UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

WORKSHOP ON "EVALUATION OF EARTHQUAKE HAZARDS AND RISK IN THE PUGET SOUND AND PORTLAND AREAS"

PROCEEDINGS OF CONFERENCE XLII

SPONSORED BY

U.S. GEOLOGICAL SURVEY
FEDERAL EMERGENCY MANAGEMENT AGENCY
WASHINGTON STATE DEPARTMENT OF NATURAL RESOURCES
WASHINGTON DEPARTMENT OF COMMUNITY DEVELOPMENT
OREGON DEPARTMENT OF GEOLOGY AND MINERAL DEVELOPMENT
OREGON EMERGENCY MANAGEMENT DIVISION

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Reston, Virginia
1988

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Olympia, Washington
April 12-15, 1988

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U.S. Geological Survey
Federal Emergency Management Agency
Washington State Department Of Natural Resources
Washington Department of Community Development
Oregon Department of Geology and Mineral Development
Oregon Emergency Management Division

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WORKSHOP ON "EVALUATION OF EARTHQUAKE HAZARDS AND RISK IN THE PUGET SOUND AND PORTLAND AREAS"

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INTRODUCTION

The workshop "Evaluation of Earthquake Hazards and Risk in the Puget Sound and Portland areas" was held in Olympia, Washington, on April 12-15, 1988. This workshop, the 42nd in a continuing series, is a part of the U.S. Geological Survey's (USGS) program element, "Regional Earthquake Hazards Assessments." The USGS, the Federal Emergency Management Agency, the Washington State Departments of Natural Resources and Community Development, the Oregon Department of Geology and Mineral Development, and the Oregon Emergency Management Division sponsored the workshop which is the 42nd overall in a series of research applications workshops and conferences that USGS originated in 1977 under the auspices of the Earthquake Hazards Reduction Act. The primary objectives of the workshop were:

1) To strengthen the capability of the scientific and technical community of Washington and Oregon 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, tectonic deformation, and tsunamis, and for assessing the risk from these hazards.

2) To work with public officials in Washington and Oregon to foster an environment for use of research results, creating partnerships and providing scientific information that can be used by State and local governments to develop and adapt hazard reduction techniques 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) assessing the present state-of-knowledge of earthquake hazards in Washington and Oregon including scientific, engineering, and hazard-reduction components, 3) determining the need for additional scientific, engineering, and societal-response information to implement an effective earthquake-hazard reduction program, and 3) developing a strategy for implementing programs to reduce potential earthquake losses and to foster preparedness and mitigation. The papers contained in this volume were presented at the workshop. A glossary of technical terms used in earthquake engineering is contained in Appendix A to assist in communicating and understanding.

Prior to the workshop, a planning meeting involving 25 people was held in Bothell, Washington, on December 9-10, 1987, to devise a draft work plan to guide the research and implementation activities for an initial 5-year period. This plan, which follows this summary, was produced by representatives of the Washington Departments of Natural Resources and Community Development, University of Washington, King and Pierce Counties, the Oregon Department of Geology and Mineral Development, FEMA, and the USGS. The policy recommendations made in 1986 by the Washington State Seismic Safety Council were an important consideration in the development of the draft work plan.

JUSTIFICATION FOR STUDYING THE PUGET SOUND AND PORTLAND AREAS

Geologic and geophysical research aimed at attaining a better understanding of the potential for the occurrence of large, damaging earthquakes in the Puget Sound and Portland areas has been carried out by USGS and university scientists and others since the early 1970's. 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 USGS Regional Earthquake Hazards Assessment program element. The geologic and geophysical data collected in these studies are essential in the evaluation of earthquakes hazards and the assessment of risk from earthquakes occurring in the area. 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 which are not readily available. They have not been synthesized or integrated into a comprehensive evaluation of the potential for the occurrence of damaging earthquake and the associated hazards of ground-shaking, ground failure, surface fault rupture, tectonic deformation, and tsunamis in the Puget Sound-Portland area.

Large subduction earthquakes on the Cascadia subduction zone pose a potential seismic hazard (see papers by Heaton and Hartzell, and Spence in this volume.) Very young oceanic lithosphere (10 million years old) is being subducted beneath North America at a rate of approximately four centimeters per year. The Cascadia subduction zone shares many characteristics with subduction zones in southern Chile, southwestern Japan and Colombia, where comparably young oceanic lithosphere is also subducting. Very large subduction earthquakes, ranging in moment magnitude (M_w) between 9 and 9.5 have occurred along these other subduction zones. If the Cascadia subduction zone is also storing elastic energy, a sequence of several great earthquakes (M_w 8) or a giant earthquake (M_w9) would be necessary to fill this 1200-kilometer gap. The nature of strong ground motion recorded during subduction earthquakes of M_w less than 8.2 as well as strong ground motions from even larger earthquakes (M_w up to 9.5) can now be estimated by simple simulations. If large subduction earthquakes occur in the Pacific Northwest, relatively strong ground shaking can be expected over a large region. Such earthquakes may also be accompanied by local tsunamis.

Ground failures due to historic earthquakes in western Washington have resulted in only a few deaths, but have caused significant damage over large areas (see paper by Schuster and Chleborad in this volume). The 1949 Olympia earthquake triggered scattered ground failures over an area of approximately 11,000 square miles, and the 1965 Seattle-Tacoma earthquake triggered ground failures within an area of about 8,000 square miles.

VALUE OF A WORKSHOP

All of the information contained in this volume could have been published and distributed without a workshop. However, experience has shown that mailing a report is the least effective way to stimulate action.

This workshop was designed to address the potential effects of earthquakes and other geological hazards that might be triggered by earthquakes in Washington and Oregon. It was designed under the auspices of the National Earthquake Hazards Reduction Program (NEHRP) to define the threat from earthquakes in the United States and improve overall earthquake preparedness and mitigation at all levels. The program followed the format used in prior workshops in Utah, Alaska, the Northeastern United States, the Central United States and Puerto Rico-Virgin Island region.

The 41 prior 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, concern, and commitment, and called for changes in the state-of-practice in earthquake-resistant siting, design, construction, and land use.

Most importantly, they have brought together more than 3,000 producers and users of geologic hazards information from every earthquake-prone part of the United States. They have fostered local-State-Federal partnerships and have enhanced the use of existing information as well as the creation of people and program networks. Seismic safety organizations have been created as a result of the workshops. Proceedings of past workshops have been disseminated to the participants to use in their program and policy development and to about 5,000 others throughout the world who have requested them for the value of the information they contain.

DECISIONMAKING AND EARTHQUAKE HAZARDS

The workshop on "Evaluation of Earthquake Hazards and Risk in the Puget Sound and Portland areas" emphasized the well-known fact that understanding the geologic processes causing earthquake hazards of ground shaking, surface faulting, ground failure, regional tectonic deformation and tsunamis is the most important step in devising practical methodologies for reducing future economic losses and social impacts from earthquakes. Without such loss-reduction measures, the potential losses in Washington and Oregon will become greater as a consequence of factors such as: 1) increased population density, and 2) increased building and lifeline stock exposed to potential geologic hazards as urban centers grow through construction of homes, schools, hospitals, high-rise buildings, factories, utility systems, power plants, and public facilities.

The choice facing decisionmakers in the Puget Sound-Portland area are difficult for three reasons: 1) earthquakes 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 various hazard-reduction techniques, and 3) hazard-reduction techniques cost money and require local-State-Federal partnerships having well-conceived short- and long-term objectives in order to be effective economically and politically. The options for reducing losses from earthquake hazards include:

1) Land-use planing 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 recurrence interval or severity of effects.

2) Avoidance - provide maps and other technical information that answer the questions Where? and How often? so that planners and decisionmakers can avoid potential hazards by selecting the least hazardous area for development.

3) Engineering design and building codes - require engineering design and construction practices that are appropriate in terms of the recurrence interval and the severity of the potential hazard.

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

5) Community and personal preparedness - prepare for the consequences of earthquake hazards that are expected to occur, taking advantage of worldwide experience and techniques used to reduce other natural hazards such as floods, volcanic eruptions, and landslides.

6) Response and recovery - plan response recovery measures that are appropriate in terms of experience, learned from damaging events in other parts of the Nation that provide specific relevant lessons that can be transferred to Washington and Utah.

It is very important to emphasize that decisionmakers have different perspectives about geologic hazards than scientists and engineers. These differences, which have been summarized by Peter Szanton in his book "Not well Advised" (Russell Sage Foundation and the Ford Foundation, 1981), are the reason that the effective use of research information to reduce potential losses from earthquakes is difficult. These differences may be paraphrased as:

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 though 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 on "best solution" with uncertainties submerged; it is multiple possibilities with uncertainties emphasized for the scientist/engineer.

These differences in perspectives emerged in this workshop, as they always do, when scientists, engineers, and decisionmakers meet together. They almost always emerge in discussions of the basic questions, listed below, that form the basis for an earthquake-hazard-reduction program:

1) Where are the potential hazards of ground shaking, earthquake-induced ground failure, surface fault rupture, tectonic deformation located? 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, tectonic deformation, and tsunamis 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 best options for reducing losses from these physical effects?

These seven differences in perspectives between decisionmakers and scientists/engineers are the main reason 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 the use of research products in loss reduction techniques.

WORKSHOP STRATEGIES

The strategies used in this workshop were designed to build on past and present activities in Washington and Oregon, 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 five-year work plan, "Regional Earthquake Hazards Assessments in the Pacific Northwest," was prepared and disseminated several months before the workshop (see "Draft Work Plan" following this summary).

2) The workshop was scheduled to take advantage of heightened awareness and concern resulting from recent earthquakes in California and Latin America

(e.g., the October 1987 Whittier-Narrows, California, and the March 1985 Chile, and the September 1985 Mexico earthquakes).

3) An all-day field trip to Grays Harbor before the workshop gave participants an opportunity to learn about the activities underway to find evidence for historic large- to great-magnitude earthquakes and to view some of the important geologic methods

4) Research reports and preliminary technical papers prepared in advance by the participants were distributed at the workshop and used as resource material. The reports and papers presented by the participants during the workshop were finalized after the workshop and are contained in this publication.

5) Earth scientists, social scientists, engineers, planners, educators, insurers, and emergency management specialists gave oral presentations in three major sessions. The objectives were to: 1) provide essential facts on the assessment of earthquake hazards and risk, 2) discuss information needed to reduce potential losses, and 3) identify any obstacles and suggest strategies to overcome those obstacles. These presentations served as a summary of the state-of-knowledge and gave a multidisciplinary perspective.

6) Presentations of the speakers were discussed in small groups. Each group suggested future research and loss-reduction programs.

MAJOR SESSIONS

Following the welcome and introductions, the overall theme of the workshop was developed in three major sessions. The theme, objective, and speakers for each session are described below:

Objective: Brief statements of workshop objectives from the sponsors and an invited guest from Canada.

Welcome: William Mayer, Federal Emergency Management Agency, Region X

Speakers: Walter Hays, U.S. Geological Survey
Terry Feldman, Federal Emergency Management Agency
Ray Lasmanis, Washington State Department of Natural Resources
George Priest, Oregon Department of Geology and Mineral Industries
Kate Heinback, Washington State Department of Community Development
Ian Madin, Oregon Department of Geology and Mineral Industries
Fred Cooper, British Columbia and Yukon Emergency Preparedness

SESSION 1: BRIEFING ON ESSENTIAL FACTS FOR THE ASSESSMENT OF EARTHQUAKE HAZARDS AND LOSSES IN THE PUGET SOUND AND PORTLAND AREAS

Objective: A series of overview discussions on assessment of hazards and potential losses in the Puget Sound and Portland areas emphasizing: earthquake potential in the Pacific Northwest; search for evidence of great earthquakes in the past; factors influencing ground shaking, and earthquake-induced ground failures, surface ruptures, and water waves; and loss estimation.

Speakers: Ted Algermissen, U.S. Geological Survey
Karl Steinbrugge, Consulting Engineer
Garry Rogers, Geological Survey of Canada
Brian Atwater, U.S. Geological Survey
Al Rogers, U.S. Geological Survey
Ken King, U.S. Geological Survey
Gerald Thorsen, Consulting Geologist (formerly with Washington Department of Natural Resources)
Robert Schuster, U.S. Geological Survey

SESSION II: BRIEFING ON ESSENTIAL FACTS FOR MITIGATING EARTHQUAKE HAZARDS IN THE PUGET SOUND AND PORTLAND AREAS

Objective: A series of overview discussions on reducing hazards through improved building practices emphasizing: land-use planning; education, awareness, and preparedness programs; and emergency management planning and response planning.

Speakers: Charles Roeder, University of Washington
Derek Booth, King County Basin Planning Program
Carole Martens, Seattle Earthquake Safety and Education
Chuck Steel, Federal Emergency Management Agency, Region X

The topics of the first two sessions were also discussed in a small group setting. The goal was to stimulate discussions between both the producers and the users of research information. The three discussion groups for Session I explored: earthquake potential; ground shaking; and earthquake-induced ground failures, surface ruptures, and water waves in the Puget Sound and Portland areas. Each group was asked to identify: 1) areas of agreement in the assessment of these hazards, 2) research needed to reduce areas of disagreement, and 3) information available or needed to improve the definition and delineation of earthquake hazards.

Group 1: Moderator: Robert Crosson, University of Washington
Panelists: Craig Weaver, U.S. Geological Survey
Curt Peterson, Oregon State University
William Spence, U.S. Geological Survey
Alan Nelson, U.S. Geological Survey
Tom Urban, U.S. Geological Survey

Group 2: Moderator: C. B. Crouse, Earth Technology Corporation
Panelists: Tom Heaton, U.S. Geological Survey
Ted Algermissen, U.S. Geological Survey
Tom Urban, U.S. Geological Survey

Group 3: Moderator: Robert Yeates, Oregon State University
Panelists: Paul Grant, Shannon & Wilson, Inc.
Joanne Bourgeois, University of Washington
Robert Schuster, U.S. Geological Survey
Gerald Thorsen, Consulting Engineer

The three discussion groups for Session II explored: building practices; land-use planning, geographic information systems, and earthquake insurance;

and emergency management and earthquake education. Each group was asked to identify: 1) successful methods to reduce earthquake potential losses and foster preparedness and mitigation, 2) information needed to develop and carry out each loss-reduction method, 3) steps necessary for implementation, and 4) barriers that need to be overcome in the Puget Sound and Portland areas.

Group 1:	Moderator:	Bruce Olson, Consulting Engineer, Seattle, Washington
	Panelists:	Roger McGarrigle, Oregon Structural Engineers Association
		Tod Perbix; Ratti, Perbix, and Clark
		William Elliot, Portland Water Bureau
		Earl Schwartz, Building Department, City of Los Angeles
Group 2:	Moderator:	Patricia Bolton, Battelle Human Affairs Research Center
	Panelists:	Jane Pruess, Urban Regional Research
		Arthur Tarr, U.S. Geological Survey
		Foster Cronyn, Washington Insurance Council
Group 3:	Moderator:	Myra Lee, Oregon Emergency Management Division
		Bill Lokey, Pierce County Department of Emergency Management
		David Norris, Portland Bureau of Fire and Emergency Management
		Carole Martens, School Earthquake Safety and Education Project, Washington
		Peter Kerr, Greater Victoria School Board
		Lance Olmstead, Municipality of Saanich

Group 1 on "building practices" isolated several important problems including:

- Lack of data on a great earthquake in the subduction zone.
- Cost-effectiveness of conservative design to resist earthquakes.
- Earthquake impacts on lifeline systems.
- Cost-effectiveness of strengthening older buildings.
- Qualifications of building inspectors.
- Requiring instrumentation in new buildings.

Group 2 identified several problems involving data; sometimes adequate information exists and sometimes it does not exist, and where information exists, it is not always well disseminated. This group made a number of suggestions including:

- Combine funding for all environmental hazards studies.
- Devise special publications to transfer research information to users.
- Identify committed users, meet their needs, and "grow" an implementor of earthquake hazards and risk reduction.
- Produce translated products to meet user needs.
- Conduct demonstration projects.

Group 3 discussed emergency management and earthquake. They identified the following problem areas and needs:

- o Urban areas having high population density need to pay particular attention to earthquake preparedness and mitigation strategies.

- o County agencies need to work together with appropriate segments of the public to reduce losses due to earthquakes.

- o Municipalities need to provide resources for those seeking the best available emergency preparedness information.

- o School districts need to have an emergency preparedness program in place to reduce the risk of injury and death to students and staff in an earthquake. The plan should include both structural and nonstructural hazard reduction techniques. Many resources are available to school districts which give priority to earthquake safety and preparedness.

SESSION III: PLANNING TO ENHANCE THE EARTHQUAKE HAZARD REDUCTION PROGRAM IN THE PUGET SOUND AND PORTLAND AREAS.

The three discussion groups for Session III formulated strategies and suggested revisions to the Puget Sound and Portland areas' draft work plan to overcome perceived and real barriers to earthquake hazard reduction within the next 5 years. The basic questions considered were:

> Do Washington and Oregon have the knowledge base, trained professionals, and Resources to achieve the long-term goal of earthquake risk reduction; if not, what can the States do to obtain them, or if yes, what are the priority actions to be taken?

In terms of these questions and in the context of the "Regional Earthquake Hazards Assessments in the Pacific Northwest Draft Work Plan," the groups concluded or recommended:

- o There is no shortage of professionals capable of doing the needed work, but there is a shortage of State and Federal financial support for the work.

- o The possibility of a great subduction zone earthquake is the most important and potentially catastrophic threat to public safety from natural hazards in the Northwest. A definitive recognition of the possibility and a preliminary assessment of the risk are needed. Such assessments should be made as soon as possible to allow adequate Resources to be directed towards better defining the hazard and planning mitigation measures.

- o The seismic network in Oregon should be expanded

- o A number of innovative independent methods should be tried to find evidence of past great subduction-zone earthquakes. If they do not work in the trial study, other methods should be tried. It is essential that the buried marsh and seismic studies be supplemented by other studies.

- o Experts on earthquake hazards with excellent scientific credentials need to work in each State to translate the scientific findings into nontechnical language. These "experts" are needed to take the message to planners and policy recommenders who must act on the findings.

- o Geologic mapping of the bedrock and young surficial deposits must be done to define potentially active faults and to delineate geologic units that might amplify ground motion.

- o Ground response and loss-estimation research needs to be expanded to include the Willamette Valley in Oregon.

- o State-mandated planning for earthquake hazards should be required at the county level.

- o Geologists should make use of existing well-dated archeological work on coastal sites.

CLOSURE

The final session of the workshop gave each partner in the "Regional Earthquake Hazard Assessments" program an opportunity to outline his or her plans for the next four years.

Speakers: Bill Kockelman, U.S. Geological Survey
George Priest, Oregon Department of Geology and Mineral Industries
Chuck Steele, Federal Emergency Management Agency, Region X
Terry Feldman, Federal Emergency Management Agency
Ben Dew, Washington State Department of Community Development
Myra Lee, Oregon Emergency Management Division
Ray Lasmanis, Washington State Department of Natural Resources

CONCLUSIONS AND COMMITMENTS

Conclusions--The ultimate goal of the studies in Puget Sound and Portland areas is the reduction of loss of life and property from the earthquake hazards of ground shaking, surface fault rupture, earthquake-induced ground failures, tectonic deformation, and tsunamis. This goal requires a long-term commitment; it will not be fully achieved in a 5-year period. However, significant progress can be made when effective partnerships are forged between scientists, engineers, architects, planners, social scientists, emergency managers, and public officials. The results of this workshop indicate that such partnerships are being forged.

Commitments -- At the conclusion of the workshop, each partners in the "Regional Earthquake Hazards Assessments" program of the Puget Sound and Portland areas pledged their support to the goals of the program. The U.S. Geological Survey renewed its commitment to the "Regional Earthquake Hazard Assessments" program element and will continue to fund internal and external research projects. USGS agreed to publish and disseminate the workshop proceedings and to take responsibility for convening the 1989 and 1990 meetings.

A final report will document the results of focused research and implementation activities in the Puget Sound and Portland areas and recommend future research priorities. The Federal Emergency Management Agency plans to assist in the loss reduction phase of the program, possibly by joint funding with USGS of some of the proposed projects, training of land-use and emergency planners, and sponsorship of a working group of the agencies and universities involved in the translation, transfer, and use of research information.

The Washington State Department of Natural Resources will facilitate translation and transfer of research through its library, bibliographies, other publications, and conferences. It will conduct applied geologic investigations, assist USGS research efforts, and encourage networking, participating, and cooperation with other government agencies and universities. The Washington State Department of Community Development, the Oregon Department of Geology and Mineral Resources, and the Oregon Emergency Management Division agreed to cooperate within their available financial and human resources. Myra Lee and George Priest graciously offered to cohost the next workshop scheduled for April 1980, probably in Portland.

APPENDICES

Appendix A gives a glossary of technical terms. Appendix B is a reprint of a basic paper on ground motion from sudden zone earthquakes. Appendix C lists prior workshops convened by USGS and its partners. Appendix D gives the names and addresses of the participants.

ACKNOWLEDGMENTS

Special appreciation is extended to each of the following individuals for his or for her contributions:

1) The Steering Committee of Walter Hays, Paula Gori, Linda Noson, Ray Lasmanis, and Ian Madin who planned and organized the workshop.

2) Linda Noson, the workshop facilitator, for her patience and skill.

3) The participants who gave papers and joined in the major sessions and 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.

4) Carla Kitzmiller and Shirley Carrico, USGS, who provided strong and capable administrative support.

REFERENCES

Szanton, Peter, 1981, Not Well Advised, Russell Sage Foundation and the Ford Foundation, 81 p.

Washington State Seismic Safety Council, 1986, Policy Recommendations, 21 p.

REGIONAL EARTHQUAKE HAZARDS ASSESSMENTS IN THE PACIFIC NORTHWEST
DRAFT WORK PLAN: FY 87-89

FOREWORD

This draft work plan describes the integrated goals, plans, and activities of the U.S. Geological Survey (USGS), the Federal Emergency Management Agency (FEMA), Washington State Department of National Resources, Washington Office of Emergency Services and others for the program element, "Regional Earthquake Hazards Assessments: Puget Sound-Portland Area," 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 87-89, the first phase of a focused effort on the Pacific Northwest. The program concentrates studies in the Puget Sound, Washington, and in the Portland, Oregon, regions. 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 the planning meeting held in Bothell, Washington, on December 9-10, 1986, and contributed to the formulation of the work plan:

Walter Hays	U.S. Geological Survey
Albert Rogers	U.S. Geological Survey
Thomas Terich	Washington University
Eugene Hoefrauf	Western Washington University
Lora Murphy	U.S. Department of Community Development
Janice Leonardo	Whatcom County Department of Emergency Services
Lt. William M. Stockham	King County Office of Emergency Management
Richard Buck	Federal Emergency Management Agency
Ayres W. Johnson, Jr.	Evergreen Safety Council
Bill Brown	Federal Emergency Management Agency
Gary Johnson	Federal Emergency Management Agency
William Mayer	Federal Emergency Management Agency
Robert Brelin	Building System Technology
Ray Lasmanis	Washington State Department of Natural Resources (WSDNR)
Anshel G. Johnson	Portland State University
Bruce C. Olson	Consulting Engineer
Peter May	University of Washington
Gerald W. Thorsen	Washington State Department of Natural Resources (WSDNR)
Karl V. Steinbrugge	Structural Engineer
Philip S. Cogan	Federal Emergency Management Agency
Chuck Steele	Federal Emergency Management Agency
Jane Pruess	Urban Regional Research
Robert S. Yeats	Oregon State University
John D. Beaulieu	Oregon Department of Geology and Mineral Industries (DOGAMI)
Patricia Bolton	Batelle Seattle Research Center

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 five interrelated program elements constituting the current NEHRP were defined as follows:

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

COMPONENTS OF THE REGIONAL EARTHQUAKE HAZARDS ASSESSMENTS PROGRAM ELEMENT

The Regional Earthquake Hazards Assessments program element has five **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 regional 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 decision-makers as a basis for "calling for change in seismic safety policy."

