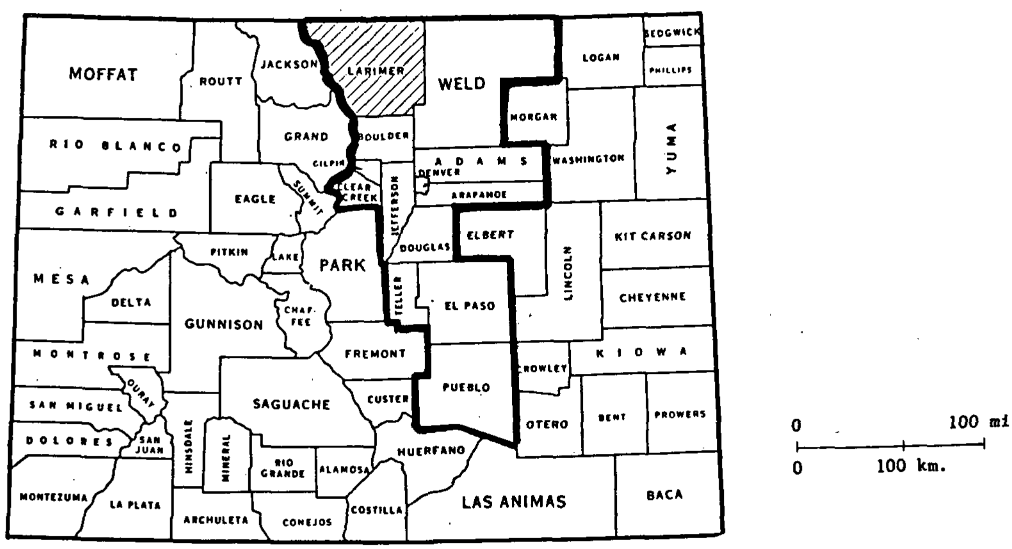

Figure 2

Larimer County and other Colorado Front Range counties

A program of mapping, automation, and sharing of land parcel information files, presently maintained separately by many departments of local government and utility companies, is but one example discussed at the workshop whereby beneficial results of computer mapping technology may be achieved. Such information resources may eventually augment or replace many land data bases presently obtained through aerial photography and other traditional sources. Emergency management, including planning to mitigate the effects of natural disasters, was cited as an application of the new technology which encompasses users at all levels of government and throughout the private economy. First steps to facilitate the recommended information exchange were taken in June and July 1984 by the Rocky Mountain Chapter of the Urban and Regional Information Systems Association (URISA), a non-profit professional organization, which had assisted USGS in conducting the May workshop.

APPLICATIONS TO EARTHQUAKE HAZARD MITIGATION IN THE WASATCH FRONT REGION

Though the Colorado Front Range is not as high a priority for earthquake hazard reduction measures as is Utah's Wasatch Front, the two regions have many similarities in the need for basic and interpreted earth science information to assist land planning and management activities. Also, both are experiencing rapid population growth and accompanying land use changes -- changes which must be continually correlated with the increasingly detailed delineation and mapping of geologic hazard zones.

This study's findings are in conformance with past research which has verified common processes involved in successful transfer and application of earth science information. One study in the field of earthquake hazards concludes, "knowledge utilization is enhanced through the development of a networking process. To be effective, knowledge producers and knowledge users must develop strong, continuous communication links, beginning at an early stage, even before the research has been fully designed or executed, and continuing until the research has been completed." (Hays and Gori, 1983).

The preliminary results of the Colorado Front Range study also support the concept of cooperative development of problem-solving strategies, where the issues are complex, interdisciplinary, and often controversial. Furthermore, broad partnerships involving both public and private participation may be necessary to fully realize the potential of digital mapping technology as applied to earthquake hazard mitigation. Results from a Southern California study are relevant:

"Disaster impact can be reduced by pre-event actions, including hazard mitigation measures, preparation for emergency response, and pre-event preparation for post-disaster rebuilding. All of these activities require planning and, in part, depend upon the same store of organized information, including:

- Characteristics of the hazard and geological areas likely to be impacted

- Population (numbers, characteristics, distribution)

- Measures of economic activity

- Resources available (financial, human)

- Powers, programs, and responsibilities of local, state, and federal governments

- Land use and building stock (numbers, characteristics, location)

- Infrastructure (water, power, communication and transportation systems).

This same information is also needed for normal local and regional comprehensive planning and programming for government. In addition, it is useful for private industry's planning and marketing. Developing and maintaining an accurate, up-to-date, and accessible store of such data should be a high-priority item." (Spangle, 1983).

Thus the Larimer County study and follow-on efforts have in common two processes increasingly recognized as essential components in acceptance and utilization of earth science information by non-scientist users: (1) two-way communication based on strong linkages between producers and users of information, and including maintenance of producer-user networks; and (2) an interdisciplinary, cooperative approach to the development of projects for utilizing earth science information, often involving public/private partnerships. These processes are recommended for application in the Wasatch Front earthquake hazard reduction program.

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EARTHQUAKE INFORMATION NEEDS OF LOCAL GOVERNMENTS

by

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There are many possible responses or adjustments to the risk posed by the earthquake hazard to urban development. Most of these responses will involve local governments in some way. Types of possible responses include emergency response planning, dissemination of public information, safer construction practices, the location and design of urban infrastructure, avoidance of faults and other particularly hazardous areas, and removal or reinforcing of particularly hazardous structures. Programs that constitute a jurisdiction's response might be based on any one, but more probably a combination of, these approaches. The implementation of any response will require significant amounts of scientific and other technical information to support local decision making. This paper will attempt to identify the kinds of information that local governments need to respond to the earthquake hazard.

To determine what type of information is needed for jurisdictions in Utah, it might be useful to look at what other local governments facing an earthquake hazard have found useful. One example would be communities in California. A 1982 mail survey of cities and counties in California provides some interesting ideas as to the type of information currently being used by local governments which have to make decisions regarding the earthquake hazard and the risk it poses to urban development. This survey focused on the nature and quality of seismic information currently available at the local level, the types of decisions in which seismic information was routinely used and the types of policies adopted by each jurisdiction to deal with the earthquake hazard. While the experiences of these communities may not be completely transferable to other areas, they do provide some interesting insights into the types of information local governments are now using to deal with the earthquake hazard.

Of the 118 agencies contacted, 105 (89%) completed and returned their questionnaires. In each community the survey was completed by the planning director or the chief administrator. Of those jurisdictions that responded, 87% were cities and the remaining 13% were counties. The average 1980 population of the cities was 46,100; the average for the counties was slightly over 700,000. Over half of the jurisdictions stated they had experienced at least one earthquake since 1970. The average intensity of these events was reported as 5.3 on the Richter scale, but most (90%) reported only minor damage as a result. In fact, only two jurisdictions reported any severe damage since 1970.

When asked how serious they consider the problem of seismic hazards in their jurisdictions, 25% said they are a serious problem. Ground shaking was identified as the most serious type of seismic hazard facing these jurisdictions. Liquefaction and landslide were also commonly mentioned as serious problems, but by less than half of the respondents in each case.

The seismic hazard information that local governments were using seemed to be fairly current, having been updated in 1976 on the average. State government and private consultants were most often listed as the principal source of seismic information. When asked to characterize the accuracy of currently available hazard information, 24% said their information was very accurate and only relatively few said their information was not very accurate (10%) or that they were unsure of its accuracy (6%). This positive view was reflected in how respondents rated the usefulness of currently available information: nearly 70% thought it was extremely or generally useful. The usefulness of the information also appears to have influenced how serious local officials consider seismic hazards in their jurisdiction. Those that considered the hazard more serious tended to think that hazard information was more useful.

Nearly all of the jurisdictions contacted included some type of hazard maps in the seismic safety element of their General Plans. A correlation analysis suggests that such maps make the General Plan more helpful to various user groups. The seismic safety element was generally rated as somewhat helpful to elected officials, planning commissioners and developers. However, roughly one-fifth of the respondents admitted that the seismic safety element has not been helpful to any of these groups. Perceived usefulness also seemed to be related to how the information was being used. For example, in jurisdictions where special building regulations were applied to hazardous areas, the information was considered more useful. There is also a strong correlation between the availability of good information on surface geology and perceived usefulness. This suggests that good information about detailed site geology should be an important consideration for most local governments affected by earthquake hazards.