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) Puget Sound, WA-Portland, OR
2) Wasatch Front, UT
3) Californial
4) Anchorage, AK
5) Mississippi Valley
6) Puerto Rico
7) Charleston, SC
8) Buffalo-Rochester area, NY

In each region, the research is performed using the resources of the USGS's internal and external programs (the external program is implemented through grants awarded annually following a national solicitation for proposals. The goal is to achieve maximum synergism of State and Federal resources with everyone having a stake in the process. In some cases, suggested task assignments outside the USGS as shown below are uncertain and are dependent on the interests and resources of those organizations.

STRATEGIES FOR CONDUCTING RESEARCH IN THE PUGET SOUND, WASHINGTON-PORTLAND, OREGON, AREA

The strategies for the Puget Sound-Portland area are:

1) Foster Partnerships--USGS and FEMA will seek to foster strong partnerships with the universities, private sector, agencies of local government, and other State and Federal agencies. Existing partnerships will be strengthened. The goal is to obtain a stronger commitment at all levels of state and local governments.

2) Take Advantage of Past Research Studies and Other Activities--Results of past research and vulnerability studies will be utilized to the fullest extent possible. Achievements of the USGS-FEMA sponsored earthquake-hazards workshop of October 1985 will be used as building blocks for future activities. Also, the recommendations of the Washington State Seismic Safety Council, published in 1986, will be addressed to the fullest extent possible.

3) Convene Annual Meetings to Review Progress and Recommend New Research--Beginning in 1988, an annual workshop will be held in the Puget Sound area 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?"

4) Publish Annual Reports and Communicate Findings--Proceedings of the workshops, which will include papers documenting results from all research projects in the Pacific Northwest area will be published as USGS Open-File Reports approximately 3- or 4-months after each meeting. In FY 89, the third year of the program, a USGS Professional Paper will be compiled. The workshops, their products, and the findings in the professional paper will be **COMMUNICATED** to policymakers whose task is to implement hazard-reduction policy.

5) Take Advantage of Earthquakes--Use knowledge gained from past earthquakes in the Puget Sound-Portland area and other areas such as the Mexico earthquake of September 1985 to improve the methodology that is currently used in the assessment of earthquake hazards and risk in the Puget Sound-Portland area. Many scientists consider the 1985 Mexico earthquake as representative of the type of earthquake that can occur in the Puget Sound-Portland area. In addition, other parts of the world have a similar tectonic setting as the Puget Sound-Portland area.

   Earthquakes in all of these areas will be investigated to provide insight into the characteristics of ground-shaking and the physical effects that might occur in a major subduction earthquake in the Puget Sound-Portland area. Because large shallow crustal earthquakes like the 1872 eastern Washington earthquake control the risk (chance of loss) to a large degree, earthquakes having similar characteristics will be investigated in detail.

RESEARCH GOALS, OBJECTIVES, AND TASKS OF THE PROGRAM ELEMENT "REGIONAL EARTHQUAKE HAZARDS ASSESSMENTS: PUGET SOUND-PORTLAND AREA"

INTRODUCTION

The five **INTERRELATED** components comprising the program element "Regional Earthquake Hazards Assessments: Puget Sound-Portland Area" are described below to provide **GUIDELINES** for researchers who are either working now or planning to work in the area. These guidelines will also help to guide the formulation of seismic safety policy in the Puget Sound-Portland area. Each component of the workplan will be reviewed annually and revised as appropriate, to meet the research goals of the program element.

Study Area--In Washington, the primary study area includes King, Kitsap, Mason, Pierce, Snohomish, Thurston, Clark, Cowlitz, Grays Harbor, Island, Skagit, and Whatcom Counties. In Oregon, the main emphasis will be on Marion and Multnomah Counties. The urban areas include: Seattle, Tacoma, Vancouver, Bellingham, and Olympia, Washington, and Portland and Salem, Oregon.

COMPONENT 1: INFORMATION SYSTEMS

Every research study will generate basic data on earthquake hazards which must be organized with existing data. A large but unorganized quantity of data relating to the earthquake hazards in the Puget Sound-Portland area 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 asystem 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. 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.

Action--The objectives listed above will be accomplished primarily by the Federal and State partners. The task statements include:

1) Inventory of Existing Data--Compile a computerized bibliography of the Puget Sound-Portland geology and geophysics 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 to meet the needs of the program element.

   USGS Role--USGS will compile a directory of hazards information to determine what data exist, 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--To the extent possible, the catalog of Puget Sound-Portland 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 Washington Seismograph Network 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.

   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.

USGS Role--The USGS will implement a new Geographical Information System (GIS) in collaboration with DOGAMI, WSDNR to integrate existing base map data with new geographical data sets developed during the course of Puget Sound-Portland studies.

3) Data Set Management--A complete library of publications, reports, and a hard copy of data sets related to the Puget Sound-Portland area are needed. These could be established as a part of the existing libraries.

USGS Role--The successful management of computerized data should expedite many research studies. Existing computer resources in Golden, Colorado and other locations will be utilized. The University of Washington 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--An earthquake information office is needed in the Puget Sound-Portland area. Such an office will 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 will provide, to a wide variety of users: historic and current data on Puget Sound-Portland earthquakes, information on current research, and advice on obtaining access to earthquake-related literature and data.

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 Puget Sound-Portland area have been carried out since the early 1970's. 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 Earthquake Hazards Assessments 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 Puget Sound-Portland area.

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 by closing gaps in knowledge.

Action--Federal, state, and university scientists (identified below) will provide leadership and perform the specified research tasks. Researchers in universities and the private sector (e.g., University of Washington, and others) will participate under the auspices of the USGS's grants program.

1) Collection and Synthesis--Research initiated in prior years will be continued. New research will also be conducted focusing on the collection and synthesis of those data needed for realistic deterministic and probabilistic calculations of hazard and risk for the region. These data collection and synthesis efforts provide: a) a broader understanding of the tectonic settings and rates of tectonic activity and b) definition of specific geologic hazards of special significance to the Puget Sound-Portland area.

   The objective of the above task is to develop synthesis reports and maps on four main topics:

   a) Geologic/tectonic setting of current seismicity of the Puget Sound-Portland area. These activities are related to source zone modeling for probabilistic hazard calculations and the revision of existing neotectonic maps of these regions. This research will seek to improve understanding of the tectonics of this region through reexamination of old fault data, collection of new fault data, and Quaternary mapping. Seismicity, geophysical, and remote sensing data will also be evaluated. (USGS: WHEELER, THENHAUS, ALGERMISSEN). Studies of current seismicity including focal mechanism, state of stress, and relationship between seismicity and faults will be conducted. This work may include reevaluation of some aspects of historical earthquakes (USGS: HOPPER, SPENCE; UW: CROSSON, MALONE; OSU--JOHNSON). For instance, reevaluation of the historic intensities as they relate to source zones will also be conducted (USGS: HOPPER).

   b) Quaternary tectonic activity of the Puget Sound-Portland area. These tasks have two principal elements: 1) to assess the potential for a great subduction zone earthquake; and 2) to assess the potential for shallow or lithospheric earthquakes. Studies related to the assessment of subduction zone earthquakes involve research on subsidence of Washington and Oregon estuarine deposits (USGS: ATWATER, NELSON; STATE SURVEYS; OSU--PETERSON, DARIENZO; UW--BOURGEOIS), coastal uplift/terraces (USGS: PERSONIUS; HUMBOLDT STATE--CARVER, KELSEY, BURKE; DOGAMI, WSDNR), back-tilted Pleistocene beach deposits (DOGAMI, WSDNR), earthquake induced landslides (USGS: MADOLE, SCHUSTER), lake sediment liquefaction or other liquefaction (USGS: MADOLE, OBERMEIER), crustal structure (TELEDYNE: McLAUGHLIN) Studies related to the potential for shallow earthquakes involve research on Quaternary stratigraphy (CASCADE VOLCANO OBSERVATORY; DOGAMI, WSDNR; OSU--YEATS), research on Quaternary deformation in the Seattle-Kitsap Peninsula area primarily from study of coastal marsh deposits (USGS; BUCKNAM, BARNHARD), high-frequency reflection/Minisosie (USGS: HARDING, URBAN, BUCKNAM, BARNHARD; WSDNR: LINGLEY, UNIVERSITIES).

   c) Timing and character of Quaternary ground-failure events: These tasks are directed at producing ground failure inventory maps

(USGS: CHLEBORAD, SCHUSTER, MADOLE; DOGAMI, WSDNR) and susceptibility maps (USGS: CHLEBORAD, SCHUSTER; DOGAMI; WSDNR).

d) Information for use in local and regional hazards reduction activities.

COMPONENT 3: GROUND MOTION MODELING

This component is concerned primarily with the prediction of the effects of source, path, and local geologic site conditions on ground shaking in the Puget Sound-Portland area. 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 Puget Sound-Portland area.

Priorities--The first priority is to install and maintain strong-motion accelerographs in the Puget Sound-Portland area and to acquire and use the MiniSosie portable reflection system in ground-response research. Ninty-six strong motion accelerographs are currently in place in Washington and Oregon. The second priority is to prepare a synthesis report of the ground shaking data available from prior studies in the Puget Sound-Portland. The third priority is to extend the results of these studies, performing deterministic and probabilistic hazard analysis and utilizing new equipment (MiniSosie, strong motion accelerographs, etc.) to acquire basic data.

Action--The research will be conducted primarily by USGS and non-USGS researchers who may participate through the Survey's external grants and contract program. The tasks are described below:

1) Synthesis Report--A report of the current knowledge of ground motion characterisitics in the Puget Sound-Portland area.

2) Deterministic and Probabilistic Hazard Analysis--Research on deterministic and probabilistic hazard analysis, applied in 1982 on a national scale by Algermissen and others, will be applied in the Puget Sound-Portland areas, and extended by using a variety of probabilistic models of earthquake occurrence (USGS: ALGERMISSEN, PERKINS, THENHAUS, WHEELER, ARNOLD). Maps of the peak acceleration, velocity, and intensity will be prepared for exposure periods of 10, 50, and 250 years. These maps will incorporate the effects of regional attenuation and local geologic conditions. Maps of spectral velocity for selected periods may also be prepared. 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--A methodology to zone the ground-shaking hazard will be applied to the Puget Sound-Portland area (USGS: KING, TARR). Site effects at a large number of sites in the Seattle-Portland regions will be measured using local earthquake

data. Uphole/downhole shear-wave velocity measurements will also be collected at select sites (USGS: KING, TINSLEY). Sites will be classified into site types or clusters according to significant geotechnical factors for three period bands (0.05 to 10 seconds). By combining and comparing the cluster results at selected sites throughout the city with mapped near-surface geology and geotechnical data (USGS; TINSLEY, KING, BUCHANAN-BANKS; UW: QAMAR), 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 scenario earthquakes.

Several approaches will be taken in the study of attenuation. Attenuation and source functions are likely to differ for each of the major source types, i.e., subduction zone events, i.e., events within the subduction plate and shallow events. Regional seismic-wave attenuation functions for the Puget Sound-Portland area will be derived using data from other subduction zone earthquakes, including data for the 1985 Chile and Mexico earthquakes (USGS: ALGERMISSEN, CAMPBELL). These two earthquakes provide a unique data sample of close-in data from major subduction zone earthquakes. Using small shallow and deep earthquakes, a Q-model will be derived that will serve as data for stochastic modeling of earthquake ground motions from the various source types (USGS: LANGER, JOYNER, CAMPBELL, HARMSEN). Deterministic modeling of subduction-zone earthquakes will also be conducted (EARTH TECH. CORP.: CROUSE; WOODWARD-CLYDE: SOMMERVILLE). Intensity attenuation for historical Pacific Northwest earthquakes will be evaluated (USGS; HOPPER, ALGERMISSEN; UNIVERSITIES).

4) Zoning Research--Beginning in FY 87, research with high-frequency techniques (e.g., MiniSosie) will be initiated to determine subsurface conditions within the study area that are known to exhibit high ground response (USGS: KING, TARR). 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 two- to five-story class. Buildings having more than five stories were also found to be at greatest risk when located at sites where the depth to basement rock 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 Seattle and Portland at sites where measured site response can be correlated with reflection data.

COMPONENT 4: LOSS ESTIMATION MODELS

This component has three parts: 1) definition of the scenario earthquake(s), 2) inventory, and 3) ground-motion-damage matrices or algorithms.

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 Puget Sound-Portland area by USGS and its consultants. A deterministic earthquake loss study was completed in 1976 (Hopper, et al 1976) to provide planning guidance for earthquake preparedness and mitigation.

Priorities--The first priority is to update the existing building inventory in the Puget Sound-Portland area (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 other inventories. The third priority is to reassess the vulnerability relationships for the Puget Sound-Portland area.

Action--Both USGS internal research and grants studies will contribute to this effort. The tasks are described below:

1) Loss Estimation, Seattle area; other urban areas--The primary emphasis will be placed on research concerning earthquake loss (risk) studies is the Seattle metropolitan areas (USGS: LEYENDECKER, ALGERMISSEN, HIGHLAND, ARNOLD, HOPPER, POWERS; OLSEN CONSULTING: ENGLEKIRK AND HART: HART; KENNEDY/JENKS/CHILTO: BALLANTYNE; TELESIS: THIEL). The data requirements are: 1) update the existing building inventory in Seattle, 2) develop an inventory of buildings in other parts of the study area, 3) reassess vulnerability relationships for the Puget Sound-Portland area 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 Seattle area. Develop scenario intensity maps for several possible major earthquakes. These maps will incorporate regional attenuation functions and site response effects (USGS; HOPPER).

   Deterministic loss and casualty estimates will be made for magnitude (M_s) 6.5 and 7.5 earthquakes (and possibly for a major subduction zone event having various locations in the Puget Sound-Portland area. 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 parts of Washington and Oregon 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 the Puget Sound-Portland area 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.

Action--Leadership for the implementation components will be provided by FEMA and USGS. FEMA, Region X, will take a major role in the implementation process. 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 and prior programs (UW: MAY). A key strategy is to build on past successful activities such as the Southern California Earthquake Preparedness Project which has produced some 20 publications on various aspects of implementation. Partnerships between the research community (USGS, DOGAMI, WSDNR, universities, and the private sector) and those who will ultimately use the information to implement loss-reduction measures are necessary for success, and the strongest possible effort will be made to achieve these partnerships within the initial three years.

1) Scientific Information--Many prior studies have already produced considerable high-quality information in the Puget Sound-Portland area. Adoption and generalization of 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 locations with forecasts of earthquake recurrence intervals and the anticipated surface displacement, coastal flooding from tsunamis, seiches and/or subsidence, 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. SOME TRANSLATION ACTIVITIES WILL TAKE PLACE USING GIS TECHNIQUES (USGS; TARR). The following actions are likely to improve use of scientific information by nonscientists:

-- Identify and catalog existing earthquake hazards maps and reports.

-- Identify the hazards maps and reports needed for loss 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, policy recommenders, 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) <u>Communication</u>--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) <u>Determine Users' Needs</u>--The past work on geologic hazards has succeeded to some extent in determining the needs for earthquake hazards information in Washington. 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) who have urgent needs and who could be expected to use the hazards information most effectively.

-- Consult with those users about their needs and priorities and prioritize the hazards 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 users in order to enable them to understand and to use the information effectively.

4) <u>Reduction Techniques</u>--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 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) <u>Evaluation</u>--Continuing systematic evaluation will be a part of this program and is a key to any successful State-local earthquake hazards 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 hazards 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 format or content of information or 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.

<u>Proposed-Selection Criteria</u>--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 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 State and local level.
- -- Evaluate proposals and fund selected projects that will enhance implementation.
- -- Enlist Federal partners.

Suggested Roles for State Agencies--Initially, the role of the State Agencies will 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 states of Washington and Oregon.

Table 1

Some Potential Users of Geologic and Hydrologic Information for Earthquake-Hazard Reduction in the Puget Sound-Portland Area.

City, County, and Area-wide 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 Government 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
DOGAMI
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
WSDNR

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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, geography, 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
American Institute of Professional Geologists
American Society of Public Administrators
American Society of Civil Engineers
Association of Engineering Geologists
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 (university, college, high school, and elementary school levels)
Governor's Advisory Council on Local Governments
Hazard-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
United States Conference of Mayors
U.S. Bureau of Land Management
U.S. Forest Service
U.S. Geological Survey
U.S. Soil Conservation Service
Western Governor's Policy Office

Table 4

Some Opportunities for Using Geologic and Hydrologic Information to Reduce Earthquake Hazards in the Puget Sound-Portland Area, Washington

Preparing development studies and plans

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

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
Strengthening or retrofitting of unsafe structures

Regulating development/construction

Building ordinances
Design and construction regulations
Grading regulations
Hazard-zone investigations
Land-use zoning districts and regulations
Special hazard-reduction ordinances
Subdivision ordinances
Critical facilities, siting, design, and construction
Public-facility or utility reconstruction or relocation
Reconstruction after earthquakes
Repair of dams

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

EVALUATION OF THE WORKSHOP ON "EVALUATION OF EARTHQUAKE HAZARDS AND RISK IN THE PUGET SOUND AND PORTLAND AREAS"

by
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A state-federal workshop on evaluating earthquake hazards and risks in the Puget Sound and Portland areas was held from April 12-14 1988. A one-day field trip to Grays Harbor, Washington, was followed by two days of sessions at the Governor House Hotel, Olympia. The workshop was followed on April 15 by a special session on developing programs to reduce potential earthquake losses and foster preparedness in the Puget Sound and Portland areas. A month after the event, participants were mailed a two-page questionnaire on which they were asked to evaluate the success of the workshop; 40 people replied.

Responses were elicited in three ways: as a ranking on a five-point scale, as a choice between yes and no, or as an open-ended comment. On the five-point scale, one and two represent the least agreement with the statement provided and four and five the most agreement. As illustrated in Figure One, which provides absolute numbers of respondents, and Figure Two, which provides percentages, three classes have been used in this analysis: 1 & 2, 3, 4 & 5.

In questions requiring a yes/no response or a ranked response, participants were asked: 1) to indicate whether they participated in the field trip, the remainder of the workshop, or the special session; 2) to rate the usefulness of the workshop for assessing various aspects of earthquake threat and response in the Puget Sound and Portland areas; 3) to signify the value of the workshop for setting research and hazard reduction goals; 4) to rate the effectiveness of the different presentations of the special session; 5) to judge the usefulness of various meeting activities; and 6) to indicate whether attendance at the meeting had been worthwhile and whether future workshops should be planned to continue the work initiated at this meeting.

In open-ended questions, participants were asked: 1) to describe how they planned to apply what they learned at the meeting; and 2) to list the positive and less positive features of the workshop.

Forty percent of the 40 respondents participated in the one-day Grays Harbor field trip to examine evidence of historic earthquakes. Eighty-three percent of those who returned questionnaires attended the following two days of the workshop and fifty-three percent of respondents attended the special session.

Sixty-nine percent of respondents found the workshop very useful for appraising earthquake potential in the Pacific Northwest. Over half of the respondents found it very useful for assessing ground shaking and ground failure hazards in the Puget Sound and Portland areas. Forty-six percent and forty-four percent, respectively, found the workshop very useful for assessing the state of earthquake awareness and preparedness and for assessing potential losses. Forty-two percent found it very useful and forty-four percent found it somewhat useful for assessing the state of building practices to reduce earthquake losses. Twenty-five percent of respondents found the workshop very useful for assessing the state of land use planning to reduce earthquake losses, but another twenty-five percent found it not very useful for this purpose. A bare majority found the workshop somewhat useful in assessing the state of emergency management and response, with twenty-two percent finding it very useful and twenty-seven finding it not.

In assessing the usefulness of the workshop for setting three-year goals, eighty-nine percent of respondents indicated its value for targeting research goals, and eighty-three percent for establishing hazard reduction goals.

Seventy-four percent of respondents who attended the special session to "Develop a Strategy for Implementing Programs to Reduce Potential Earthquake Losses and Foster Preparedness in the Puget Sound and Portland Areas" rated very highly the summaries of effects of past earthquakes, earthquake potential, and efforts to mitigate earthquake hazards in the Puget Sound and Portland Areas. Presentation of policy options was rated very highly by forty-seven percent of respondents and rated poorly by twenty-one percent. The session devoted to recommending future state earthquake hazard reduction and preparedness policies and programs was rated highly by only seventeen percent of respondents and poorly by thirty-nine percent.

The majority of respondents rated all activities as being very useful. Eighty percent of respondents found the informal discussions during breaks and after hours very useful, while seventy-four percent found the formal presentations very useful and sixty-two percent of them found the discussions following presentations very useful. The discussion group process was found the least useful of the activities, with fifty-three percent rating it very useful. The workshop information folder was rated extremely valuable by sixty-nine percent of respondents.

Almost all of the respondents would welcome the opportunity to repeat workshop participation. There was unanimous support for continuing the work initiated at this meeting at future workshops.

Over seventy-five percent of the respondents addressed how they planned to apply what they had learned at the workshop. Since many respondents suggested more than one application, absolute numbers of comments are discussed here rather than percentages of responses. Seventeen comments described how respondents are incorporating or intend to incorporate what they have learned into their work. For example, workshop information is being used in a major earthquake disaster exercise, in evaluating current structural design criteria, in developing better models for seismic risk assessment, and in the loss estimation model of the Seattle water system. Thirteen people commented that they would disseminate the information from the workshop to others within their own agencies, to other public officials, or to the general public.

Four people said they intend to tap into the network of resource people they met at the workshop. One man remarked that he would apply his new-found understanding of how his work builds on the work of others and of how others use the information he generates.

Thirty four respondents commented on those aspects of the workshop which they found positive and those which they viewed as less than positive. Negative comments ranged from the lack of scientific consensus to the deficiencies in the meeting facilities.

Two people commented on the manner in which the scientific evidence was presented. In different ways, they each suggested that concentrating on the most likely magnitude of future events rather than on possible ranges of seismic hazards is too constraining at this early research stage.

The lack of scientific consensus was regarded as a problem by three respondents. One participant noted the reluctance of speakers to provide specific information to assist local governments with land use and construction. Three others commented that a number of presentations were too specialized and too technical for non-geoscientists. One person suggested making a clearer distinction between the presentation of technical data and summaries of data for non-technical participants. One person found the legal analysis unclear.

The question of focus was raised by eleven people. One individual said the structure of panels did not contribute to cross-disciplinary concerns. Another participant called for more local input on panels. Two people commented that more evidence was presented about Washington than Oregon. Others felt that the sessions should be more focussed, with panels explicitly

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addressing what we know and what we don't. One person argued this would help to ensure that the stated workshop aims were achieved. Two felt that the next workshop should involve a smaller number of participants with a more narrowly defined subject area, with a more limited objective to follow up on identified needs. Two people felt that this workshop did not set itself apart from other similar conferences such as the 1985 Seattle workshop on "Earthquake Hazards in the Puget Sound, Washington, Area".

The allocation of workshop time was an issue for five individuals. While one person decried the shortage of time to present relevant background information and another person the lack of time for discussion groups, someone suggested the scheduled days were too long. Two comments related to the disregard of time limits by speakers and moderators. Three people noted the time lag between the workshop and receiving the evaluation questionnaire.

Over one-fifth of the negative comments received related to the inadequacies of the workshop facilities. Two people commented on the intermittent audio-visual difficulties. Three others commented on the inadequacy of the meeting rooms for the number of attenders.

While two people praised the workshop as a whole, others were more specific. The field trip was considered a success by four people because of participants' enthusiasm and the effectiveness of on-site explanations. The employment of an interdisciplinary approach and the comprehensive coverage through a variety of discussion groups was also lauded. One person appreciated the emphasis on reducing earthquake hazards now despite uncertainty over the degree of the threat. Ten people remarked on the wealth of information presented by the speakers. Two other people mentioned the high quality of the handouts. Thirteen people commented on how the workshop provided an opportunity to network with other people with diverse perspectives. The workshop was regarded as a useful means of disseminating understanding about earthquakes and as a good general introduction to the National Earthquake Hazards Reduction Program.

Figure 1

Evaluation of workshop by individual participants

		Yes		No
1.	Did you participate in the field trip to Grays Harbor?...........	16		24
2.	Did you attend the next two days of the workshop?................	33	5(1 day)	2
		Low		High
		1 & 2	3	4 & 5
	a) Did you find the workshop useful for assessing:			
	1) Potential losses in the Puget Sound and Portland areas?..	9	13	17
	2) Earthquake potential in the Pacific Northwest?...........	5	7	27
	3) Ground shaking hazards in Puget Sound and Portland areas?	4	13	22
	4) Ground failure hazards in Puget Sound and Portland areas?	6	12	20
	5) State of building practices to reduce earthquake losses in the Puget Sound and Portland areas?.................	5	16	15
	6) State of land-use planning to reduce earthquake losses in the Puget Sound and Portland areas?...........	9	18	9
	7) State of earthquake awareness and preparedness programs in Puget Sound and Portland areas?.............	7	13	17
	8) State of emergency management and response planning for earthquakes in the Puget Sound and Portland areas?......	10	19	8
		Yes		No
	b) Did you find the workshop useful to the process for setting research goals for the next 3 years?................	32		4
	c) Did you find the workshop useful for setting hazard reduction goals for the next 3 years?......................	30		6
3.	Did you attend the special session to "Develop a Strategy for Implementing Programs to Reduce Potential Earthquake Losses and Foster Preparedness in the Puget Sound and Portland Areas"?.....	20		18
		Low		High
	Rate the following:	1 & 2	3	4 & 5
	a) Summaries of effects of past earthquakes, earthquake potential, and efforts to mitigate earthquake hazards in the Puget Sound and Portland area?......................	2	3	14
	b) Presentations of policy options available in the Puget Sound and Portland areas including other jurisdiction's experiences and legal liability?..........................	4	6	9
	c) Afternoon session devoted to recommending future State earthquake hazards reduction and preparedness policies and programs?..	7	8	3
4.	Considering the meeting as a whole, did you find the following activities to be useful:			
	a) Presentations by speakers and panelists?.....................	3	7	29
	b) Discussions following presentations of speakers and panelists?	4	11	24
	c) Discussion group process?.....................................	3	15	20
	d) Workshop information folder?..................................	2	10	27
	e) Informal discussions during breaks and after hours?..........	2	6	31
		Yes		No
5.	If the clocks were turned back and the decision to attend the workshop were given to you again, would you want to attend?.....	38		2
6.	Should future workshops be planned to continue the work initiated at this meeting?....................................	37		0

Figure 2

Evaluation of workshop by percentages of question respondents

	Yes		No
1. Did you participate in the field trip to Grays Harbor?..........	40%		60%
2. Did you attend the next two days of the workshop?..............	83%	(13% 1 day)	5%
	Low		High
	1 & 2	3	4 & 5
a) Did you find the workshop useful for assessing:			
1) Potential losses in the Puget Sound and Portland areas?..	23%	33%	44%
2) Earthquake potential in the Pacific Northwest?...........	13%	18%	69%
3) Ground shaking hazards in Puget Sound and Portland areas?	11%	33%	56%
4) Ground failure hazards in Puget Sound and Portland areas?	16%	31%	53%
5) State of building practices to reduce earthquake losses in the Puget Sound and Portland areas?.................	14%	44%	42%
6) State of land-use planning to reduce earthquake losses in the Puget Sound and Portland areas?...........	25%	50%	25%
7) State of earthquake awareness and preparedness programs in Puget Sound and Portland areas?.............	19%	35%	46%
8) State of emergency management and response planning for earthquakes in the Puget Sound and Portland areas?......	27%	51%	22%
	Yes		No
b) Did you find the workshop useful to the process for setting research goals for the next 3 years?...............	89%		11%
c) Did you find the workshop useful for setting hazard reduction goals for the next 3 years?.....................	83%		17%
3. Did you attend the special session to "Develop a Strategy for Implementing Programs to Reduce Potential Earthquake Losses and Foster Preparedness in the Puget Sound and Portland Areas"?....	53%		47%
	Low		High
Rate the following:	1 & 2	3	4 & 5
a) Summaries of effects of past earthquakes, earthquake potential, and efforts to mitigate earthquake hazards in the Puget Sound and Portland area?......................	10%	16%	74%
b) Presentations of policy options available in the Puget Sound and Portland areas including other jurisdiction's experiences and legal liability?..........................	21%	32%	47%
c) Afternoon session devoted to recommending future State earthquake hazards reduction and preparedness policies and programs?..	39%	44%	17%
4. Considering the meeting as a whole, did you find the following activities to be useful:			
a) Presentations by speakers and panelists?....................	8%	18%	74%
b) Discussions following presentations of speakers and panelists?	10%	28%	62%
c) Discussion group process?..................................	8%	39%	53%
d) Workshop information folder?...............................	5%	26%	69%
e) Informal discussions during breaks and after hours?..........	5%	15%	80%
	Yes		No
5. If the clocks were turned back and the decision to attend the workshop were given to you again, would you want to attend?...	95%		5%
6. Should future workshops be planned to continue the work initiated at this meeting?..................................	100%		0%

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ESTIMATION OF GROUND SHAKING IN THE PACIFIC NORTHWEST

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INTRODUCTION

The expected ground motion in the Pacific Northwest has been estimated in U.S. Geological Survey studies as part of national probabilistic ground motion maps produced in 1976 (Algermissen and Perkins, 1976), 1982 (Algermissen and others, 1982) and in a revision of the 1983 national probabilistic maps to be published this year (Algermissen and others, 1988). Only a 50 year, 10 percent probability of exceedance acceleration map was produced in 1976. In 1982, acceleration and velocity maps (in rock) were developed for periods of time of interest (exposure times) of 10, 50 and 250 years, with a 10 percent chance of exceedance. The 1982 maps were produced using mean values of ground motion attenuation and fault rupture length. The national probabilistic hazard maps to be published this year are based on the probabilistic model, seismic source zones and attenuation used in the 1982 maps but they include parameter variability in attenuation and in fault rupture length.

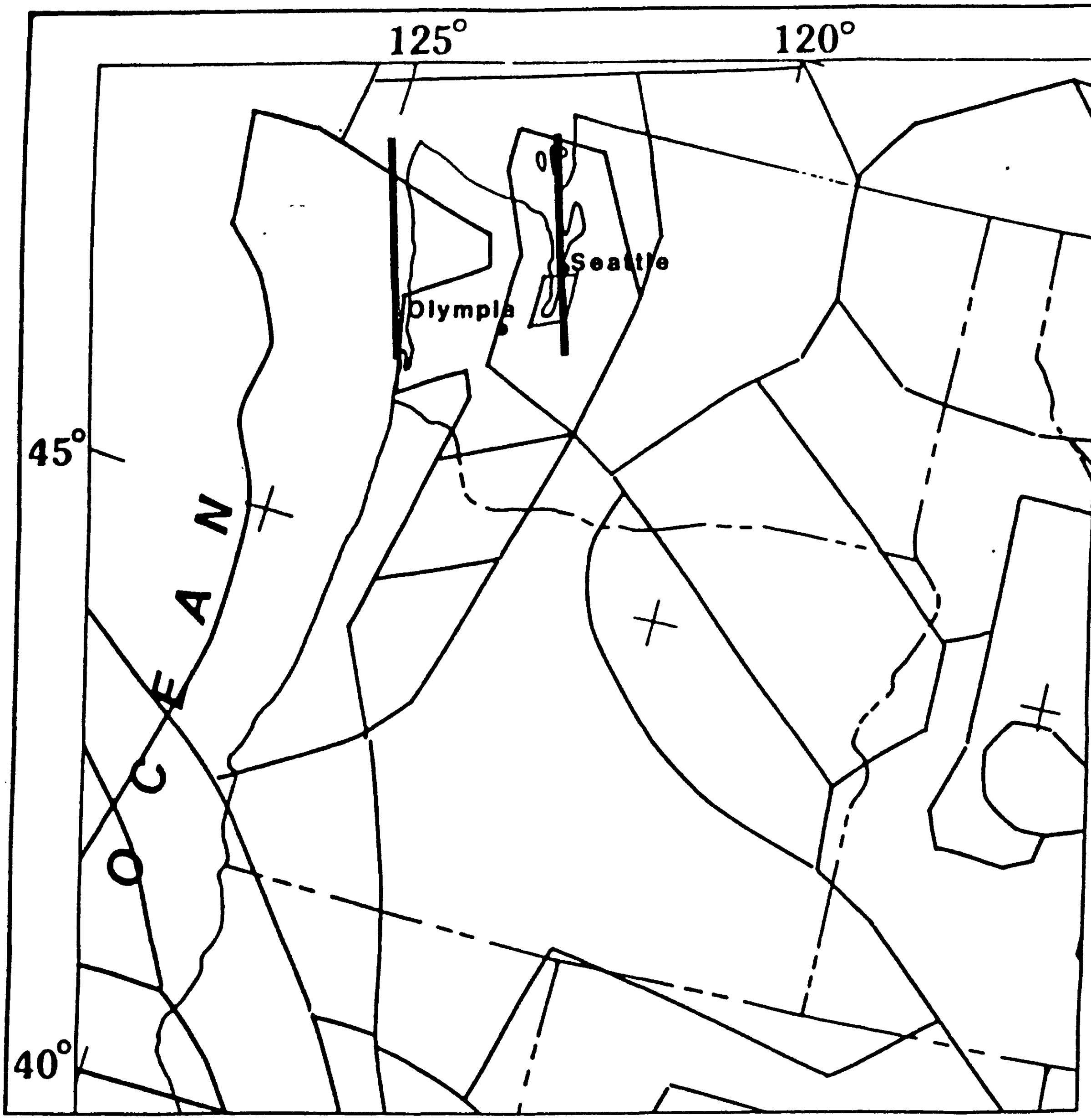
The seismic source zones used in the 1982 and 1988 maps are identical and are shown in Figure 1. Figure 2 shows the 50 year, 10 percent chance of exceedance acceleration map produced in 1982 for the Pacific Northwest. Figure 3 shows the 50 year acceleration map recently prepared (1988) that includes parameter variability.

NATURE OF THE SEISMIC HAZARD

The earthquakes important in seismic analysis for the Puget Sound area are: (1) The possibility of a large subduction zone shock; (2) the recurrence of historical earthquakes up to magnitude 7.1 that have caused damage in the Puget Sound area and occur at depths of about 40-70 km; and (3) the possible occurrence of damaging shallow shocks.

Recently, Heaton and Kanamori (1984) have suggested the possibility of very large, shallow subduction zone earthquakes at the Juan de Fuca-America plate boundary. No historical large plate boundary earthquakes are known in this region but paleoseismic data are emerging to support this view (Atwater, 1987). Historically, all of the recent damaging earthquakes (1939, 1946, 1949, 1965) are believed to have occurred at depths of 40-70 km either within a region of bending of the subducted Juan de Fuca plate or near the plate interface.

Very little attention has been given to the possibility of a large M_s=7.0, shallow earthquake, even though one is believed to have occurred. There is other evidence of recent significant shallow activity. Evidence of the occurrence of an earthquake in 1872 east of the Cascades with a magnitude of approximately 7.0 M_s has been extensively reviewed by a number of investigators, most recently by Hopper and others (1982) who believe that the



Seismic Source Zones in the Pacific Northwest

Figure 1. Seismic source zones used in the development of national probabilistic ground motion maps in 1982 (Algermissen and others, 1982) and in 1988 (Algermissen and others, 1988). The two heavy black lines superimposed on the source zones represent faults used to model the location of subduction zone earthquakes discussed in this paper.

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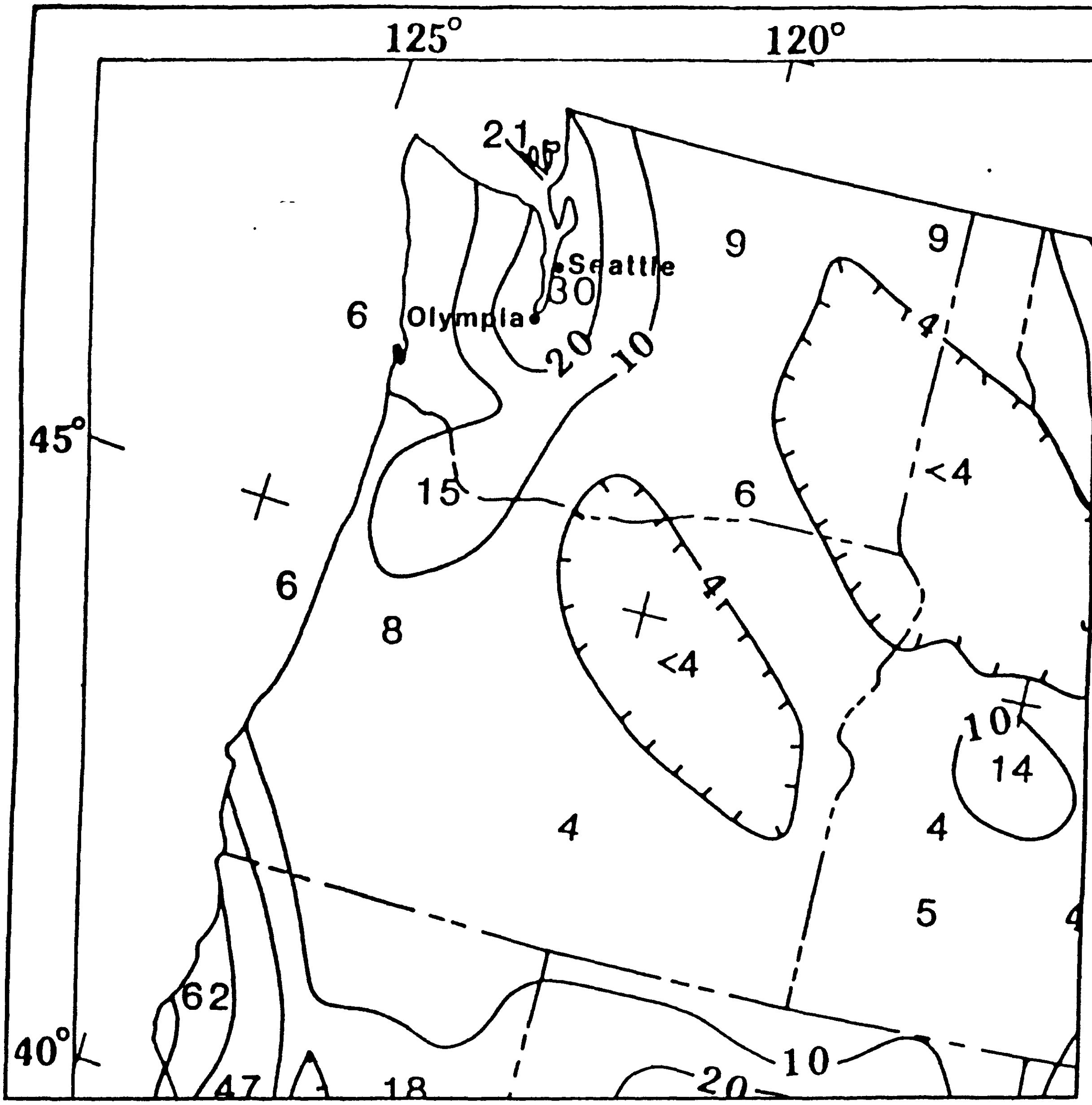

1982 50-Year Acceleration Map

Figure 2. Pacific Northwest portion of the 50 year, exposure time 10 percent chance of exceedance, map of maximum acceleration in rock (Algermissen and others, 1982).

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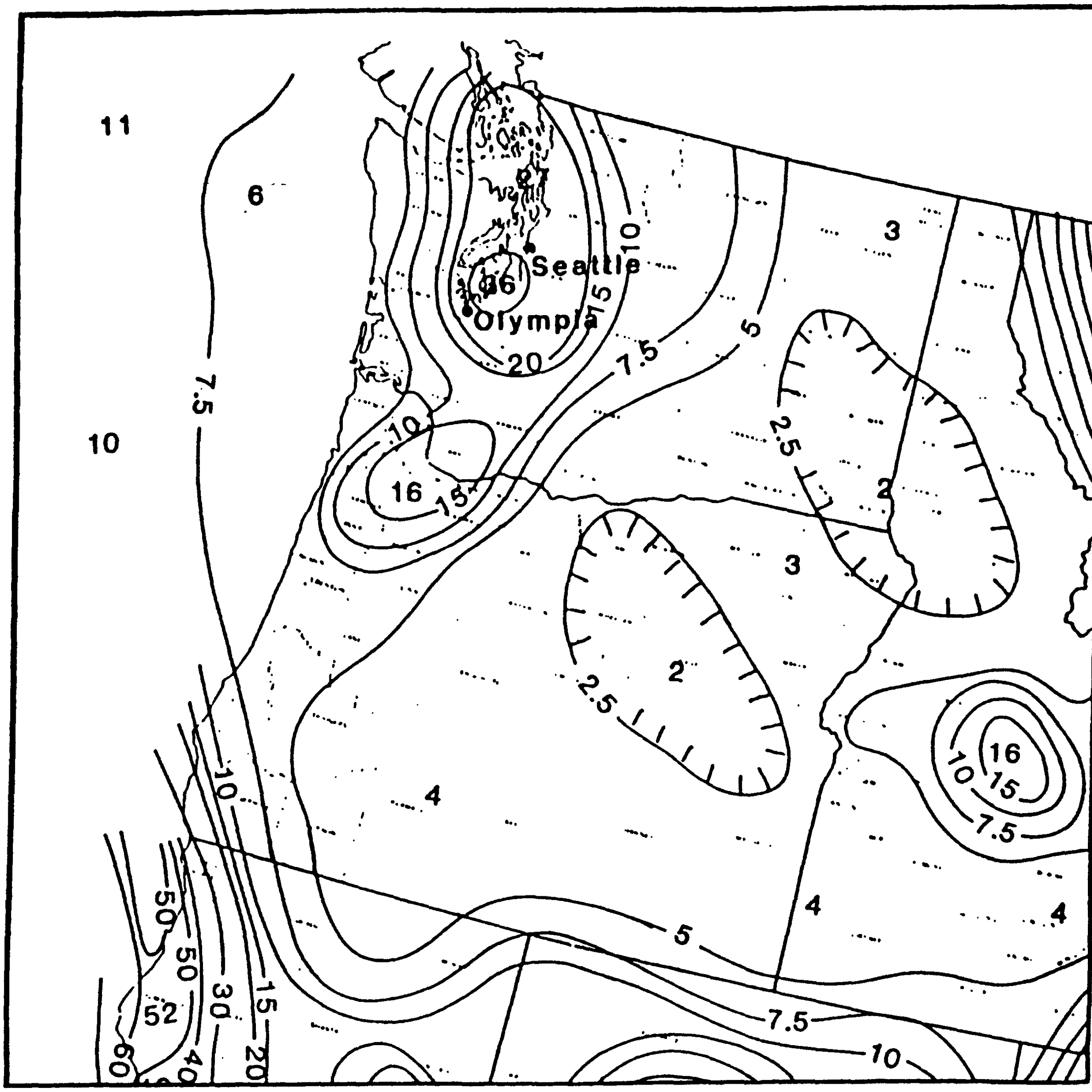
earthquake was located near Lake Chelan, Washington and had a shallow focus. Other recent significant shallow activity has occurred in the Elk Lake (Grant and others, 1984) and Goat Rocks (Zollweg and Crosson, 1981) areas of Washington, and there is evidence of Holocene faulting west of the Hood Canal (Gower, 1978). The sources of uncertainty in earthquake origins is summarized in Table 1.

Table 1.--Uncertainties in ground motion hazard assessment in the Puget Sound area

Hypothesis	Evidence
Very large plate boundary earthquakes M_w=8.5 - 9.0 might occur.	No known historical evidence but possible paleoseismic evidence from recent studies (Atwater, 1987). Conflicting views regarding the rate of subduction of the Juan de Fuca plate and the accumulation of strain. Ground motion attenuation relationships for such an earthquake not well known.
Large, shallow (M_s=7.0) earthquakes might occur onshore.	Evidence of an M_s=7.0 shock near Lake Chelan in 1872 but location and magnitude very uncertain (Hopper and others, 1982). Evidence of Holocene faulting west of the Hood Canal (Gower, 1978). Very limited available seismotectonic or seismological data to identify possible source areas of large shallow shocks.
Large (M_s=7.0) earthquakes occur at depths of 40-70 km.	Well-documented historical shocks, but the possible spatial distribution is uncertain.

The portion of the 1982 acceleration map shown in Figure 2 and the recently prepared (1988) acceleration maps shown in Figure 3 represent a more conservative modeling of shallow earthquakes in the Puget Sound area than was taken by Algermissen and Perkins (1976). For the national ground motion maps developed in 1982, 25 percent of the earthquakes with M_s magnitudes greater than 6.5 were assumed to occur at shallow depth. The choice of 25 percent was very arbitrary. All large shocks were assumed to occur at depths of 50 km in the development of the 1976 national map. None of the maps (1976, 1982, 1988) consider the possibility of a subduction zone earthquake. Thus, there is considerable uncertainty in probabilistic ground motion assessment in the Puget Sound area because of the difficulty in quantifying the occurrence of large subduction zone earthquakes and the occurrence of damaging shallow shocks.



1982 50-Year Acceleration Map

with Parameter Variability (1988)

0 100 200 300 400

Kilometers

Figure 3. Pacific Northwest portion of a 50 year, 10 percent chance of exceedance, map of maximum acceleration in rock that is under development at the present time (Algermissen and others, 1988). The model is exactly the same as used to produce the map in Figure 2, except that variability is included in attenuation and fault rupture length. The variation in attenuation of $\log_e$ of acceleration (T_A) is 0.62 and in $\log_{10}$ of fault rupture length (T_L) is 0.52.

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Approximate calculations of the effect of the occurrence of a large (M_w=8.5) earthquake at two possible locations in the subduction zone were undertaken in an attempt to roughly estimate the effects of such an earthquake in the Seattle urban area. The position of these postulated earthquakes are shown in Figure 1. The fault rupture length assumed in both cases is 225 km, although the rupture length is not critical for the present discussion as long as it is at least 100 km. The offshore earthquake is assumed to occur at a depth of about 20 km. The earthquake beneath Puget Sound is assumed to occur at a depth of about 50 km. In both cases, calculations of probable ground motion were made assuming average recurrence times for the earthquakes of 300, 600 and 900 years. Each earthquake, in turn, was included in the probabilistic model used to compute the 1982 national maps and in the 1988 model which included parameter variability in attenuation and fault rupture length. The results give only a general idea of the influence on expected ground motion since the subduction zone earthquake was only approximately modeled and since our future work in modeling ground motion in the Pacific Northwest will include a careful modeling of all source zones, new attenuation relations, etc. Nevertheless, the results are interesting. A large subduction zone earthquake offshore (Figure 1) would not appreciably affect the 50 year acceleration or velocity at Seattle for average recurrence times of 300 through 900 years. The accelerations and velocities (in rock) computed for a 50 year exposure time and 10 percent chance of exceedance at Seattle did not appreciably differ from the values shown in Figures 2 and 3 (for the 1982 and 1988 models).