When asked what necessary hazard information they currently lack, most respondents seemed to feel they had adequate information on the location of faults. Many of the jurisdictions (90%) said they need better information on surface geolcgy and a majority (51%) said they needed better information on the estimated damages which would result from a seismic event. Though mentioned by less than a majority, several other types of information were widely regarded as lacking. These included (1) the probabilities and intensities of potential seismic events; (2) the structural condition of existing buildings; and (3) the effects of seismicity on areas prone to landslide and liquefaction.

The next phase of the analysis focuses on how local governments are using hazard information. A majority of the respondents stated that they routinely use seismic hazard information in environmental impact reviews (82%), building code enforcement (71%) and subdivision review (53%). Building code enforcement was rated the single most important use of seismic hazard information. This corresponds with the fact that nearly 70% of the respondents said their jurisdictions had special building requirements for construction in areas of potential seismic hazard. Few respondents mentioned retrofit/redevelopment as an important use of seismic hazard information, and only one in five said that their jursidiction would require demolition or retrofit of existing structures on account of seismic safety concerns. Thus, most jurisdictions were using seismic hazard information in relation to new development, but not in relation to existing development.

While a substantial proportion reported using hazard information in comprehensive planning and emergency response planning, the survey suggests that currently most jurisdictions place major emphasis on site specific decisions. When asked directly, respondents also tended to think their information was better suited for project level decisions than for comprehensive decisions. However, over 75% thought that seismic hazard information should be applicable to both project level and comprehensive decisions. Surprisingly few (39%)

of the jursidictions reported using seismic hazard information in zoning decisions. While zoning has often been suggested as an important hazard mitigation tool, many jurisdictions do not apply seismic hazard information to this comprehensive land use control.

Roughly half (51%) of the jurisdictions reported that they give special attention in their General Plans to development of areas near active faults. Many also give special attention to development in areas of potential landslide (49%) and liquefaction (41%). Half of the jurisdictions also said they place special requirements on all critical facilities (i.e., hospitals, power plants, schools, etc.).

Thus, in California most jurisdictions seem to have access to fairly current, detailed hazard information. The information seems to be used primarily in making site specific decisions about new development. These local governments indicated they needed better information on surface geology, earthquake-induced landslide and liquefaction hazards, the likelihood of earthquakes of various intensities, and the structural condition of the existing building inventory.

In Utah, local governments will generally need similar types of information. However, the specific information needed by any particular local government will depend on the type of mitigation strategy it has chosen. Given the relatively limited amount of research that has been done on the Wasatch and related faults in the past, most local governments in Utah probably need better information on the probability of occurrence for earthquakes of various intensities.

Rapidly growing communities which are experiencing large amounts of new development will probably want to focus on hazard mitigation strategies directed toward new development. Such anticipatory strategies rely largely on designing structures to withstand strong ground motion and on land use planning to avoid fault rupture zones and areas subject to exceptionally strong ground shaking, high liquefaction potential, and earthquake induced landslides or flooding. To deal with these hazards to new development, the local government will need detailed mapping of fault locations and surface geology, including interpreted maps which rate the severity of these secondary hazards in various locations. This detailed geologic information will probably have to be obtained from state or federal agencies, although university personnel or consultants are an alternative for communities which can afford to pay for this type of expertise.

In communities with a large number of buildings already at risk, the emphasis should be on defining the extent of the existing problem and finding ways to cope with it. In such communities identification of particularly hazardous structures and accurate estimates of expected damage to various types of structures will probably be the most useful types of information. Detailed damage estimates, which include rough mapping of damage patterns, will be quite helpful in planning how to respond to an earthquake emergency. Such damage estimates will require damage or vulnerability functions which relate earthquake intensity to damage for a particular type of structure. When combined with an inventory of existing structures, these functions can provide useful damage estimates for emergency response planning. For even approximate damage estimates, local communities will need an inventory of their overall building stock and a more detailed analysis of critical facilities, such as schools, hospitals and water treatment plants. Much of this information should be available from the communities own records or through limited field investigation by building inspectors or engineering consultants.

Local governments require considerable amounts of information to respond to the earthquake hazard. The scientific information must come primarily from outside sources. Here, local governments must make sure that the information that they receive is in a form and at a scale which they can use. In terms of damage estimates, local governments already have much of the necessary building inventory information, but they need estimates of the damage-intensity relationship and estimates of the level of ground shaking intensity they are likely to experience. In addition to technical information, local governments also need to understand what their options are for responding to the hazard. They need to know what types of policies other communities have used and how they have worked. They need to know the legal and political constraints which may limit their response to the earthquake hazard.