It should be understood that the occurrence of a large subduction zone earthquake would in all probability cause damage in Olympia, Tacoma and Seattle. Damage would most likely occur to unreinforced masonry of any height and selectively to other buildings principally in the range of 5-25 stories in height. The important point is that the ground motion caused by such an earthquake with an average recurrence time of greater than 300 years doesn't contribute significantly to the expected peak ground motion in a 50 year period. The principal damaging ground motions contributing to the 50 year peak motion appears to be associated with the rather frequent occurrence of shocks in the range $6.0<M_w<7.5$ that occur beneath the three urban areas considered at a depth of about 50 km (for example in 1939, 1946, 1949 and 1965).

A large subduction zone earthquake at a depth of 50 km beneath Seattle would not appreciably change the 50 year, peak acceleration or velocity at Seattle for an average recurrence time of 900 years but it would approximately double the peak velocity at Seattle for an average recurrence time of 300 years for a subduction zone earthquake. It should be understood that the suggested doubling of the 50 year velocity at Seattle is only a rough approximation since no entirely suitable attenuation relations are available for such an earthquake.

DISCUSSION

The probabilistic model for the estimation of ground motion in the Pacific Northwest must be considered very tentative at present since two of the three major possible sources or rates of damaging earthquakes (large subduction zone shocks and shallow damaging shocks) are not very well understood. Much new paleoseismic research data are becoming available concerning recurrence rates for subduction zone shocks but very little has been done to resolve the problem of possible damaging shallow shocks. These uncertainties in defining the sources of earthquakes and the emergence of new data on attenuation of subduction zone earthquakes (for example from studies of the 1985 earthquakes in Chile and Mexico) guarantees that probabilistic ground motion models for the Pacific Northwest will undergo extensive revision over the next few years.

PROPOSED RESEARCH PROGRAM FOR THE PACIFIC NORTHWEST

The USGS urban hazards program in the Pacific Northwest currently underway will address a number of important problems critical to earthquake hazard analysis and to the estimation of expected ground motion. The strategy is outlined briefly here:

1. Incorporation of paleoseismic evidence for large subduction zone earthquakes into probabilistic ground motion models

   Major paleoseismic studies are underway to investigate the possibility of subduction zone earthquakes. These studies are crucial to disaster preparedness, but the contribution of these earthquakes to the expected maximum ground motion appears to depend heavily on the location of the shock (at least for exposure times <50 years).

2. Improvement in attenuation relations

   Significant new data on the attenuation of seismic waves from large, subduction zone earthquakes has become available recently (for example, as a result of the 1985 earthquake affecting Central Chile and Mexico City). These data need to be considered in developing a new model for ground motion hazard assessment.

3. Site response

   Recent large earthquakes have clearly shown the importance of site response in ground motion assessment. New models for ground motion assessment developed in the current USGS urban hazard program will include site response in the urban areas of the Puget Sound region and will be based on the site response data currently being recorded and analyzed (King and others, presentation at this meeting).

4. Shallow earthquakes

   Attention needs to be given to the problem of the possibility of damaging shallow earthquakes in the area. Shallow earthquakes of quite modest magnitude (for example, the 1986, M_s=5.5 earthquake that occurred at a depth of about 5 km beneath the city of San Salvador, causing major damage to the city) could cause great damage.

SUMMARY

The development of ideas concerning the assessment of earthquake ground motion in the Puget Sound area has been outlined and areas where significant improvements in these assessments are believed possible have been suggested. These areas of uncertainty and opportunities for improvement in hazard assessment are currently major research efforts in the USGS urban hazards program underway in the Puget Sound area. Success in this research will lead to much improved probabilistic models for the assessment of ground shaking and in estimates of ground shaking.

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BUILDING INVENTORIES:
CONSIDERATIONS OF EARTHQUAKE POTENTIAL LOSSES

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Several disciplines are involved when estimating the amount of damage and its monetary loss as a result of earthquake. A few of the necessary geophysical parameters have been covered by Dr. Algermissen. Additionally, the Bruce Olsen panel is scheduled to cover building practices in the Puget Sound cities and Portland, Oregon.

Our presentation fits into the foregoing pattern on the simple and prosaic subject of building inventories, but it is is of great importance due to the costs if new ones must be developed. Emphasis is given to the inventory requirements for government vulnerability studies and also those for major financial institutions such as insurance companies, banks, and savings and loans.

"Building inventory" is broadly defined as a list of all buildings and other structures within a given area which could be damaged in a shock. Included in the inventory are selected construction, occupancy, function, and value data needed for damage and resulting dollar loss estimates. For certain types of monetary loss estimation purposes, damage to the supporting city "lifelines" must be included. For example, loss of function and/or loss of occupancy due to lifeline failure can be measured in economic terms.

We may summarize the driving forces for quantifying inventories from three perspectives:

1. Damageability and its relationships to deaths and injury.
2. Damageability and its relationships to property damage.
3. Damageability resulting in loss of function, including lifelines.

Inventory detail is similar for casualty and property loss estimates, but it is not identical.

User Needs and Costs

For the limited purposes of this paper, the direct monetary loss to large numbers of smaller value properties, such as dwellings, will be given principal attention. However, it is valid to ask why the same inventories are not used for larger value structures or for individual buildings.

For a single structure, the "real world" hazard analysis may be limited to a proposal which "brings the building up to code" with the implication that life safety is being adequately considered and changing damageability is not a concern. A older flexible steel frame habitational or office occupancy can be strengthened without changing the damageability of high value fragile partitions, for example. Alternatively, it may be partially brought to code requirements in some jurisdictions, or the owner may use insurance as an alternative, thereby commingling life safety with property damage. He may sell the building to pass the hazard to others. This low cost hazard analysis will cost more than that available for a government vulnerability analysis on a per building basis and yet not be useful for the vulnerability study.

The other end of the cost and hazard analysis scales are the properties of very large corporations where skilled engineering risk organizations are at their best. These risk engineers can and do study the construction drawings, inspect buildings and sometimes test the concrete. They may recommend strengthening or demolition, eliminate hazardous features in manufacturing processes, recommend dollar amounts of insurance based on expected loss, and otherwise provide service to the corporation's risk manager. These are very useful reports to all parties. But it appears that more than one major corporation may have spent more on their hazard and correction study than did the government on its entire southern California vulnerability study. Both satisfied their user's needs, but their inventories and findings have not been interchangeable.

Financial institutions often obtain these reports and may ask for an independent review. Certain insurance companies which underwrite "highly protected risks" (HPR) have substantial in-house engineering competence. They and a few others can adequately analyze major properties such as aircraft manufacturers. Values at risk may represent billions of dollars and their sophisticated all-hazard approaches are beyond this discussion.

Governmental vulnerability studies for disaster response planners must consider all structures, large and small, in the study area on a uniform basis. This area may be as large as the Puget Sound region or the Los Angeles basin. Emphasis is normally on casualties, homeless, and impairment of critical facilities ("lifelines").

My experience as a participant in 10 regional vulnerability studies throughout the western United States shows that gathering building and lifeline inventories may require up to 80% of the available money. Budget limitations do not allow a mathematical analysis of individual buildings and only a minimal review of drawings of a very few selected buildings.

A similar situation exists for the financial institutions. Thousands of homes and businesses may be earthquake insured or have loans against them. Let us examine the economics of hazard analysis on low value properties from an insurance standpoint. For example using expense allocation for dwelling fire insurance policies in California as a guide (Steinbrugge, 1982, Table 8-9), a $200,000 earthquake insured house would require a $400 annual premium at the usual rate of $2 per $1000, of which:

Losses, adjustments, production, taxes	86.6%, or $347
Internal expense and inspection costs	10.1%, or $40
Profit and contingency reserves	3.3%, or $13

These dollars are reasonably correct today. Should an underwriter wish to know if a dwelling was superior, average, or deficient before writing the business, he would immediately have to send out an inspector and not wait for a more auspicious time. The costs for even a minimally qualified person would run over a hundred dollars (including car and overhead). This extreme is absurd. Also recall that the insureds must eventually pay for the overheads incurred for those owners who were premium comparing or didn't buy. More practical alternatives exist, but are difficult to make cost effective.

Quite evidently, loss estimation data must be gathered on a simplistic and generalized basis if dwelling earthquake insurance premiums are not to increase.

Wood Frame Dwelling Inventories: California Example

In the interests of time and space, further discussion will be limited to wood frame dwelling inventories in California and their dollar loss estimates. Similar methods apply to other classes of buildings, such as tilt-up, unreinforced unit masonry, reinforced unit masonry, and the like.

Before an earthquake, non-technical persons such as insurance agents and property owners can provide certain construction related information when the policy is written or renewed. Approximate year of construction, for one example, can be used to good advantage to infer local or regional construction practices. Pre-1933 or post-1933 in California is a general criteria for determining earthquake bracing. Location by city or region along with dwelling age can be related to changes in kinds of foundation, anchor bolting practices, veneer anchorage, reinforcement in brick chimneys, improvements (or otherwise) in wall sheathing practices including its nailing, and numerous other construction features.

Computer programs using the implications of these data can easily compute aggregate regional dollar loss estimates based on previously observed damage patterns and losses. The 1971 San Fernando and the 1983 Coalinga earthquakes have given reliable data for various types of wood frame dwellings (Steinbrugge, 1982, Table 6-1 and Figure 6-17; Steinbrugge, et al, in press). The number of insured dwellings, values, ages, and locations can be machine read from internal records. These are then by machine related to the distance from a postulated earthquake fault rupture (i.e. region of seismic energy release). Dollar losses are attenuated for distance. Soil influences on damage are included as well as long period effects. ZIPs are used as the unit area. Printouts from these computations provide the aggregate probable maximum loss (PML) for each of an ensemble of earthquakes on selected faults at selected epicenters.

Likewise, government economic and vulnerability studies can use the same or counterpart data. Similar dollar loss estimates have been prepared with updated California census tract housing and tract value.

Verification by Earthquake Experience

Loss estimates must be based on, or proven by, loss experience.

Post-earthquake field data on over 12,000 dwellings after the 1971 San Fernando earthquake are summarized in Table 1. Table 2 is the analysis summary of the field data in Table 1. Equation 1 is a relation between deductible and loss over deductible for values in the second column (All Ages) in Table 2.

$$(\% \text{ loss over deductible}) = 8.87 - 0.74 \times (\% \text{ deductible}) \qquad \text{Eq. 1}$$

For general loss estimation purposes, this equation is modified for different magnitudes and different soil conditions. Equation 1 is satisfactory for the 0% to 10% range, but a more complex equation is desirable for greater deductibles.

Table 3 is a summary of the field survey of every dwelling in Coalinga after the 1983 earthquake. Table 4, also of Coalinga, shows one of the comparisons between the aggregate losses as computed by Steinbrugge, et al (1982) and the losses paid by a major insurance company. The large number of insurance company's paid claims were under a quirk of California law known as concurrent causation, and payments do not include any significant deductibles. The 331 paid losses were compared on a house to house basis, and represents about 15% of the Coalinga dwellings. The correlations are excellent, possibly somewhat fortuitous.

One may conclude that appropriately devised post-earthquake field surveys can provide adequate practical loss data for public and private sector use.

Future Dwelling Loss Estimation Techniques

California oriented loss estimation techniques discussed above should be expanded and be kept on a continuing basis, with research improving these techniques.

In areas such as Salt Lake City, dwelling construction practices have also changed over time. Change has taken place from unreinforced brick to wood frame to wood frame with brick veneer. Studies in the midwestern states have shown the need for another set of parameters which often involve the type of

TABLE 1

WOOD FRAME DWELLING DAMAGE
1971 SAN FERNANDO EARTHQUAKE

Construction Component	Percentage of Buildings Having Described Damage			
	None	Slight	Moderate	Severe
Foundation	91.9%	5.8%	1.6%	0.7%
Damage to frame	78.8%	16.0%	3.3%	1.9%
Interior finish - plaster	4.2%	78.4%	11.1%	6.3%
Interior finish - gypsumboard	12.1%	78.0%	6.5%	3.4%
Exterior finish - stucco (plaster)	20.7%	74.1%	4.0%	1.2%
*Brick chimney damage	67.6%	16.1%	6.6%	7.4%

*Total brick chimney damage was found in 2.3% of the cases. "Total" means exactly that; essentially no bricks were left standing, or the chimney was otherwise so damaged as to be non-repairable.

From Steinbrugge (1982), Table 6-6.

TABLE 2

PERCENT LOSS OVER DEDUCTIBLE FOR WOOD FRAME DWELLINGS

Percent Loss Over Deductible Values from Field Data
1971 San Fernando, California, Earthquake

%	Percent Loss Over Deductible							
	All Dwellings, no Exceptions				All Dwellings, Exceptions Below			
Ded.	All Ages	Pre-40	1940-49	Post-49	All Ages	Pre-40	1940-49	Post-49
0	9.03	11.84	8.93	8.91	8.16	10.46	7.99	8.13
1	8.22	11.07	8.12	8.08	7.37	9.71	7.20	7.33
2	7.41	10.31	7.32	7.26	6.58	8.97	6.41	6.52
3	6.61	9.56	6.52	6.44	5.79	8.23	5.63	5.71
4	5.82	8.83	5.73	5.63	5.02	7.51	4.86	4.92
5	5.03	8.09	4.94	4.82	4.24	6.79	4.09	4.13
6	4.24	7.36	4.16	4.03	3.48	6.08	3.33	3.34
7	3.53	6.82	3.47	3.28	2.78	5.56	2.66	2.61
8	2.82	6.28	2.77	2.53	2.09	5.05	2.00	1.87
9	2.12	5.76	2.09	1.79	1.41	4.55	1.35	1.14
10	1.88	5.44	1.88	1.54	1.21	4.26	1.17	0.92

Exceptions (last 4 columns of table): Dwellings located on faulting or on observed ground disturbance, split level dwellings, 1 and 2 story dwellings, and dwellings in areas adjacent to mountains where soil amplification was observed.

Source: Steinbrugge, unpublished study.

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TABLE 3

WOOD FRAME DWELLING LOSSES IN COALINGA

As a Function of Age and Floor Type

	Number of Dwellings	Average Percent Loss
Pre-1940 age group:		
Wood supported floor	780	28.7
Concrete floor on grade	29	17.9
Both of the above	799	28.4
1940-1949 age group:		
Wood supported floor	287	14.2
Concrete floor on grade	34	11.5
Both of the above	321	13.9
Post-1940 age group:		
Wood supported floor	352	14.3
Concrete floor on grade	395	9.5
Both of the above	747	11.8
All age groups:		
Wood supported floor	1,442	21.2
Concrete floor on grade	453	9.3
Both of the above	1,895	18.1

From Steinbrugge, et al, Table 16, USGS Prof. Paper, in press.

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TABLE 4

COMPARISON OF MONETARY LOSS ESTIMATES

In dollars

1983 Coalinga, California, Earthquake

Age group	Steinbrugge, et al Estimates (Column A)	Insurance Company Paid Claims (Column B)	Ratio of Columns A to B
Pre-1940	1,268,000	1,431,000	0.89
1940-49	379,800	317,300	1.20
Post-1949	876,000	553,200	1.58
All ages	2,559,000	2,375,000	1.08

From Steinbrugge, et al, Table 15, USGS Prof. Paper, in press.

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basement walls and other features. Further work is needed for the Puget Sound and Portland regions.

These kinds of information should be expanded to all seismic areas. Expansions and improvements should not be made in a vacuum away from the realistic inventory requirements of the public and private sectors.

Finally and certainly not least, compatible post-earthquake field surveys are mandatory for future validation of theoretic studies.

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PROBABLE LOCAL PRECEDENT FOR EARTHQUAKES OF MAGNITUDE 8 OR 9 IN THE PACIFIC NORTHWEST

By

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Great earthquakes probably can happen in the Pacific Northwest. Such earthquakes, being of magnitude 8 or 9, would release as least as much energy as did the 1906 San Francisco earthquake. Their source would be the plate-bounding fault that descends gently eastward beneath the continental margin from southern British Columbia to northern California. This huge fault, the Cascadia subduction zone (fig. 1a), is not known to have produced great earthquakes in the 200 years since white people arrived in the Pacific Northwest. But Cascadia has much in common with subduction zones elsewhere on which great earthquakes have occurred historically (Heaton and Hartzell, 1987). Moreover, as reviewed in this report, great earthquakes seem to have occurred on the Cascadia subduction zone itself--at least twice in the past 1700 years.

COASTAL EVIDENCE FOR THE PAST OCCURRENCE OF GREAT CASCADIA EARTHQUAKES

If great earthquakes have occurred on the Cascadia subduction zone during the past 1700 years, evidence of the earthquakes should abound on the Northwest coast. This is chiefly because a great subduction-zone earthquake usually causes the adjoining coast to undergo meters of uplift or subsidence. The uplift can result in the permanent emergence of wave-cut coastal benches; the subsidence can cause the estuarine burial of well-vegetated coastal lowlands that drop to the level of tideflats. In addition, coastal lowlands may preserve anomalous bodies of sand that result from shaking during the earthquake and from the tsunami that comes ashore minutes later.

Earth scientists have barely begun to ask whether all these great-earthquake telltales are present on the Northwest coast. But in just the past two years they have found much evidence for rapid subsidence, some evidence for consequent tsunamis, and a little evidence for uplift and shaking.

Subsidence. That great Cascadia earthquakes probably have occurred is indicated chiefly by evidence of sudden coastal subsidence. This evidence takes the form of marshes that have been buried by tidal mud. First recognized in the Northwest in 1986, such buried marshes are now known to range in location from southernmost British Columbia to northern California (Rogers, 1988; Atwater, 1987, 1988; Grant and McLaren, 1987; Darienzo and Peterson, 1987; Nelson, 1987; G.A. Carver, oral commun., 1988). Simple tests can eliminate storms, floods, far-traveled tsunamis, differential compaction, and global sea-level rise as alternative explanations for the marshland burial (Atwater, 1987, p. 943).

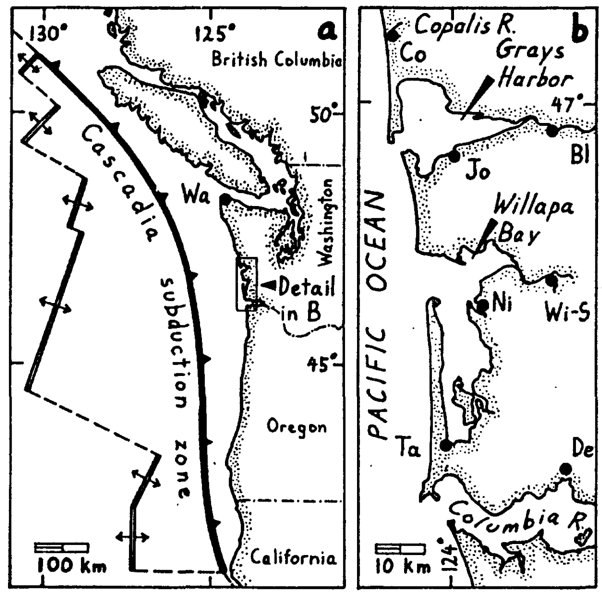

Fig. 1. Index maps. (a), Cascadia subduction zone. (b), coastal southwestern Washington.

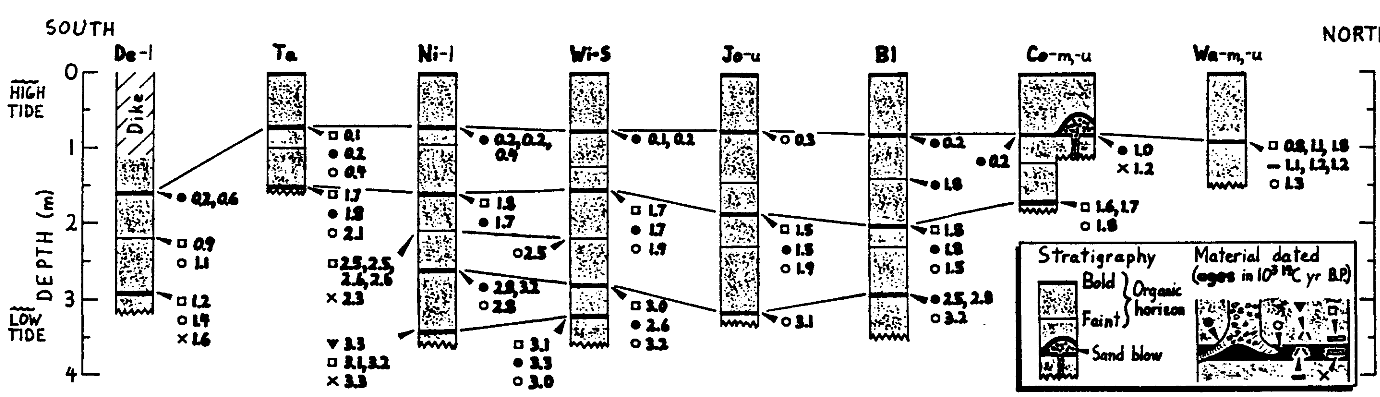

Fig. 2. Organic horizons and radiocarbon ages of buried-wetland soils in coastal Washington (Atwater, 1988). Solid lines between columns denote correlations among radiocarbon-dated soils. Localities (letter symbols at top) keyed to figure 1 and to tables of Atwater (1988). Material dated, with stratigraphic position shown at lower right: (●) root of tree, chiefly Sitka spruce; (▼), (▬) rhizome [below-ground stem] of <u>Triglochin maritima</u>, a grass-like tidal-marsh plant; (◘), (✕) stick(s) or cones or both; (○) uppermost 0.5 or 1.0 cm of organic horizon.

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At least in southwestern Washington, jerky coastal subsidence probably had too much areal extent to be explained by anything other than great Cascadia earthquakes. A great Cascadia earthquake is likely to entail subsidence of a coastal strip at least 100 km long and tens of kilometers wide (Atwater, 1987). Subsidence on that scale is suggested by regionality in the sequence and radiocarbon age of buried marshland soils in southwestern Washington (figs. 1b, 2). This regionality implies that at least two jerks of subsidence--one about 300 years ago[1], the other about 1700 years ago--involved a coastal strip no less than 85 km long and no less than 30 km wide.

It is remotely possible that each correlated soil in figure 2 represents a series of moderate earthquakes that successively jerked adjoining areas during an interval too brief to dissect by conventional radiocarbon dating. This possibility is now being tested by the tree-ring dating of cedars that died from sudden subsidence into the intertidal zone about 300 years ago (D.K. Yamaguchi, written commun., 1988).

Tsunami. Tsunamis probably resulted from at least some of the events that jerked the coast downward in Washington and Oregon. The evidence for tsunamis consists of sand that locally veneers some of the buried coastal marshes (Atwater, 1987; Reinhart and Bourgeois, 1987; Grant and McLaren, 1987). This sand is typically coarser than other intertidal deposits in the vicinity. Landward thinning of the sand indicates deposition by surge from a bay or from the sea. About 300 years ago in southwestern Washington, the sand from such a surge entombed the rooted stems and leaves of grass that had been living on the marsh when the marsh was jerked downward. This relation indicates that the surge took place within a few years of the jerk. Such coincidence, though unlikely for storms or far-traveled tsunamis, would be expected of tsunamis from great Cascadia earthquakes.

It remains conceivable that storms or seiches caused the surges from which the sand was deposited. These alternatives are now being tested through inference of the duration, depth, and velocity of the surges (M.A. Reinhart and Joanne Bourgeois, written commun., 1988).

Uplift. Analogies with uplift at other subduction zones imply that great Cascadia earthquakes would produce elevated shorelines on the Northwest coast (West and McCrumb, 1988), particularly where a subduction-zone rupture extends beneath the coast. Two candidates have been identified thus far (fig. 1)--one a beach gravel containing 3000-year-old wood in southern Oregon (Kelsey and others, 1988), the other a wave-cut bench perhaps 1000 years old in northern California (G.A. Carver, oral commun., 1988). These poorly understood features may record Cascadia earthquakes whose ruptures splayed upward into subsidiary faults. As shown by Kelsey and Carver (1988), faults probably rooted in the Cascadia

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[1] All ages in text are in sidereal years; calibration of radiocarbon ages follows Stuiver and Pearson (1986) and Pearson and Stuiver (1986).

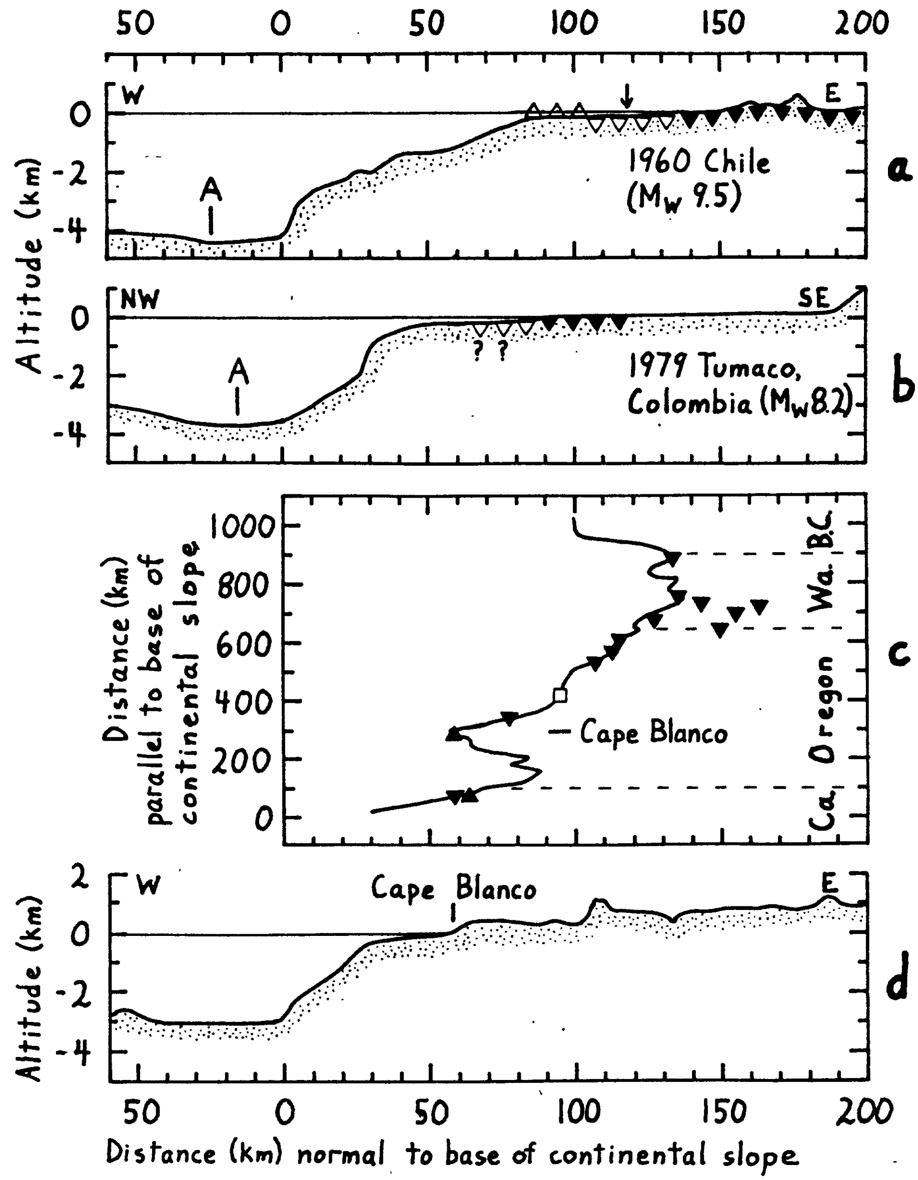

Fig. 3. Bathymetry and coseismic deformation versus distance from base of continental slope. Triangles point in direction of coseismic vertical movement; open triangles denote offshore movement, queried where doubtful. Moment magnitudes (M_w) from Kanamori (1977) and Kanamori and McNally (1982). A, axis of trough or channel. (a) Profile S82E through Valdivia, Chile. Bathymetry from Prince (1980). Coseismic deformation from Plafker and Savage (1970); arrow shows projected location of coseismically subsided coast 17 km SSW of profile. (b) Profile S53E through San Juan, Colombia (Herd and others, 1981). (c) Shoreline location between central Vancouver Island (top) and Cape Mendocino (bottom). Triangles show sites evincing coseismic subsidence or uplift of late Holocene age (Darienzo and Peterson, 1987; Grant and McLaren, 1987; Nelson, 1987; Atwater, 1988; Kelsey and others, 1988; G.A. Carver, oral commun., 1988). Square denotes site with evidence for only gradual coastal submergence (Nelson, 1987). (d) East-west profile through Cape Blanco. Bathymetry from National Ocean Survey (1974).

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subduction zone come ashore in northern California. The most recent thrusting on at least one of these faults occurred about 300 years ago (Carver and Burke, 1987). Kelsey and Carver (1988) liken northern California to the Gulf of Alaska, where thrusting on subsidiary faults produced a complex pattern of uplift, and may have also caused local subsidence, during the great (magnitude 9.2) Alaskan earthquake of 1964 (Plafker and Ruben, 1978, p. 706, 721).

Youthful uplifted terraces are scarce or absent on the coast of northern Oregon and Washington (West and McCrumb, 1988), probably because these areas undergo only subsidence during great Cascadia earthquakes. By analogy with the 1960 Chile earthquake (magnitude 9.5) and the 1979 Tumaco, Colombia earthquake (magnitude 8.2), uplift might be chiefly confined to areas within 105 km (Chilean analogy) or 90 km (Colombian analogy) of the base of the continental slope (fig. 3a, b). At such distances, little or no coseismic uplift would occur along the northern quarter (Chilean analogy) or northern half (Colombian analogy) of the Oregon coast (fig. 3c). Even Cape Blanco (fig. 3c, d) could escape coseismic uplift if the Colombian analogy applies and if, as seems likely (Herd and others, 1979), the Colombian subsidence extended tens of kilometers offshore (fig. 3b).

Shaking. The published case for great Cascadia earthquakes includes no compelling evidence that shaking accompanied the jerks of coastal subsidence. The strongest known hint is vented sand, containing clasts of the mud through which it rose, that buried part of a spruce woodland in coastal southwestern Washington about 1000 years ago (sand blow at site Co-u, fig. 2). The venting, indicative of strong shaking, does not seem to have accompanied subsidence of the woodland, or of coastal southwestern Washington regionally. But rapid subsidence did occur about 1000 years ago in northwesternmost Washington and, perhaps, near the mouth of the Columbia River (site De-1, fig. 2). Only by this kind of permissive correlation does shaking seem have accompanied a jerk of coastal subsidence in the Pacific Northwest.

The hypothesis of shaking during subsidence needs to be tested wherever easily vented sand underlies subsided wetlands that are well exposed in cross section. Few such places exist in coastal southwestern Washington. Additional evidence of shaking could take the form of landslides, provided that wet weather and non-Cascadia earthquakes can be excluded as triggers.

CONCLUSIONS

Earth scientists have recently begun to study ancient subsidence, uplift, tsunamis, and shaking as clues to the seismic potential of the Pacific Northwest. The little work done so far shows that great earthquakes probably have occurred on the Cascadia subduction zone in the recent pre-white-man past. Particularly suggestive is the widespread evidence for sudden coastal subsidence and accompanying tsunamis. This evidence implies local precedent for the future occurrence of great earthquakes in the Pacific Northwest.

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GEOPHYSICAL STUDIES IN SUPPORT OF SEISMIC HAZARDS ASSESSMENT OF SEATTLE AND OLYMPIA, WASHINGTON

By

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INTRODUCTION

According to plate tectonics theories, the Juan de Fuca oceanic plate and the continental North American plate are converging at about 3-4 cm/yr in a subduction zone more or less parallel to the Pacific Northwest coast. One consequence of this convergence is the occurrence of earthquakes, active volcanism, and tectonic deformation. The potential exists in the Puget Sound area for (1) large, shallow earthquakes along the interface of the underthrust zone, (2) major earthquakes within the cold, brittle Juan de Fuca slab, (3) moderate earthquakes associated with active volcanism in the Cascade Range, and (4) major shallow earthquakes within the North American plate landward of the underthrust zone. The Pacific Northwest cities of Seattle, Tacoma, and Olympia, Washington and Portland, Oregon are urban centers with significant risk from the occurrence of large earthquakes.

Major earthquakes occurred in the Puget Sound area in 1946, 1949, and 1965 (Fig. 1). The 1949 shock caused major damage to high-rise structures in Olympia; highest intensities were VII. The 1965 shock caused widespread damage in both Seattle and Tacoma, and intensity VII effects in Olympia; the highest intensity effects (VIII) were observed in West Seattle and Harbor Island.

URBAN HAZARDS INVESTIGATION

The USGS is engaged in a regional earthquake hazards assessment program in the States of Washington and Oregon, concentrating on the Puget Sound and Portland urban areas. The program is a partnership among governmental (Federal, State, and local), academic, and private entities to study how the Northwest would be impacted if a large, potentially-damaging earthquake were to occur in the region. The program is the outgrowth of two earthquake hazards workshops (USGS, 1983; USGS, 1986) and is divided into five, interrelated components:

(1) Information Systems
(2) Synthesis of geological and geophysical data
(3) Ground motion modeling
(4) Loss estimation models
(5) Implementation

The studies described in this report were conducted by the Urban Hazards Field Investigations project in support of the ground motion modeling component of the urban hazards program. The objective of the ground motion modeling component is to produce deterministic and probabilistic ground-motion models and to produce maps of ground-shaking hazard. One element of the ground motion modeling component is predicting relative ground response to strong vibratory motion from a model earthquake. Relative ground response is determined from observations of ground motion and from extrapolations of those measurements into areas where ground motion data are not available. The

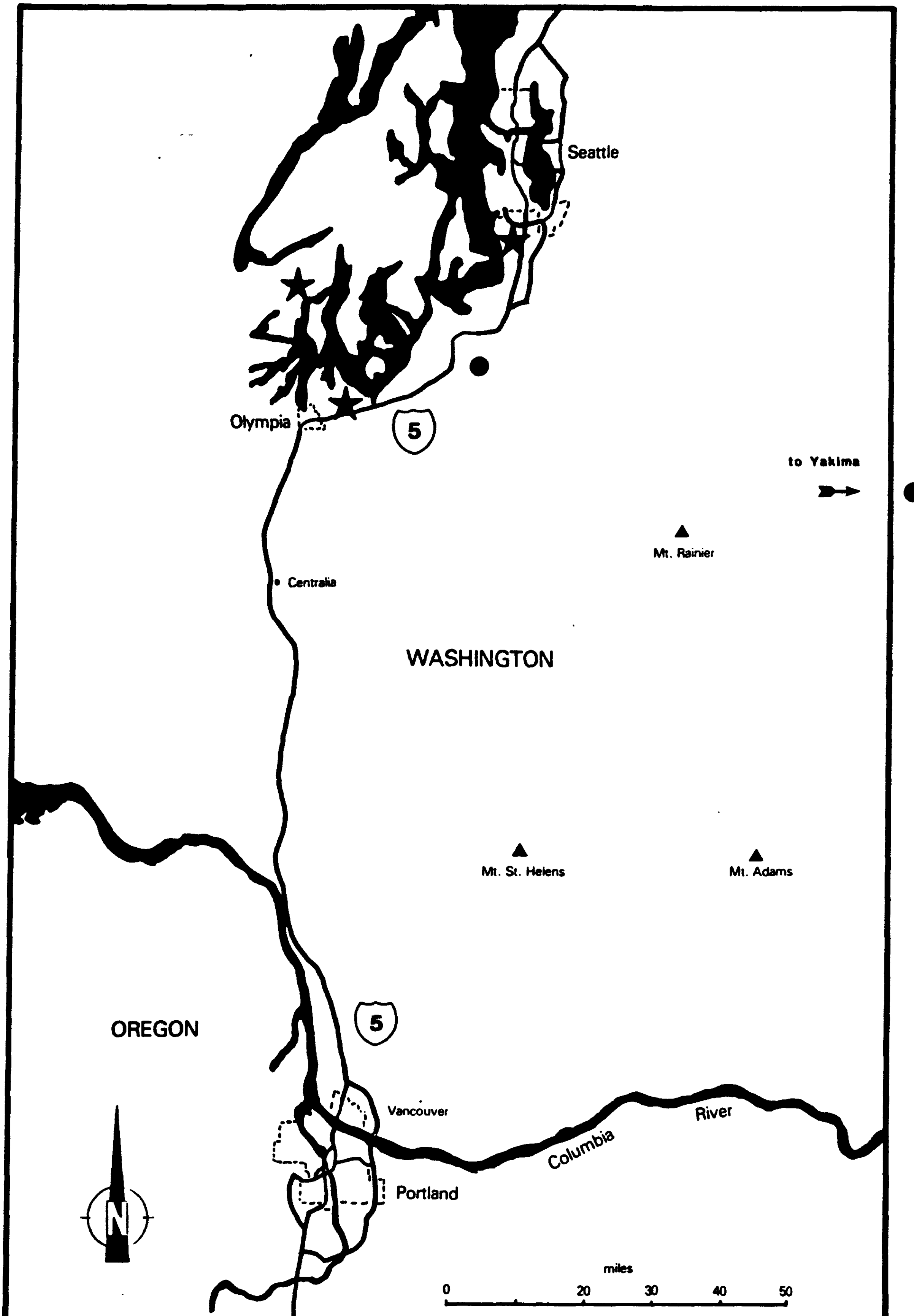

Figure 1. Location map showing ★ 1946, 1949 and 1965 earthquake locations; ● recent local microearthquakes; and energy source locations.

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geophysical studies described in this report are designed to provide seismic data from which relative ground response values are determined and to collect geotechnical data which assist in making the extrapolations.

OBJECTIVES

The objectives of the Urban Hazards Field Investigations project are to:

(1) Directly record, in digital form, seismograms of actual vibratory ground motion at sites in urban areas where ground response data are desired.

(2) Collect geotechnical (geological and engineering) data from sites near where the ground motion measurements were made.

(3) Correlate geotechnical data with seismic response data by clustering sites of similar geotechnical parameters.

METHODS

Relative ground response is determined by comparing the ground response at a site with a standard or reference response site. In this study, relative ground response is obtained by dividing the Fourier amplitude spectrum of a site by the amplitude spectrum of the reference location. The resulting spectral ratio may then be smoothed or averaged over any number of bandwidths; the average spectral ratio is the value of relative ground response within that band. In the relative ground response method, it is assumed that the ground response is due to ground conditions only, that is, the seismic inputs to the crust under the response site and reference site are essentially identical for a specified event and that any changes in response are due to difference between reference and response sites. If it is possible to correlate those difference in terms of physical parameters and geological description characterizing the sites, it may be possible to predict ground response from geotechnical data in locations where seismic observations are not available.

Desirable seismic waveforms for the study may occasionally be masked by seismic noise of natural and manmade origin. It is important to know the characteristics of noise to minimize the effects of contaminating a desirable signal and to help identify the frequencies of interest for site response studies.

Recordings of vibratory ground motion and geotechnical data of specific sites are the principal kinds of data which are required for predictive ground response studies. Ground motions resulting from various seismic sources were recorded by portable digital seismic systems for this study. The seismic data used in the studies described in this report were recorded by calibrated portable digital seismic systems especially for the urban hazards program. The sources of seismic energy were both natural (microearthquakes and microseisms) and artificial (nuclear explosions and mining explosions).

Digital recordings of induced ground vibrations in the Seattle and Olympia areas were successfully acquired for four nuclear explosions at the Nevada Test Site (approximately 1,100 km distance) and seven mining explosions at an open pit coal mine near Centralia, Washington (about 80 km from Seattle) (Figs. 1,2,and 3). The general procedure for recording these explosions was to manually start all recorders within 15 min of the expected arrival time of the seismic waves and record up to one hour for each.

Five to eight seismic stations were installed at temporary locations in the West Seattle Area. The recorders at the stations continuously store approximately 15 seconds of data in a digital memory and will permanently

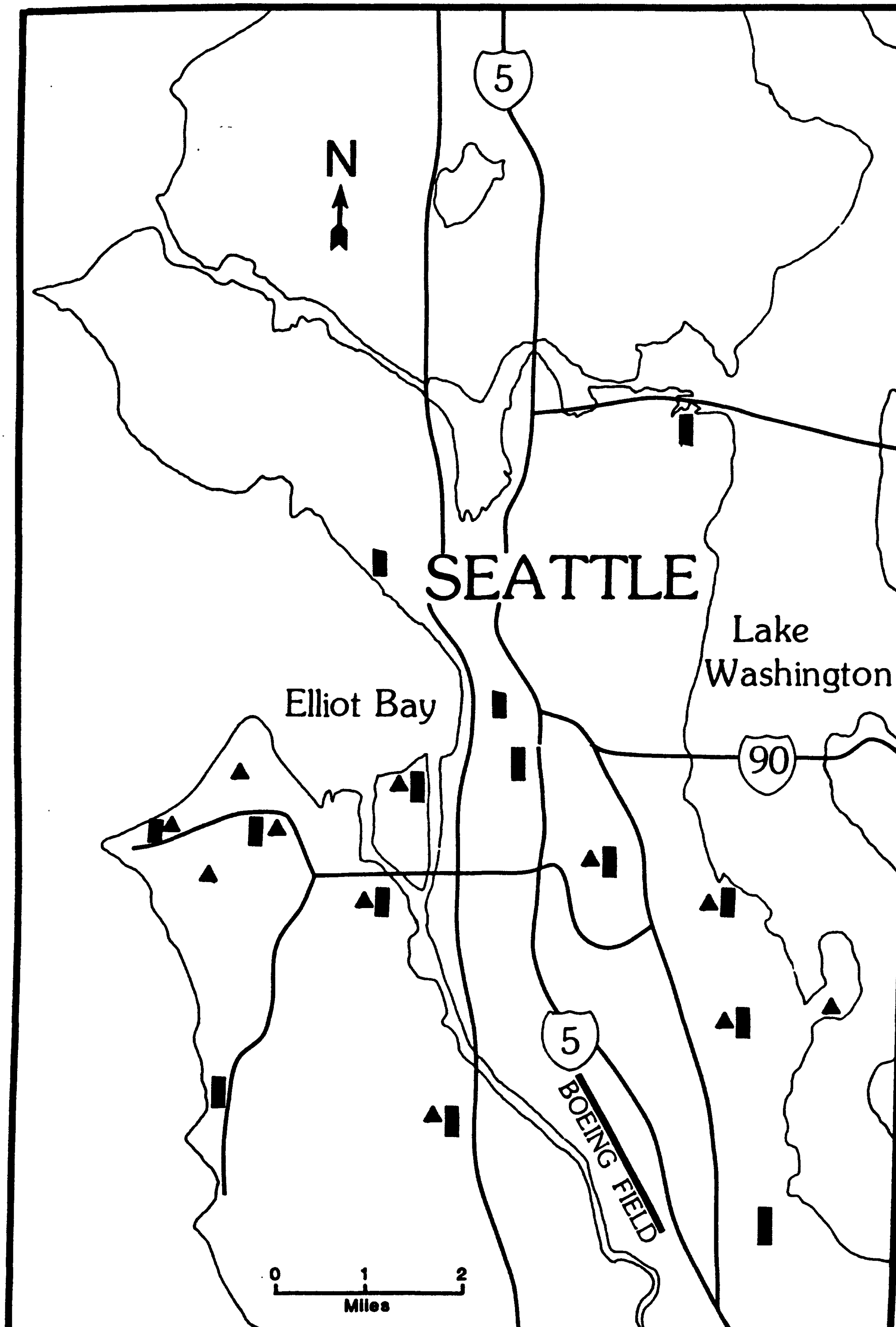

Figure 2. Locations of reflection/refraction lines = ▬; and site response status ▲.

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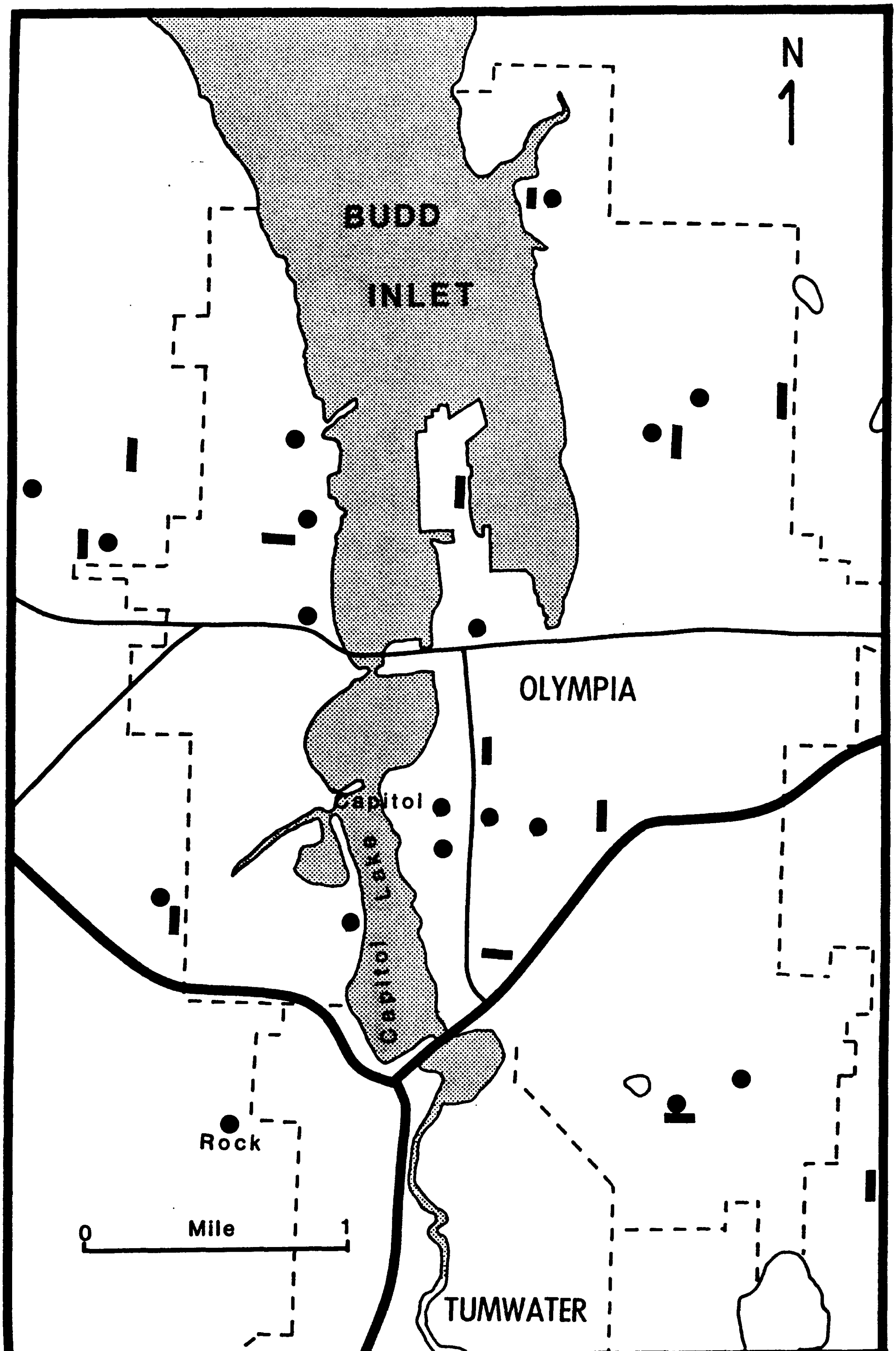

Figure 3. Locations of reflection/refraction lines = ▬; and site response status ●.