Whether a community is attempting to avoid hazardous areas, to ensure building safety through engineering solutions, or to develop emergency response plans to better cope with the aftermath of a serious earthquake, there are three main sources of information must be considered. The scientific community can provide technical information which describes the hazard; the community's own records can provide information on the nature and condition of the building stock; and other communities and legal experts can provide guidance as to the types of policies which are possible and the likelihood of various types of measures to be successful. Communities facing a serious earthquake hazard should avail themselves of the best possible information in all three areas to mount an effective mitigation strategy.

LEGAL ISSUES RELATED TO HAZARD MITIGATION POLICIES

by
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Professionals involved in design, construction, and maintenance of structures, facilities, and graded areas have become the target of litigation within the past decade when failures and losses have occurred. Court decisions nation-wide have moved slowly, but consistently in the direction of holding the professionals responsible where negligence, errors, or omissions have been involved. Recent out-of-court (or pre-trial) settlements and superior court decisions in California have carried that another step and have developed a recognizable trend toward holding the professional responsible when there is an indication of negligence and/or work that falls below that which a responsible, prudent professional would perform. Prior to this change in philosophy by the courts, the professional had only to reach the level of work or quality commonly attained or agreed upon by members of a prescribed discipline or profession in the geographic area in which those professionals practiced; that locally - applicable level of work had been called "standard practice". In some geographic areas, it has been noted that persons of a given profession may have, by group action or agreement, set the "standards-of-practice" -- in some instances stating that, for a variety of reasons or rationale, "they" need not meet as high a standard as achieved elsewhere. Some local governments have agreed to accept these lower standards as the locally accepted standard.

Responsible professionals should be aware that the "same or similar" concept is now a part of the legal vocabulary in California, Utah, and many other states. Some California judges during the past decade have suggested that it may be possible for "standard practice" in a given geographic area to be judged substandard relative to professional standards utilized elsewhere. A professional who uses a lower standard adopted by a lax governmental jurisdiction for a project within that jurisdiction, but who knows or should have known of higher standards utilized elsewhere, can be held responsible for a failure or losses resulting from the use of those lower standards. In a recent case in San Diego, California, the consulting firm was found responsible for losses related to what the court determined to be substandard practice, even though the local government had accepted the work and the professional standards utilized.

The practicing professional architect, engineer, geologist, and planner should be aware of their responsibilities and to what "responsible, prudent practice" equates. They should be aware that many states have adopted the concept of "same or similar" for area of practice and/or method of practice. Thus, a professional architect working in Salt Lake City, Utah may be held responsible for knowing and utilizing the prudent practices normally used for earthquake resistant design used in California considering that: 1) earthquakes are anticipated in both areas; 2) the earth materials are similar; 3) the fault-seismic activity can be equated reasonably well; 4) similar construction materials are used; 5) the professional societies dealing with architecture and seismic design criteria are nationwide in membership; 6) the Universities teach similar subjects; 7) conferences dealing with earthquakes and design are held in both cities; 8) geologic mapping and seismic zonation has been accomplished in both geographic areas and with similar techniques; 9) active faults have been identified as well as other miscellaneous factors; and 10) the relative ease in locating the techniques and procedures of the "similar" jurisdiction. The case can easily be made for use of the "same or similar" concept.

Many professionals and/or firms practice in both Salt Lake City and Los Angeles; thus, it would be almost impossible for them to argue that it would be prudent to drop to a lower standard of practice just because "Salt Lake City was less stringent at the time of design and construction than Los Angeles". The courts in California are overwhelmingly finding the professional responsible (or guilty) when they drop their standard of care to whatever local government accepts. In the past, some professionals have set their standard of care to the lowest allowed by local government.

It will be interesting to monitor the course of the Utah courts during the next decade as they determine whether professionals and/or their firms, which offer service in Utah will be permitted to ignore the higher standards (related to site analysis and design criteria) which must be met in California, which is a "similar" locality in order to use the lower requirements acceptable in Utah. In cases involving severe damage to structures and loss of life, will the professional be able to argue that he or she knowingly dropped professional standards to address only the lower standards of care accepted in Utah with full knowledge that failure or loss of life might occur? Granted economical concern is a factor and the client may not be willing to pay for more than the bare minimum required by an inept governmental agency, but should the professional be willing to work at a substandard and subprofessional level? The courts will certainly answer this question and dilemma. If a building collapses and kills scores of people and the cause can be shown to be substandard design or construction -- can this be called an act of God or will it be termed negligence?

It is the opinion of the author that the courts will hold the professionals responsible for the high standards that have been established in jurisdictions such as the city of Los Angeles or the State of California. Furthermore, the engineering geologist will most likely be held responsible to meet or exceed the standard of care outlined in the guidelines for reports developed more than a decade ago (1971) by the Association of Engineering Geologists (see attached). These guidelines were adopted by the California Division of Mines and Geology in 1973 (CDMG Notes #37) and the California Board of Registration for Geologists in 1979.

In addition, it is the opinion of the author that eventually the courts will recognize that the planners and planning commissions usually make the land-use and planning decisions that predicate essentually all of the events to follow. Thus, the planners and planning commissions may, in all liklihood, become the prime targets in future lawsuits. If the planning commission approves a housing development to be designed and constructed below or downstream from a known, older, unsafe dam located near the Wasatch Fault -- a known active fault-- and a predictable 6½ to 7 magnitude earthquake occurs causing failure of the dam, flooding of the subdivision, and loss of life - who then is responsible?

SPECIAL SESSION -- NEEDS IDENTIFIED

by

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The final two hours of the special session were set aside for a brainstorming session. The audience was comprised of over 50 individuals, of whom 35 were users of earth-science information and about 15 were representatives of the Utah Geological and Mineral Survey, the United States Geological Survey, the Federal Emergency Management Agency, and other producers of information. The users represented the Utah State Board of Education and departments of Transportation and Health, county commissions, county planning organizations, utility companies, the American Red Cross, and other individuals and organizations with similar interests.

The users selected as panelists began the brainstorming session by commenting on the usefulness to their organizations of the techniques previously presented by the seven speakers. They were asked to list types of information that they felt rated the highest priorities. One of the moderators made notes on the blackboard as the panelists presented their views. The six members of the panel were:

Mr. Jerrold Barnes -- Planner, Salt Lake County

Mr. Darrel Crawford -- Engineering Coordinator,
Mountain Fuel Supply Company

Mr. G. Allen Fawcett -- Director, Richfield Community Planning

Hon. Don LeBaron -- Member, Utah State House of Representatives

Mr. George Shaw -- City Planner, Sandy

Hon. Harold Tippetts -- Commissioner, Davis County

The meeting was then thrown open for brainstorming by the users in the audience. It was difficult for the representatives of the information-producing community to resist responding to the users with comments such as "too costly," "already available," or "not effective when tried in other places." However, the purpose of the session was to collect a listing of the needs of this particular set of users as perceived by them. Consequently, the brainstorming approach was scrupulously followed and resulted in a blackboard filled with a list of needs. The items listed were organized into the following categories: (1) scientific research topics, (2) translation of science for use by non-technical users, (3) dissemination of the information to the users, (4) use of the translated information to reduce hazards, and (5) evaluation of the uses of the information to ensure effectiveness. There was, of course, some duplication and overlapping.

After the needs were organized, the moderators asked for a weighing of the importance of each need by a simple showing of hands. The users were asked whether they would actually use the information if it were available. Both information producers and users fully understood that a "no" vote did not mean that the information was not necessary or useful to someone else, but rather that this particular group of users did not think that they would use the information. The spontaneous voting by only the user attendees resulted in a rating on a scale of 1 to 10. The number 10 indicates that virtually all the users present felt that their organizations needed and would, or should, use a specific type of information. The results are reproduced below without interpretation.