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store the digital data for longer duration when activated by a radio signal from a master station or by a local vibratory ground motion which coincides with a pre-set algrorithm. Two microearthquakes have been recorded to date. The time history data for one of the earthquakes and for one of the nuclear events are shown in Figs. 4,and 5.

Three separate experiments were conducted to evaluate the nature of seismic noise and microseisms in Seattle. The first experiment consisted of recording 10 min of background vibrations at five sites at three times (at 1 a.m., 2 a.m., and 3 a.m.) on two successive days. The second experiment consisted of recording 15 min of background noise at five stations during a Saturday afternoon in the Brighton district of Seattle. Two of the sites were located on bedrock while the other three were located on varying thickness of sediment. The third experiment consisted of recording 15 min of background noise at five stations on a windy, rainy Sunday morning in West Seattle, extending inland along a line about a mile long.

Seismic refraction and high-resolution reflection are geophysical methods used to determine the subsurface structural details at a site, based on the acoustic contrast across interfaces. The two methods are complementary: Seismic refraction is most accurate in determining average velocities of layers whereas seismic reflection is most accurate in determining layer thickness. In this study, seismic refraction experiments were run to determine layer velocities and approximate layer thickness at several response sites. Seismic reflection experiments were run, using an approximate velocity model determined from refraction, to determine more accurate thickness and structure of the shallow layers. In addition, longer reflection lines were run to detect deep interfaces which were not accessible to the refraction experiments.

In all cases, refraction lines were run in both forward and reverse directions, and the reflection methods used the "push-pull" technique to give a minimum 18-fold summary of the common depth points. Several data reduction techniques were used to derive the velocity model and depths from the travel-time data. Fourteen refraction/reflection lines were run in the Seattle area (Fig.2). Examples of the high-resolution reflection profiles are shown in Fig.6.

The method used to determine building response parameters is to artificially force the structure into oscillation and to record the vibration using a seismograph. An impulse delivered to the structure produces a damped vibration whose waveform allows a damping constant to be measured. A spectrum of the waveform indicates the predominant resonant period of the structure. Ten one-story single-family dwellings, with brick chimneys in the West Seattle area were tested for building response. In all cases, both the dwelling and the chimney were tested (Fig.7).

SUMMARY

Only preliminary conclusions can be derived from the present data set. The comparison of the derived spectra from the ground motions induced by the Nevada Test Site nuclear explosions and the spectra derived from the ground motions induced by small earthquakes suggest that the spectra derived from the large nuclear event ground motions are comparable and therefore useful at frequencies less than approximately 1.5 Hz.

The ground motions at Seattle and Portland induced by the quarry and mine blasts at the Centralia, Washington coal area are too small to be used for site response studies. The study has shown that ground motions induced by

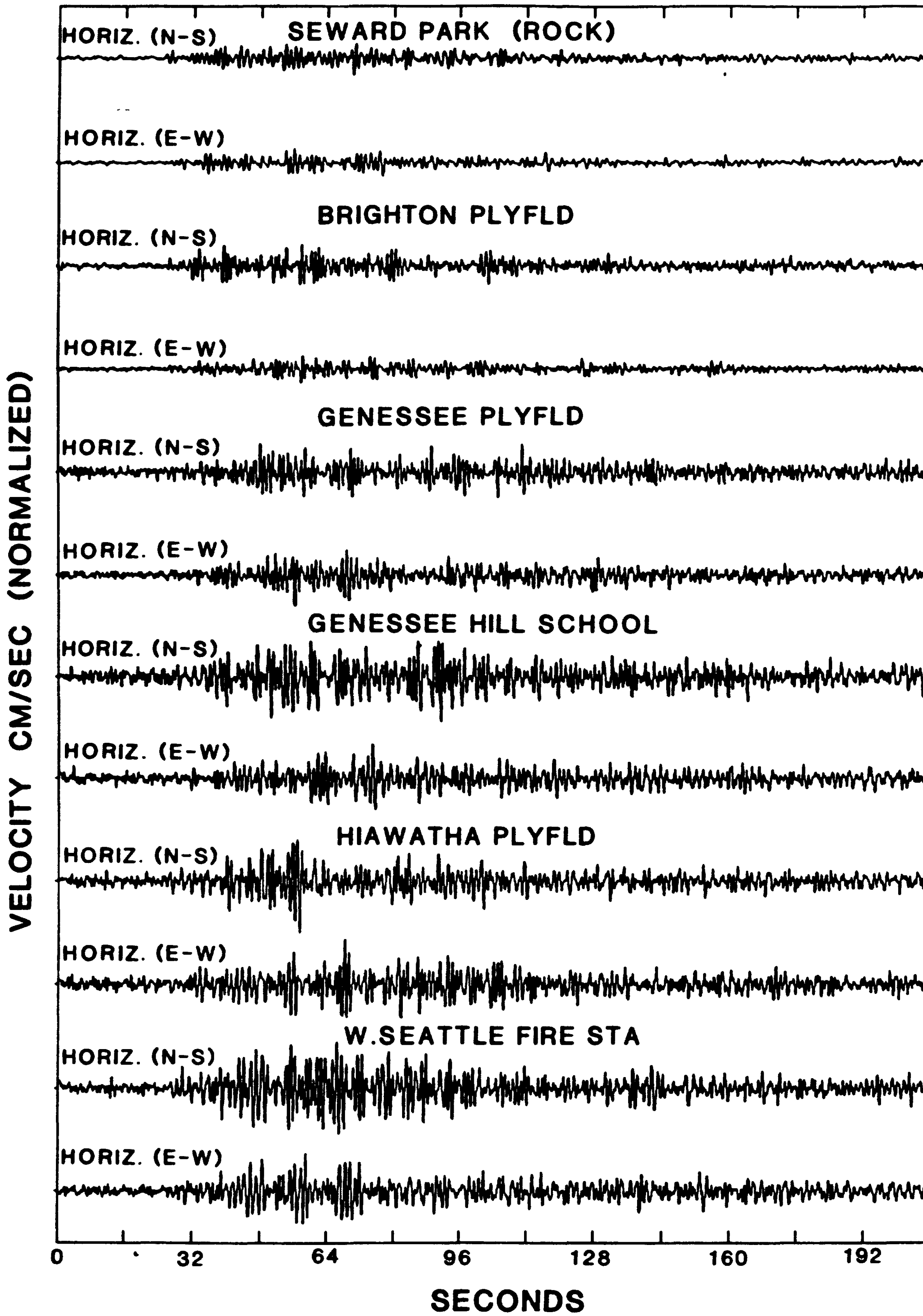

Figure 4. Time history of ground motions recorded in West Seattle. Induced source is a nuclear explosion at the Nevada Test Site.

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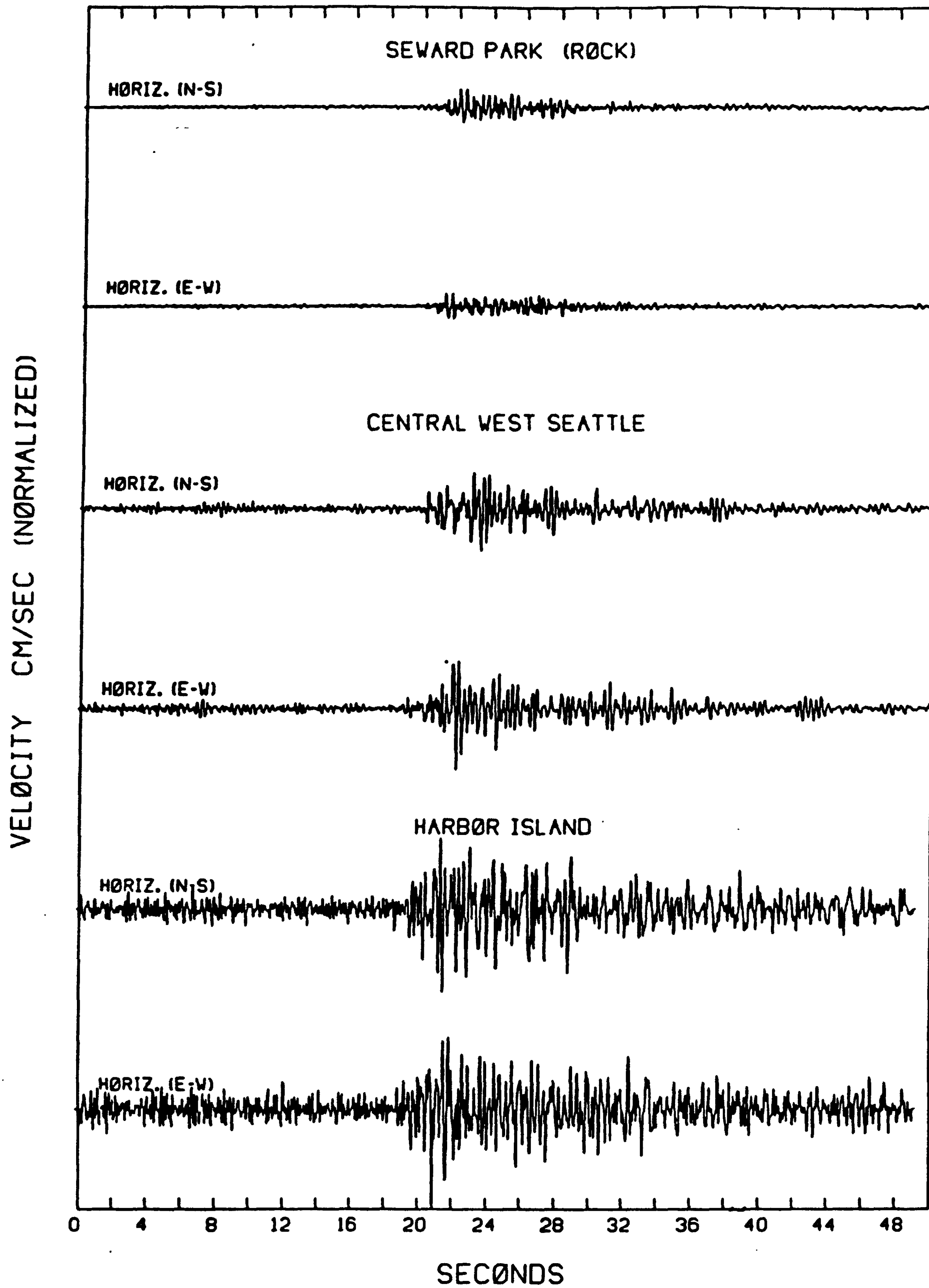

Figure 5. Time history of ground motions recorded in West Seattle. Induced source is a local microearthquake.

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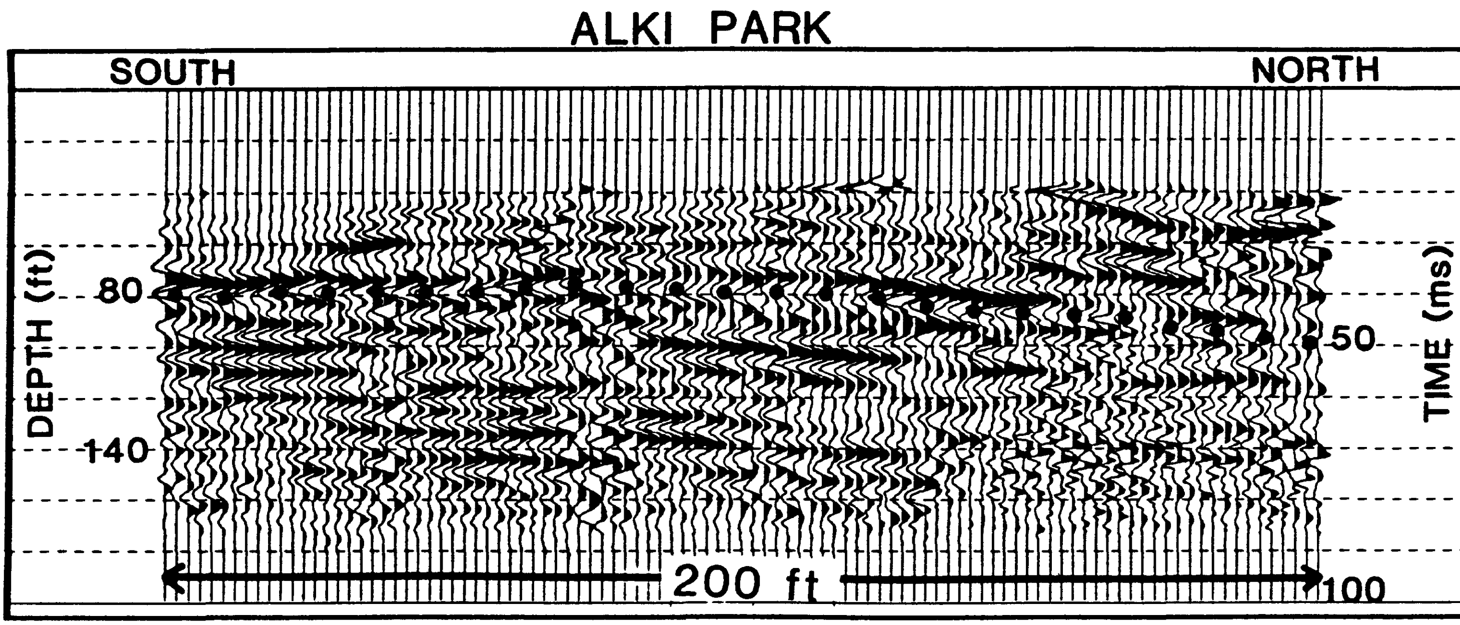

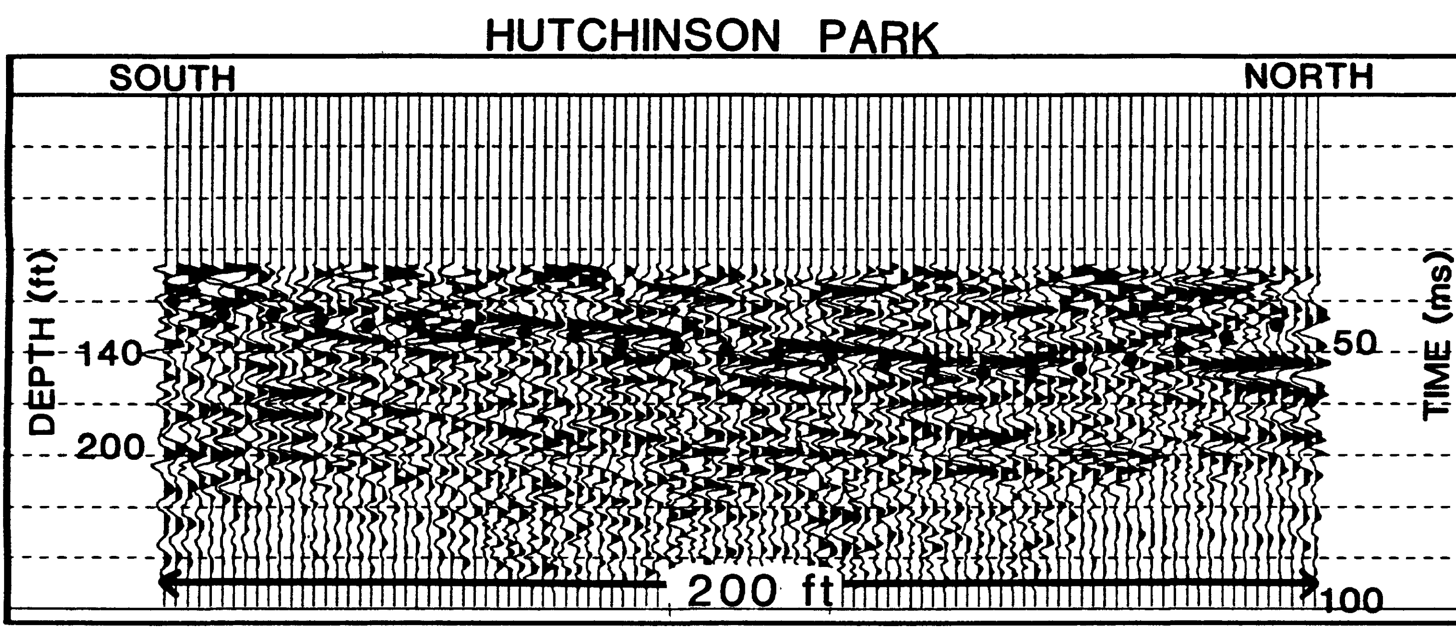

Figure 6.--Shows the 24-fold high-resolution seismic-reflection stacked profiles from Alki Park, West Seattle (top), and Hutchinson Park, southeast Seattle (bottom). Dotted reflection on both profiles indicates probable top of the 8500 ft/s bedrock seen in the refraction records at Seward Park. Reflection data were collected using a 4 ft geophone interval (2 ft CDP interval), single 100 Hz geophones, 220 Hz low-cut recording filters, and a 30-06 rifle for the seismic source.

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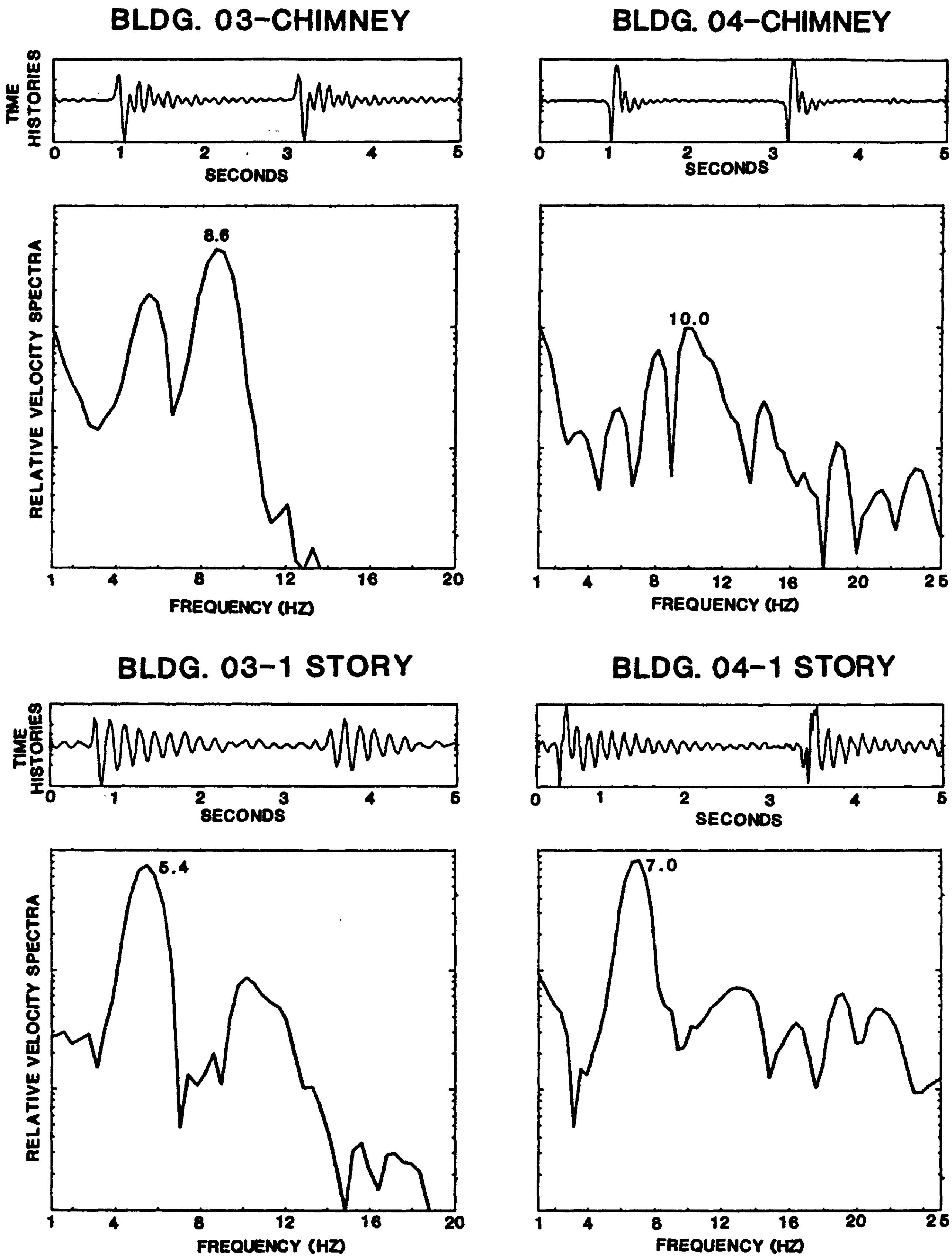

Figure 7. West Seattle building response studies.

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local earthquakes are the only technically-acceptable source at this time for ground motion studies in these areas. The ground motions induced by the quarry blasts at Centralia are less than desirable, but are adequate for site response studies in Olympia, Washington.

The derived site response values in the Olympia, Washington area from the motions induced by the Centralia quarry blasts correspond favorably with the MM intensities from the 1965 earthquake; that is, the higher response sites are located at areas of higher intensities, the medium response values are at sites of medium intensities and low response values are located at areas where no intensities or damage was reported Fig.9. The few site response values derived thus far for the sites in the West Seattle area from the motions induced by the nuclear blasts and local earthquakes do not seem to agree as well with the 1965 MM intensity values as the Olympia data do except in a very general sense; that is, the highest response value derived for the West Seattle area from the limited data available is at Harbor Island which experienced higher shaking damage in the 1965 earthquake than did the West Seattle Area Figs.10,and 11..

In many cases, the noise spectrum at a response site was amplified above the corresponding reference spectrum. Prominent peaks were apparent at several sites and remained prominent at different times of day and on different days. These results suggest that microseisms are a possible fourth source of seismic energy for ground response measurements.

Refraction and reflection lines were run at sites to help determine local subsurface geologic structure, to determine near-surface variability of seismic velocities, and to establish the velocity of bedrock. The highest velocity observed, about 8,500 ft/sec, was also the velocity of the exposed bedrock unit at Seward Park. The velocity of the surface soil layer was less than 1000 ft/sec and the velocity of the intermediate till layers ranged from 2,400 to 5,100 ft/sec.(Fig.6).

The low-rise building testing established the range of the period and damping parameters of one-story houses and chimineys in the West Seattle area. The predominant frequency of the dwellings ranged from 5.4 Hz to 14.8 Hz. and the chimneys ranged from 6.2 Hz. to 13.7 Hz. The building dampings varied from 2.5% to a high of 6% of critical.

The microseismic data, reflection data, refraction data and past intensity data all suggest interesting correlations to the site response values; however, the amount of site response data and the number of sites under study are too small to make any but preliminary conclusions or trends. A basic conclusion is that a larger data set from ground motions induced by earthquakes are needed to continue and complete the study.

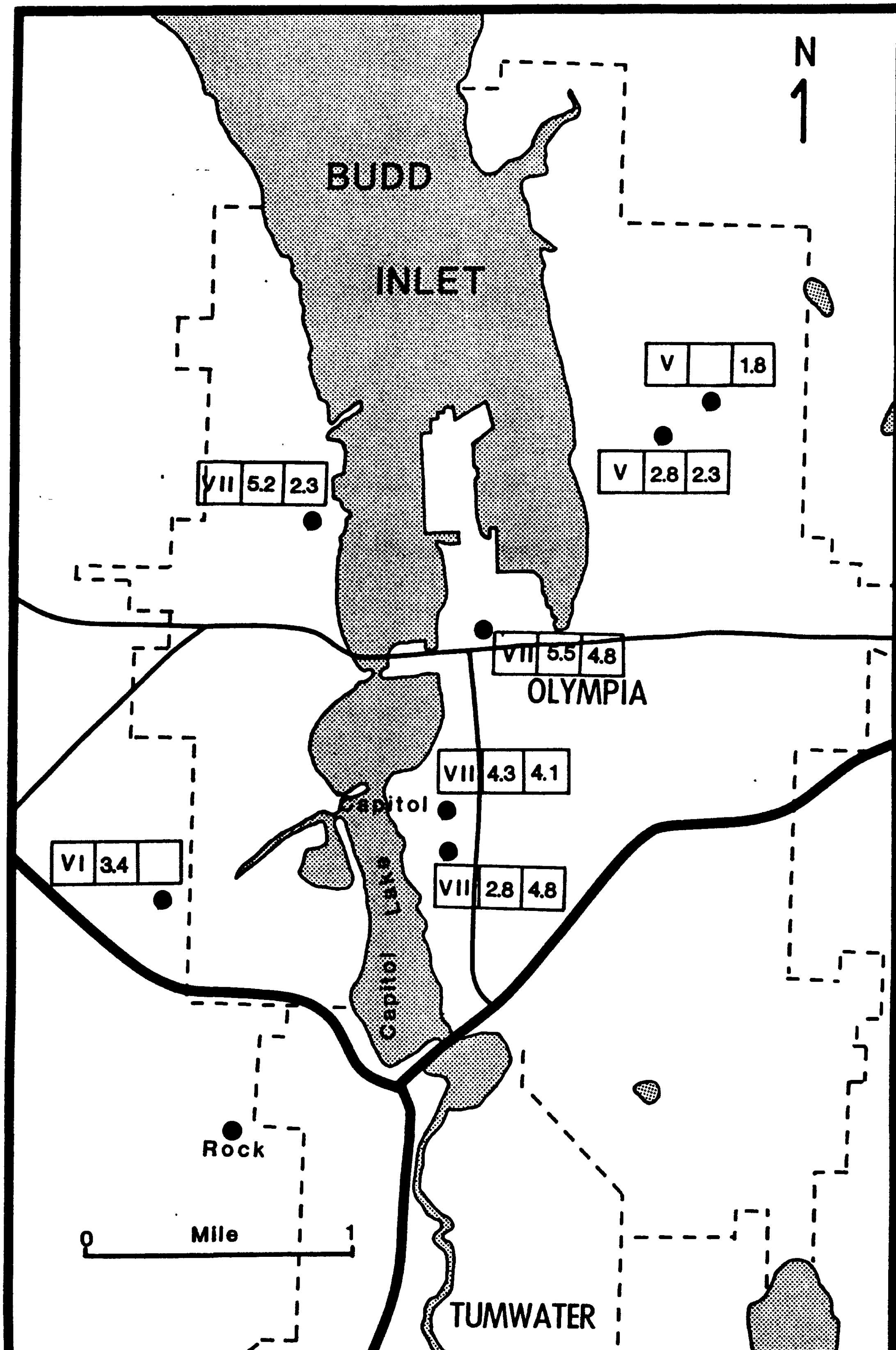

Figure 9. Stations of ground motion site response studies. Box 1 is Modified Mercalli Intensity. Boxes 2 and 3 are spectral ratios of 0.5-1 Hz and 1-2 Hz, respectively.

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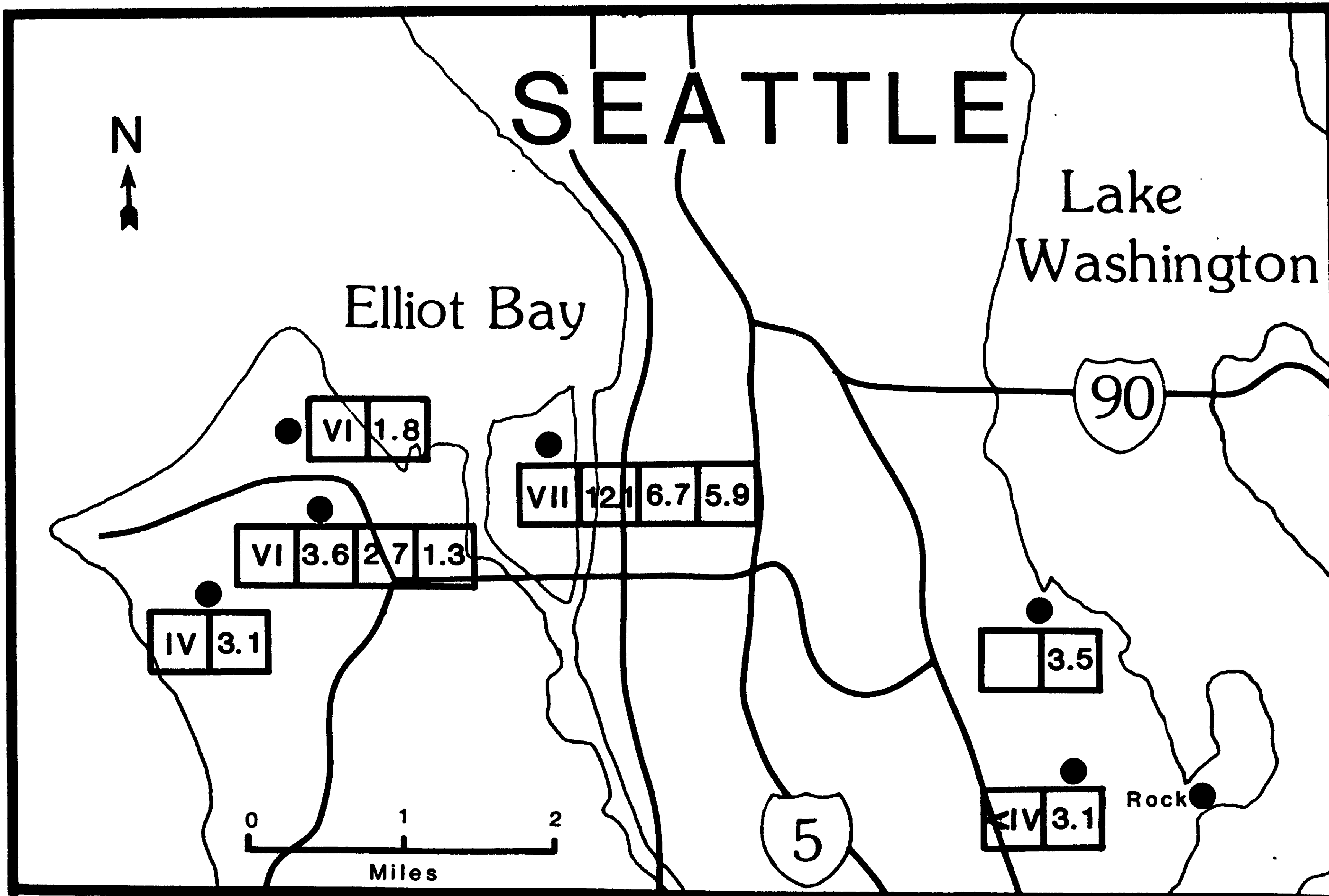

Figure 10. Stations of ground motion site response studies. Box 1 is Modified Mercalli Intensity. Boxes 2, 3 and 4 are Spectral Ratios of 0.5 to 2 Hz, 2 to 6 hz, and 6 to 10 Hz, respectively. Signal source is earthquake Q-3.

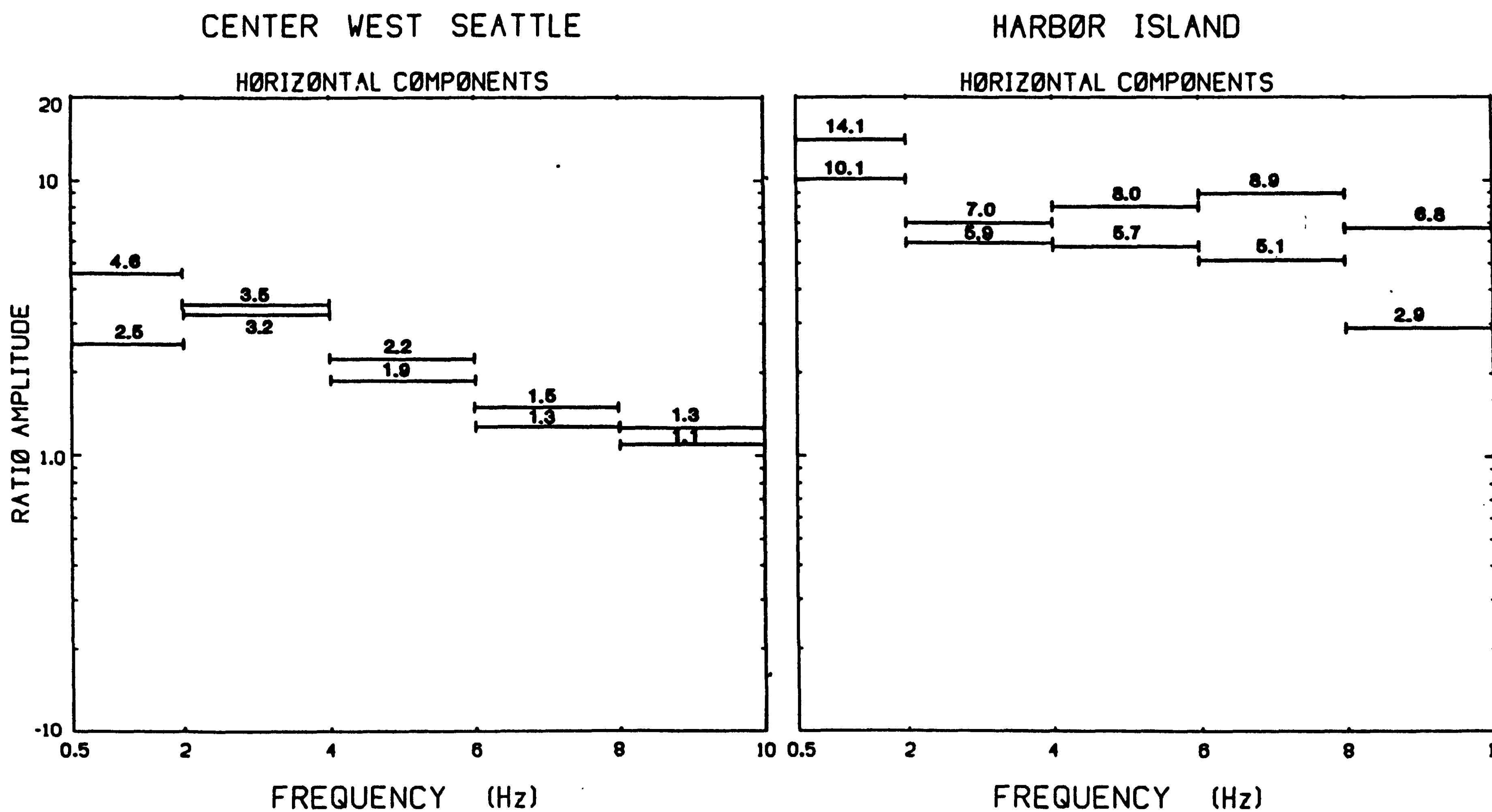

Figure 11. West Seattle spectral ratios from local microearthquake Q-3.

OVERVIEW OF EARTHQUAKE-INDUCED WATER WAVES IN WASHINGTON AND OREGON

by

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INTRODUCTION

In some settings water waves can cause greater loss of life and property damage than building collapse and all other effects of earthquake shaking combined. Such waves are generated in a variety of ways and are not necessarily confined to coastal areas. In addition to ocean-crossing tsunamis, landslide-generated waves and seiches may impact nearby shores in inlets, lakes, and reservoirs. In 1964, several Alaskan towns were devastated by landslide-induced waves within minutes of the earthquake. That same earthquake radiated tsunamis that impacted the Pacific Northwest hours later. Losses in the Pacific Northwest and along the California coast included 15 deaths and more than $100 million (1988) worth of damage. The 1964 event was the largest of the six tsunami recorded at the Neah Bay tide gage in the past 42 years. Memories of the 1964 events were still vivid enough in some areas along the Northwest coast to have spurred evacuation after the May 1986 earthquake in the central Aleutians.

Quake-induced water waves arrive at shores in many forms, but rarely as the huge curling breakers commonly portrayed by Hollywood. Tsunamis on open coastlines generally arrive as rapidly rising or falling tides; some of these have a much greater range than normal tides. The same tsunami, tide-like on an open coast, may form a "wall of water" or bore where it encounters a restricted channel in a bay or estuary. The rapid, and commonly large, rise or fall of water accompanying such waves creates strong currents. Such currents can drag ships at anchor and erode (scour) bottom sediments that support breakwaters and seawalls. Onshore, they are capable of carrying locomotives from their tracks or slamming logs, boats, and cars against structures. Damage from the impact of objects carried along by the waves is commonly much greater than the damage that would occur from the waves alone.

TSUNAMIS

Tsunamis Generated at Distance

Tsunamis capable of impacting distant shores are usually generated by abrupt vertical displacement of the sea floor during large subduction earthquakes. Because subducting plate boundaries are common along the Pacific Rim and relatively rare throughout most of the rest of the world, it is not surprising that "About 80% of all tsunamis occur in the Pacific Ocean" (Steinbrugge, 1982, p.234). Since such tsunamis have wave lengths much longer than the

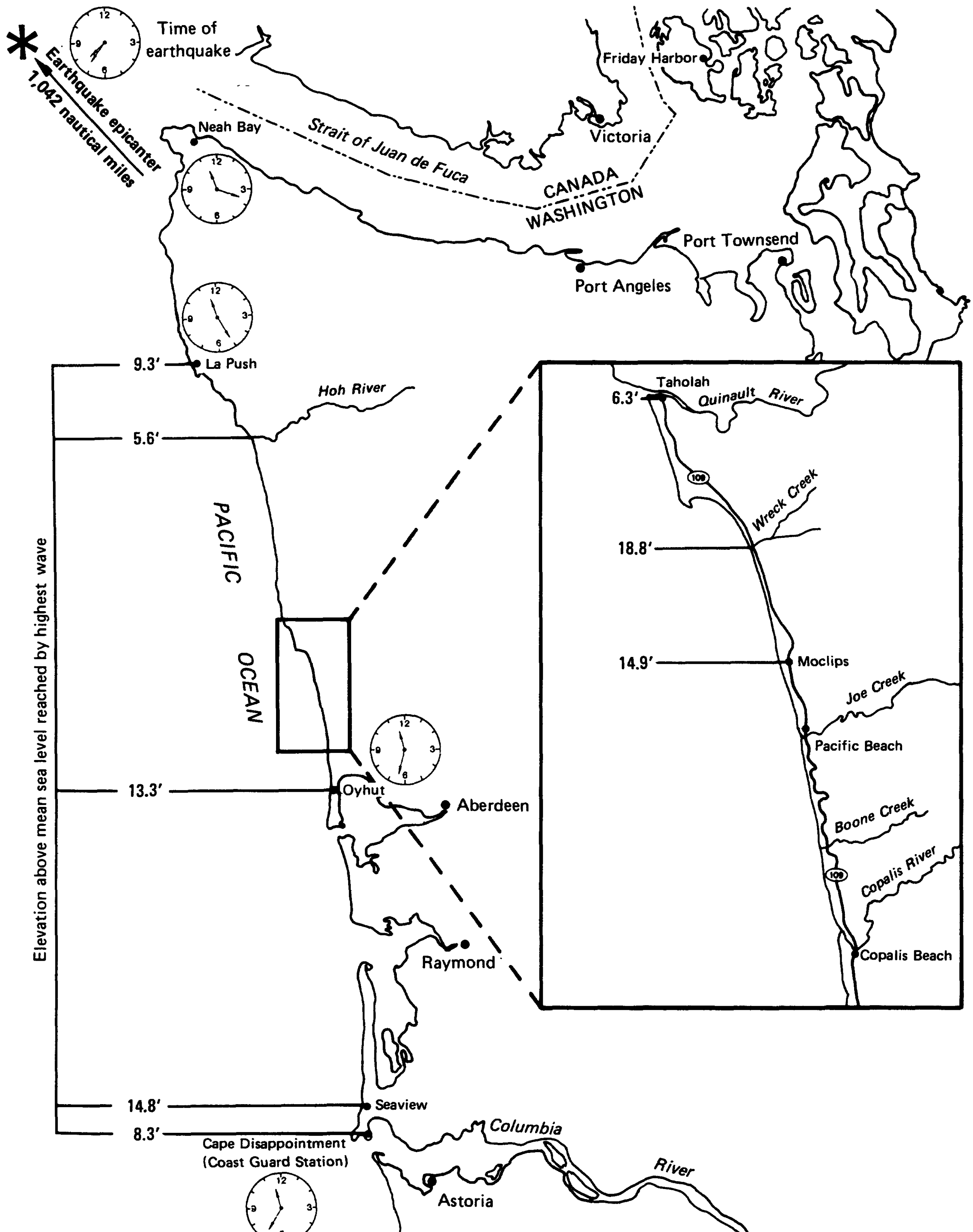

Figure 1. Clocks show time of 1964 Alaska earthquake and arrival of first tsunami along Washington coast (PST). Explanation, facing page (from Noson and others, 1988).

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La Push--Boats and floating dock broken loose, possible shoaling of channel.

Taholah--Crests below street level, no structural damage, loss of some nets and skiffs.

Wreck Creek--Debris on highway and bridge, washout of approach fills.

Moclips--Flooding one foot above ocean-front street, south end of town. Eight buildings damaged by drift logs or moved from foundation. Extensive damage to bulkheads and fills.

Pacific Beach--Dwelling* moved from foundation and destroyed, another building damaged.

Joe Creek--Logs and occupied home* slammed into bridge, three pile bents damaged or destroyed, two 20-foot spans lost.

Boone Creek--Debris on road, shoulder washout, dwelling flooded.

Copalis Beach--Damage to buildings, mobile homes.

Copalis River--Pile bents of bridge damaged, two bridge spans lost, others damaged.

Oyhut--Debris in yards and streets where dunes breached.

*(probably same structure, Joe Ck. ref. from Washington Highway News, v. 11, no. 5, p. 2).

Figure 1. (continued) Description of tsunami damage at indicated sites, 1964. Damage reports from Hogan and others (1964), unless otherwise indicated.

depth of the ocean, they act like shallow-water waves, even in depths of thousands of feet. Thus, wave fronts tend to curve toward shallows such as continental shelves or "wrap around" oceanic islands or seamounts. Such refraction is the reason that the wave fronts generated by the 1964 Alaska earthquake arrived from the west, reaching the Washington and Oregon coasts almost simultaneously (Wilson and Torum, 1972).

Coastal impacts

The report of tsunami damage along the Washington coast by Whipple (in Hogan and others, 1964), summarized in figure 1, emphasizes the vulnerability of development along the small estuaries just north of Grays Harbor). A similar damage pattern was experienced south of the Columbia River. Spaeth and Berkman point out (1972, p. 58) that "much of the damage in Oregon occurred away from the ocean front". Homes and businesses along estuary channels, as well as bridges, were severely damaged or destroyed in places. The size, shape, and depth of such estuaries apparently were the main factors in determining whether the tsunamis were propagated upstream or dissipated (Schatz and others, 1964). Development along the open ocean was generally protected by dunes (Hogan and others, 1964; fig. 2).

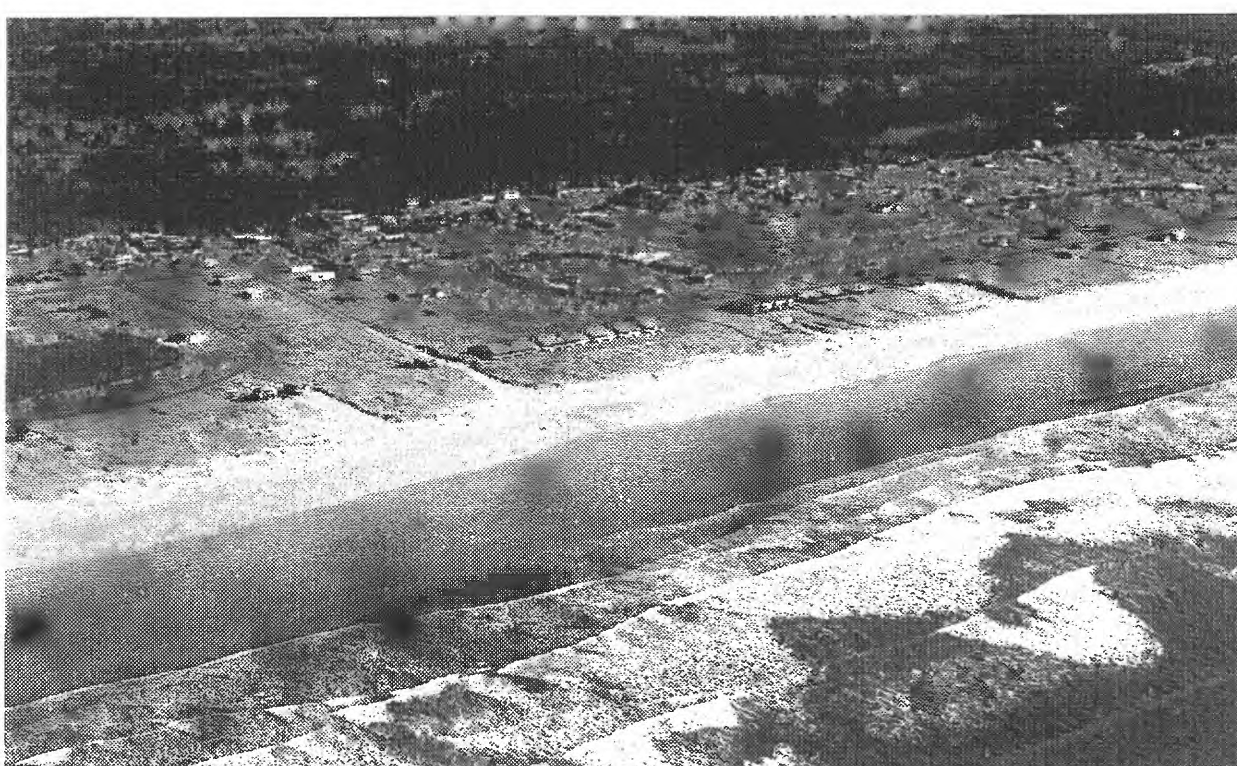

Figure 2. The dunes that protected much of Washington's south coast in 1964 were removed in places to improve views. Some of these gaps were being restored when this 1988 photo was taken.

The 1964 tsunamis were, in places, described as coming "with a terrible rush" without "any notification", and sending beach "logs flying around like toothpicks" (Aberdeen World, March 28, 1964, p. 1). In other places, such as at La Push, the waves were described as a gradual rise in the water level (Hogan and others, 1964). These seeming contradictions may be partially accounted for by the darkness, by the location of the observers, and by whether or not they were caught by surprise. No accounts of bore development were found. However, it is obvious that strong debris-laden currents had to be responsible for some of the damage, especially to bridges. Slow flooding and buoyancy forces alone could not have caused much of the damage described along the Oregon and Washington coastal estuaries.

Some appreciation of the possible velocity of tsunami-induced currents that March night, especially near the mouths of bays and estuaries, might be gained by considering normal tidal currents at the entrance to Grays Harbor. A "spring tide" drop of 10 or 11 feet on nearby ocean beaches can result in ebb currents approaching 5 knots at the entrance. This is with a high-to-high tidal cycle of about 12 hours. Compare this to the 1964 water level drop of about 14 feet (estimated) between tsunami crests 1 hour and 28 minutes apart at nearby Pacific Beach, or a drop of 11.9 feet between crests 1 hour and 15 minutes apart at Cape Disappointment (Hogan and others, 1964).