Scientific Research Topics

- Liquefaction (5)
- Landsliding (10)
- Geology (3)
- Exchange of information between states (3)
- Standardization of maps and scales (5)
- Consistancy in scales of published maps (4)
- Geotechnical data collected and indexed by county (8)

Translation of Science for Use by Non-technical Users

- Simplified interpretive analog information from other states (5)
- Site-specific geologic reports that are legally and politically defensible (10)
- Maps showing susceptibility to hazards (10)
- Early warning "red flag" maps at scales 1:9600 or more detailed (10)
- Location of hazardous parapets (2)
- Location of critical facilities such as lifelines (10)
- Evaluation of the safety of dams by engineering geologists (10)

Structure types susceptible to failure by shaking (8)

Location of fault-rupture zones (7)

Maps showing level of susceptibility to hazards in red, yellow, and green colors (3)

Estimates of the cost of damage from postulated earthquakes (7)

Maps showing multi-hazards at scales of 1:2400 or more detailed (10)

Maps showing susceptibility to damage or hazard (10)

Retain five staff geologists to serve 10 counties (9)

"Red-flag" hazard maps for counties at a scale of 1:100,000 (6)

Maps interpreting research for use by nontechnical persons (10)

Maps showing ground acceleration (1)

Update 7½-minute maps (topographic series) (1)

More-detailed information for smaller cities (5)

Update Ridd's maps of Davis County (5)

Hazard-scenario maps, **e.g.**, floodway simulation (8)

Dissemination of the Translated Information to Users

Model seismic-safety plans (5)

Education of local planning commissioners (10)

Public education for both adults and school children (5)

Increased awareness of hazards (10)

Definitions of public policy concerning hazards (5)

Library of geotechnical reports (9)

Clarify the government's responsibility for seismic safety (3)

Educational materials explaining earthquake processes and their effects that are meant for adults but can be understood by sixth-graders (5)

Advisory services (10)

Increased media coverage (8)

Training for local-government employees (10)

Training for local planners (10)

Lists of experts in earthquake-hazard research, damage, and reduction (4)

Prototypical community training exercises (9)

New legislation requiring minimum seismic standards for construction of publicly occupied buildings (9)

New legislation requiring site investigations for construction of public facilities (10)

New legislation requiring minimum seismic standards for publicly owned buildings (9)

Use of the Translated Information to Reduce Hazards

Site-specific scenario for a postulated earthquake (10)

Specific preparedness plans (5)

Model administrative techniques (3)

General scenario of the effects for a postulated earthquake (5)

Legal support of hazard-reduction techniques (9)

Criteria for, and examples of, site investigations (7)

Model grading ordinance (5)

The ten best mitigation techniques for large cities (5)

The ten best mitigation techniques for small cities (5)

Building set-back standards to avoid hazardous areas (3)

Definitions of owner or government liability (3)

Evaluation of the Uses to Ensure Effectiveness

Benefit-cost analysis (5)

List of skilled reviewers (9)

This list of needs is neither interpreted nor evaluated; therefore its value is limited. For example, under the heading **Scientific Research Topics**, the entry "Landsliding" was assigned a rating of 10, whereas "Geology" was assigned a rating of only 3; regional geologic studies of landslide processes are prerequisites to providing and translating landslide-hazard information.

It should be understood that this type of compilation is highly unstructured, unscientific, biased, and easily misinterpreted, but it can be of use to those information producers who want to have specific persons and organizations use their information for planning and decisionmaking.

APPENDIX A

GLOSSARY OF TERMS FOR PROBABILISTIC SEISMIC-RISK AND HAZARD ANALYSIS

This glossary of technical terms is provided to facilitate their use in a standard manner. These terms are encountered frequently in the literature and in discussion of earthquake hazards and risk.

ACCEPTABLE RISK - a probability of social or economic consequences due to earthquakes that is low enough (for example in comparison with other natural or manmade risks) to be judged by appropriate authorities to represent a realistic basis for determining design requirements for engineered structures, or for taking certain social or economic actions.

ACTIVE FAULT - a fault that on the basis of historical, seismological, or geological evidence has a high probability of producing an earthquake. (Alternate: a fault that may produce an earthquake within a specified exposure time, given the assumptions adopted for a specific seismic-risk analysis.)

ATTENUATION LAW - a description of the behavior of a characteristic of earthquake ground motion as a function of the distance from the source of energy.

B-VALUE - a parameter indicating the relative frequency of occurrence of earthquakes of different sizes. It is the slope of a straight line indicating absolute or relative frequency (plotted logarithmically) versus earthquake magnitude or meizoseismal Modified Mercalli intensity. (The B-value indicates the slope of the Gutenberg-Richter recurrence relationship.)

COEFFICIENT OF VARIATION -- the ratio of standard deviation to the mean.

DAMAGE - any economic loss or destruction caused by earthquakes.

DESIGN ACCELERATION - a specification of the ground acceleration at a site, terms of a single value such as the peak or rms; used for the earthquake-resistant design of a structure (or as a base for deriving a design spectrum). See "Design Time History."

DESIGN EARTHQUAKE - a specification of the seismic ground motion at a site; used for the earthquake-resistant design of a structure.

DESIGN EVENT, DESIGN SEISMIC EVENT - a specification of one or more earthquake source parameters, and of the location of energy release with respect to the site of interest; used for the earthquake-resistant design of a structure.

DESIGN SPECTRUM - a set of curves for design purposes that gives acceleration velocity, or displacement (usually absolute acceleration, relative velocity, and relative displacement of the vibrating mass) as a function of period of vibration and damping.

DESIGN TIME HISTORY - the variation with time of ground motion (e.g., ground acceleration or velocity or displacement) at a site; used for the earthquake-resistant design of a structure. See "Design Acceleration."

DURATION - a qualitative or quantitative description of the length of time during which ground motion at a site shows certain characteristics (perceptibility, violent shaking, etc.).

EARTHQUAKE - a sudden motion or vibration in the earth caused by the abrupt release of energy in the earth's lithosphere. The wave motion may range from violent at some locations to imperecptible at others.

ELEMENTS AT RISK - population, properties, economic activities, including public services etc., at risk in a given area.

EXCEEDENCE PROBABILITY - the probability that a specified level of ground motion or specified social or economic consequences of earthquakes, will be exceeded at the site or in a region during a specified exposure time.

EXPECTED - mean, average.

EXPECTED GROUND MOTION - the mean value of one or more characteristics of ground motion at a site for a single earthquake. (Mean ground motion.)

EXPOSURE - the potential economic loss to all or certain subset of structures as a result of one or more earthquakes in an area. This term usually refers to the insured value of structures carried by one or more insurers. See "Value at Risk."

EXPOSURE TIME - the time period of interest for seismic-risk calculations, seismic-hazard calculations, or design of structures. For structures, the exposure time is often chosen to be equal to the design lifetime of the structure.

GEOLOGIC HAZARD - a geologic process (e.g., landsliding, lequefaction soils, active faulting) that during an earthquake or other natural event may produce adverse effects in structures.

INTENSITY - a qualitative or quantitative measure of the severity of seismic ground motion at a specific site (e.g., Modified Mercalli intensity, Rossi-Forel intensity, Housner Spectral intensity, Arias intensity, peak acceleration, etc.).

LOSS - any adverse economic or social consequence caused by one or more earthquakes.

MAXIMUM - the largest value attained by a variable during a specified exposure time. See "Peak Value."

MAXIMUM CREDIBLE
MAXIMUM EXPECTABLE
MAXIMUM EXPECTED
MAXIMUM PROBABLE

These terms are used to specify the largest value of a variable, for example, the magnitude of an earthquake, that might reasonably be expected to occur. In the Committee's view, these are misleading terms and their use is discourage. (The U.S. Geological Survey and some individuals and companies define the maximum credible earthquake as "the largest earthquake that can be reasonably expected to occur." The Bureau of Reclamation, the First Interagency Working Group (Sept. 1978) defined the maximum credible earthquake as "the earthquake that would cause the most severe vibratory ground motion capable of being produced at the site under the current known tectonic framework." It is an event that can be supported by all known geologic and seismologic data. The maximum expectable or expected earthquake is defined by USGS as "the largest earthquake that can be reasonably expected to occur." The maximum probable earthquake is sometimes defined as the worst historic earthquake. Alternatively, it is defined as the 100-year-return-period earthquake, or an earthquake that probabilistic determination of recurrence will take place during the life of the structure.)

MAXIMUM POSSIBLE - the largest value possible for a variable. This follows from an explicit assumption that larger values are not possible, or implicitly from assumptions that related variables or functions are limited in range. The maximum possible value may be expressed deterministically or probabilistically.

MEAN RECURRENCE INTERVAL, AVERAGE RECURRENCE INTERVAL - the average time between earthquakes or faulting events with specific characteristics (e.g., magnitude $\geq$ 6) in a specified region or in a specified fault zone.

MEAN RETURN PERIOD - the average time between occurrences of ground motion with specific characteristics (e.g., peak horizontal acceleration $\geq$ 0.1 g) at a site. (Equal to the inverse of the annual probability of exceedance.)

MEAN SQUARE - expected value of the square of the random variable. (Mean square minus square of the mean gives the variance of random variable.)

PEAK VALUE - the largest value of a time-dependent variable during an earthquake.

RESPONSE SPECTRUM - a set of curves calculated from an earthquake accelerogram that gives values of peak response of a damped linear oscillator, as a function of its period of vibration and damping.

ROOT MEAN SQUARE (rms) - square root of the mean square value of a random variable.

SEISMIC-ACTIVITY RATE - the mean number per unit time of earthquakes with specific characteristics (e.g., magnitude $\geq$ 6) originating on a selected fault or in a selected area.

SEISMIC-DESIGN-LOAD EFFECTS - the actions (axial forces, shears, or bending moments) and deformations induced in a structural system due to a specified representation (time history, response spectrum, or base shear) of seismic design ground motion.

SEISMIIC-DESIGN LOADING - the prescribed representation (time history, response spectrum, or equivalent static base shear) of seismic ground motion to be used for the design of a structure.

SEISMIC-DESIGN ZONE - seismic zone.

SEISMIC EVENT - the abrupt release of energy in the earth's lithosphere, causing an earthquake.

SEISMIC HAZARD - any physical phenomenon (e.g., ground shaking, ground failure) associated with an earthquake that may produce adverse effects on human activities.

SEISMIC RISK - the probability that social or economic consequences of earthquakes will equal or exceed specified values at a site, at several sites, or in an area, during a specified exposure time.

SEISMIC-RISK ZONE - an obsolete term. See "Seismic Zone."

SEISMIC-SOURCE ZONE - an obsolete term. See "Seismogenic Zone" and "Seismotectonic Zone."

SEISMIC ZONE - a generally large area within which seismic-design requirements for structures are constant.

SEISMIC ZONING, SEISMIC ZONATION - the process of determining seismic hazard at many sites for the purpose of delineating seismic zones.

SEISMIC MICROZONE - a generally small area within which seismic-design requirements for structures are uniform. Seismic microzones may show relative ground motion amplification due to local soil conditions without specifying the absolute levels of motion or seismic hazard.

SEISMIC MICROZONING, SEISMIC MICROZONATION - the process of determining absolute or relative seismic hazard at many sites, accounting for the effects of geologic and topographic amplification of motion and of seismic microzones. Alternatively, microzonation is a process for identifying detailed geological, seismological, hydrological, and geotechnical site characteristics in a specific region and incorporating them into land-use planning and the design of safe structures in order to reduce damage to human life and property resulting from earthquakes.

SEISMOGENIC ZONE, SEISMOGENIC PROVINCE - a planar representation of a three-dimensional domain in the earth's lithosphere in which earthquakes are inferred to be of a similar tectonic origin. A seismogenic zone may represent a fault in the earth's lithosphere. See "Seismotectonic Zone."

SEISMOGENIC ZONING - the process of delineating regions having nearly homogeneous tectonic and geologic character, for the purpose of drawing seismogenic zones. The specific procedures used depend on the assumptions and mathematical models used in the seismic-risk analysis or seismic-hazard analysis.

SEISMOTECTONIC ZONE, SEISMOTECTONIC PROVINCE - a seismogenic zone in which the tectonic processes causing earthquakes have been identified. These zones are usually fault zones.

SOURCE VARIABLE - a variable that describes a physical characteristic (e.g., magnitude, stress drop, seismic moment, displacement) of the source of energy release causing an earthquake.

STANDARD DEVIATION - the square root of the variance of a random variable.

UPPER BOUND - see "Maximum Possible."

VALUE AT RISK - the potential economic loss (whether insured or not) to all or certain subset of structures as a result of one or more earthquakes in an area. See "Exposure."

VARIANCE - the mean squared deviation of a random variable from its average value.

VULNERABILITY - the degree of loss to a given element at risk, or set of such elements, resulting from an earthquake of a given magnitude or intensity, which is usually expressed on a scale from 0 (no damage) to 10 (total loss).

APPENDIX B

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