There are few accounts of scour (the erosion of bottom sediments by fast-flowing currents) and none of structural damage resulting from such scour along the Washington/Oregon coast. There seems little doubt, however, that tsunami-generated currents were responsible for the damage reported to oyster beds within Grays Harbor and Willapa Bay, even though such currents there would be substantially less than at harbor entrances. Predicted oyster losses from the 1964 tsunamis were as high as $900,000 over a period of years (Aberdeen Daily World, April 30, 1964). Abnormal currents also broke loose three log rafts at Aberdeen but apparently caused no other significant damage (Aberdeen Daily World, March 28, 1964).

In regard to the prediction of tsunami frequencies and runup elevations, Houston and Garcia (1978) include, in their deep-ocean and nearshore numerical models, coastline interaction and tidal statistics. In their predictions of 100-year and 500-year runups on the west coast of the continental United States they considered source areas in the Aleutian and Peru-Chile trench. They place considerable emphasis on source orientation and break the Alaskan area into 12 segments because tsunami "elevations produced on the west coast are very sensitive to the location of a source along the Trench" (p. 25).

The results of Houston and Garcia's computations for the Washington/Oregon coasts are generalized in Figure 3 and in another form in Houston (1979). Comparing these results with storm data for two Washington coastal counties, flood insurance consultants concluded that predicted levels of flooding by the 100-year tsunami are "lower than that caused by winter storms" (FEMA, 1985, p.25; 1986, p. 11). While this may be true in regard to relatively static water levels alone, it may not accurately portray the full hazard potential from tsunamis. Flooding caused by storm surge, even though to the same elevations, is not apt to cause the kind of damage that the multiple and relatively short-term water-level fluctuations of tsunamis can cause.

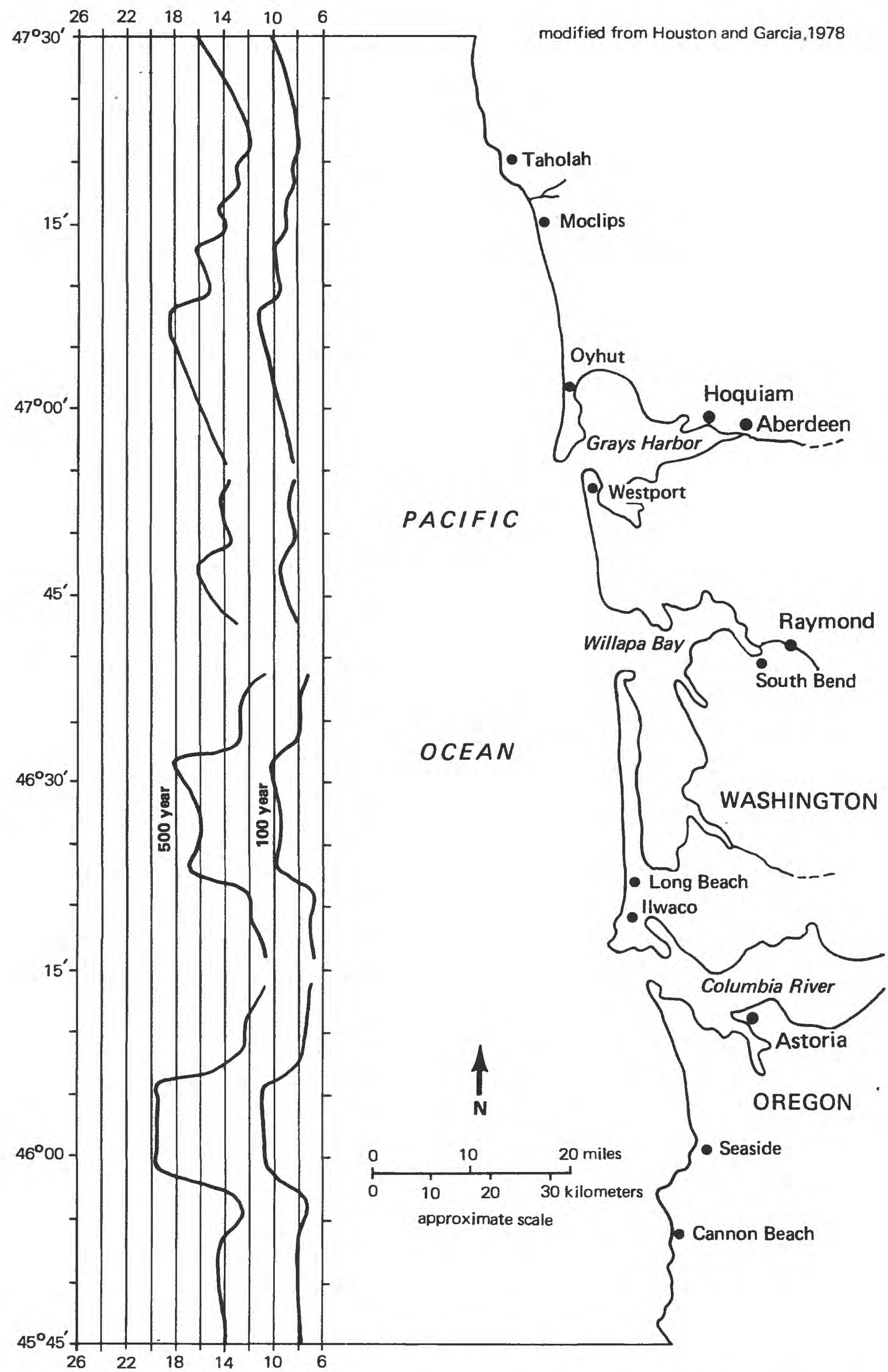

Figure 3. Computed 100-and 500-year tsunami elevations in feet above mean sea level.

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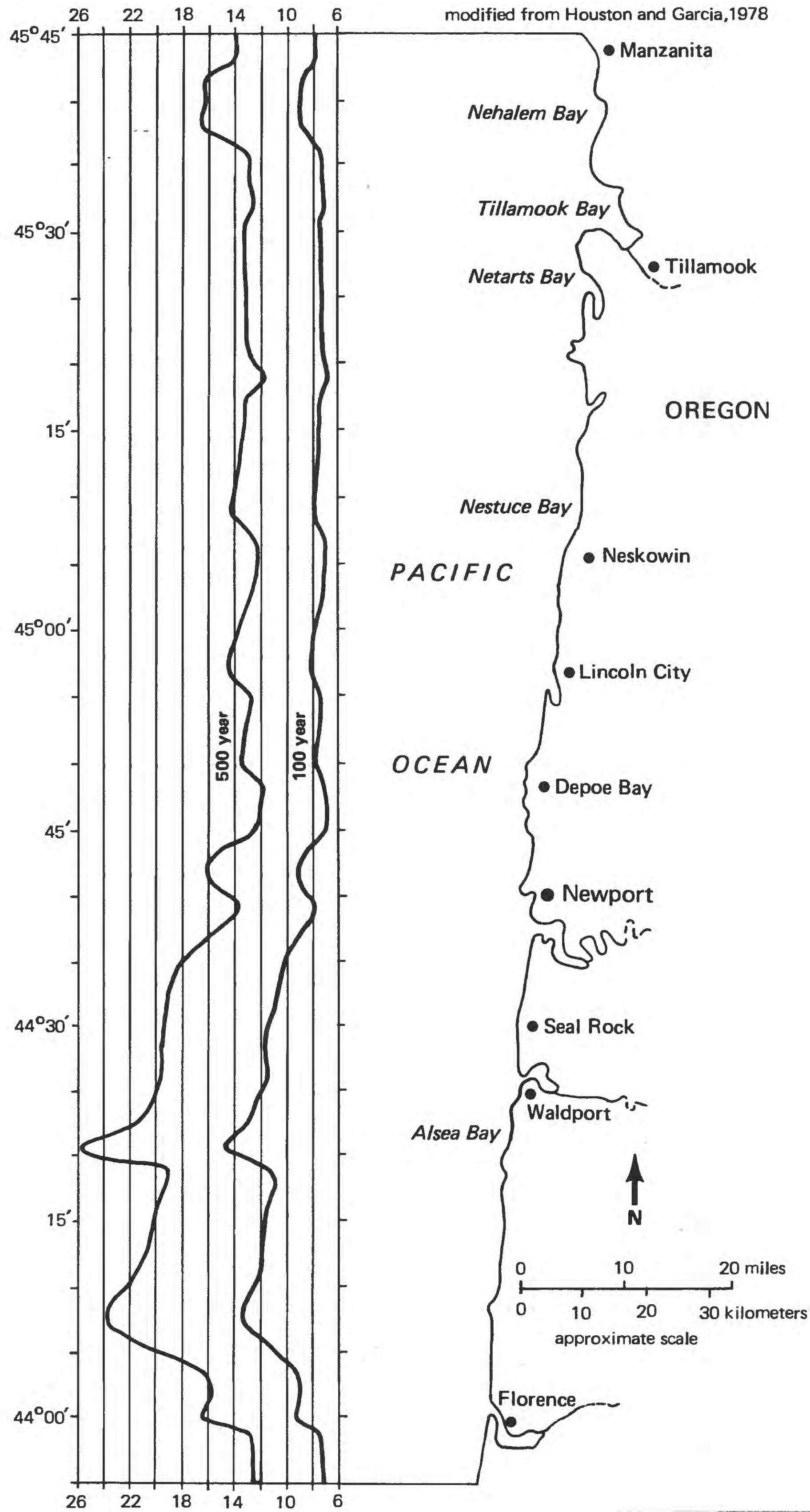

Figure 3. Computed 100-and 500-year tsunami elevations in feet above mean sea level.

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As previously discussed, strong currents generated by such fluctuations can cause major structural damage beyond that of flooding alone.

A study by Kowalik and Murty (1984) focuses specifically on the seismic gap in the Shumagin Island area of the Aleutians as a tsunami source. They cite research suggesting "the possibility of occurrence of a major earthquake within the Shumagin Gap in the next two decades" (p. 1243). Their computations of tsunami energy from such an event "shows strong directionality" towards Hawaii. Nevertheless, they calculate that a tsunami would arrive near the coast of Washington in about three hours. Its computed amplitude as a function of time at the mouth of the Strait of Juan de Fuca shows a pattern and magnitude similar to that of the arrival of the 1964 Alaska tsunami as it was recorded at the Neah Bay tide gage. Pruess (1986) discusses the potential impact of a "Shumagin Gap"-generated tsunami on the city of Aberdeen.

Impacts along inland waters

The attenuation of tsunamis generated by the 1964 Alaska earthquake as they progressed into more protected waters is shown in Figure 4. No reports of damage inside the entrance to either the Strait of Juan de Fuca or the mouth of the Columbia River were found in preparing this paper. It appears likely that few people on or near the water noticed the tsunamis; however, they were detected on tide gages as far inland as Pitt Lake, near Vancouver, B.C., at Seattle, Washington (Spaeth and Berkman, 1972), and on the Columbia as far inland as Vancouver, Washington (Wilson and Torum, 1972).

Garcia and Houston (1975) modeled 100- and 500-year tsunami runups for shorelines of the Strait of Juan de Fuca and for Puget Sound as far south as Tacoma. For this study they used tsunami sources along the Aleutian trench only and used the 1964 Alaska tide gage record at Neah Bay to calibrate the model. The computed runups, which included astronomical tides, were reported on segments of U.S. Geological Survey quadrangle maps (fig. 5). They considered "the simultaneous occurrence of a storm surge and tsunami .... highly improbable" and also did not include wind waves in their computations. In general, they found that:

> "...tsunamis waves in Puget Sound had small amplitudes, and runup values were governed largely by the effect of astronomical tides. Therefore, although waves had larger amplitudes at Port Townsend, Washington, than at Seattle, Washington, the greater tidal range at Seattle resulted in larger combined runup values there" (p. 14).

In comparing the Strait and Puget Sound with San Francisco and Monterey Bays, they found that resonance was not so much a factor in Puget Sound as was wave decay "along a narrow body of water".

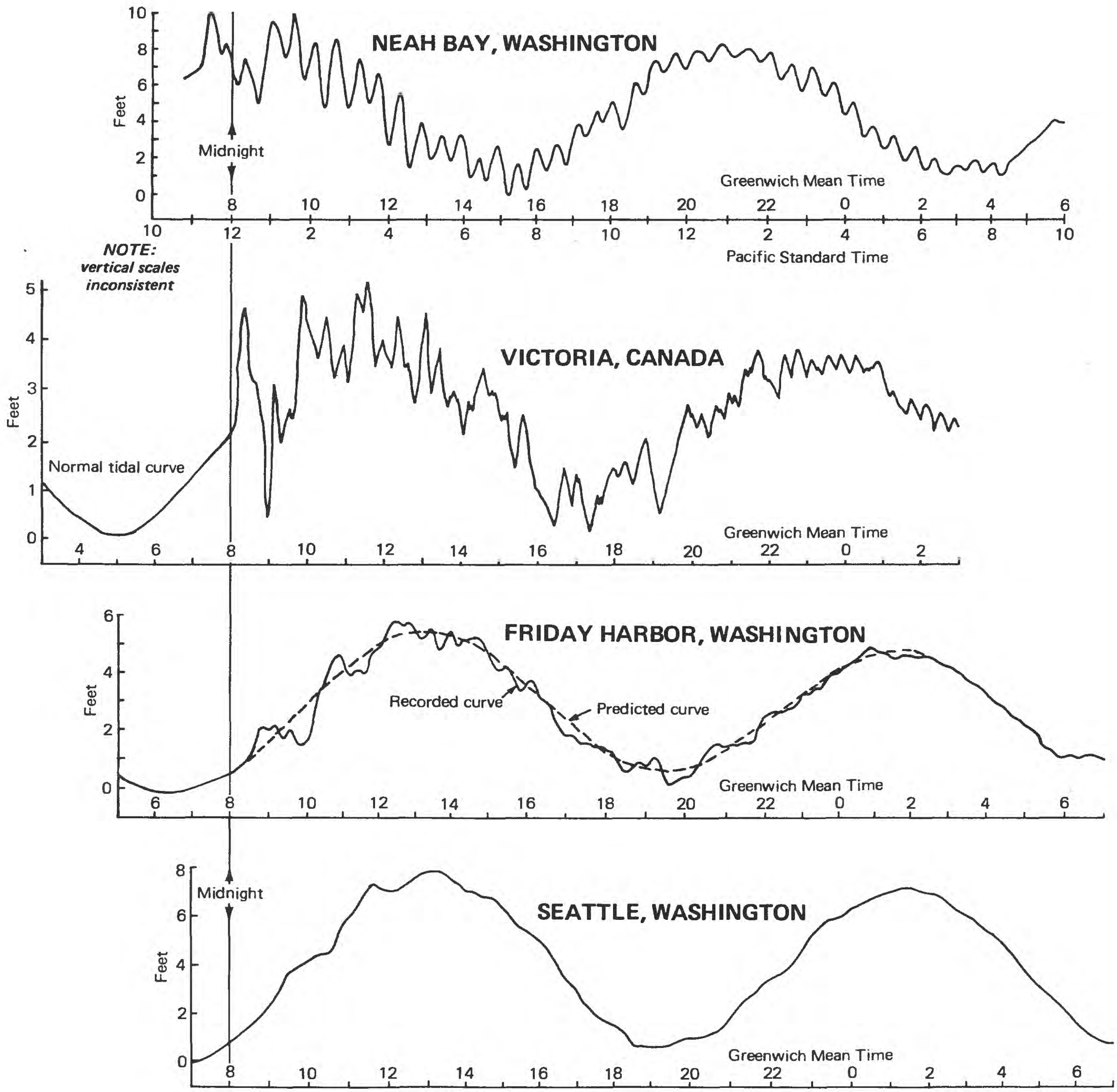

Figure 4. Tide gage records on March 27 and 28, 1964, showing tsunamis from Alaska earthquake. Superimposed on the normal tidal fluctuations with a 12-hour period are tsunami oscillations with a period of about a half an hour. Note time lag and wave attenuation as the tsunamis progressed into more inland waters (Modified from Spaeth and Barkman, 1972).

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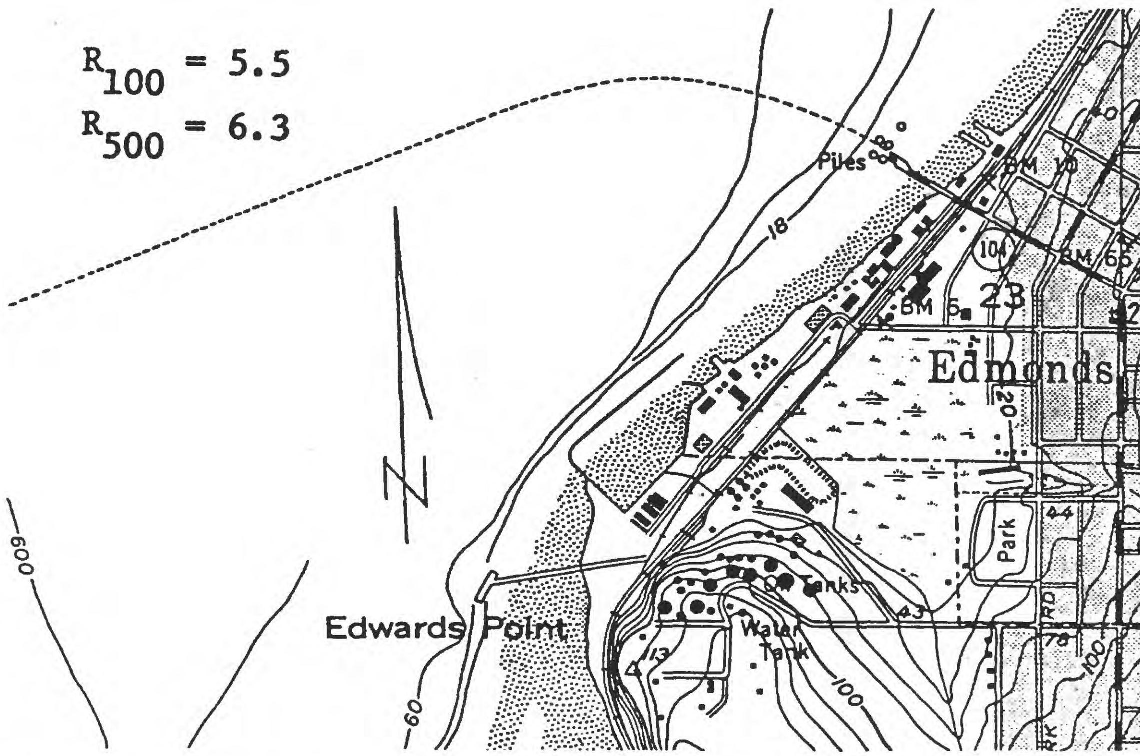

Figure 5. Map with computed tsunami runup values for a particular shoreline segment of Puget Sound R_{100} is runup in feet above mean sea level "That is equalled or exceeded with a frequency of once every 100 years". Note the elevations of benchmarks (From Fig. 121, Garcia and Houston, 1975).

Locally Generated Tsunamis

Seismic sea waves generated by a nearby offshore quake are apt to have significantly greater runups than waves from a remote quake of the same magnitude. An additional element of hazard is that they may strike within as little as ten minutes or so after the earthquake. Thus, the extended duration of shaking common to such quakes may be the first, and possibly only, warning of impending tsunamis to individuals along nearby shores. Evidence for such historically unprecedented earthquakes off the coast of the Pacific Northwest is summarized by Heaton and Hartzell (1987). Among the more compelling data discussed are geologic indications of repeated episodes of abrupt subsidence along the coast of Washington (Atwater, this volume).

Coastal impacts

Simply "scaling up" the impacts of the 1964 tsunami described earlier will not describe what to expect in the event of a major subduction earthquake along the coast of the Pacific Northwest. Even Houston and Garcia's 500-year runup predictions (fig. 3) will not be generally applicable (Houston, 1987, personal communication). Hebenstreit (1988) is currently addressing this problem with computer simulations of subduction quakes off the coast of Oregon, Washington, and Vancouver Island. In his simulations, source areas, fault rupture lengths, and fault displacement are being varied. The model used predicts areas of both uplift and subsidence. He points out (p. 552) that the model is "not capable of simulating runup on shore" but that "in all cases, given the shallow dip angle" of the fault used (10 degrees), "subsidence will occur on land". Any such subsidence would, of course, compound the impact of a tsunami.

Impacts along inland waters

The generation of tsunamis in inland marine waters of the Pacific Northwest is currently being studied by T. S. Murty (personal communication, 1988). He is examining the direct generation of water waves by earthquake motion rather than indirect generation such as by quake-triggered landslides. Murty's computer simulations assume three hypothetical earthquakes of magnitude 7.3, similar to the June 1946 Vancouver Island event. Epicenters were selected near Vancouver and Victoria, British Columbia, and Seattle, Washington.

Landslide-induced waves

Landslides into, as well as within, bodies of water can cause destructive water waves. Earthquakes can trigger both types of landslide. Like seismic sea waves, the waves are generated by the sudden displacement of water. In general, the larger the volume and the more rapid the displacement, the larger the waves. This is why some of the more spectacular water waves are created in areas of high relief adjacent to deep water, such as along fjords or glacially scoured lakes. The 1946 Vancouver Island earthquake (felt widely in Washington) triggered a rockslide into a lake near the center of the island that created a wave more than 80 feet high at the lake outlet (Evans, 1988). Numerous other landslides were triggered along lakes and inlets, causing beaches to disappear, underwater cables to break, and alluvial fans to slump. One such slump triggered a wave that drowned a man in a small boat (Rogers, 1980).

Landslides into water

The landslide into the Tacoma Narrows that was triggered by the 1949 Olympia earthquake (Shuster and Chleborad, this volume) created an 8-foot wave that caused minor damage to nearby docks. Washington's inland waters are lined with hundreds of miles of unstable bluffs such as border the Narrows. Historically, Puget Sound shoreline bluffs have not been particularly sensitive to earthquake-induced failures. This is in spite of the existence of horizons of potential liquefaction such as caused devastating landslides in Anchorage, Alaska, during the 1964 earthquake (James Yount, personal communication, 1983). A possible explanation might be that the duration of strong shaking of historic Puget Sound earthquakes has tended to be brief (less than 20 seconds) and the shaking of relatively short period (high frequency). Neither would be the case in the event of a major subduction quake such as devastated parts of Anchorage in 1964 and Mexico City in 1985.

One factor that tends to mitigate the hazard of landslide-induced water waves along Washington's inland marine waters is the almost universal existence of a wave-cut terrace fronting the bluffs. Such terraces are commonly wider than the bluff is high. Another mitigating factor is that dense beachlevel residential developments are uncommon and in only a few places directly face a nearby unstable bluff. Nevertheless, major fast-moving coastal bluff landslides, quake-triggered or not, could generate potentially hazardous waves, especially if they occurred during a high tide.

Possibly at greater hazard from waves induced by slides into water bodies are settlements along and downstream from deep lakes and reservoirs. One landslide into the reservoir behind Grand Coulee Dam created a wave 65-feet high (Jones and others, 1961). Fortunately, residential development along this and similar water bodies in such areas of western Oregon and Washington tends to be sparse. However, downstream populations are potentially vulnerable to waves that might overtop a reservoir impoundment. Washington has three stratovolcanos with reservoirs near their bases. The Columbia Gorge is another area of high relief, unstable slopes, and a reservoir. The U.S. Army Corps of Engineers has carefully examined slides in this area in relation to the raising of the reservoir behind Bonneville Dam.

Underwater Landslides

Massive submarine landslides caused much of the damage during the 1964 Alaska quake. These slides commonly included adjacent shorelands with port and industrial development. The slides created "backfill waves" as water rushed to fill the void created by the downward drop of the head of the slide, as well as "far-shore waves" created by displacement of water by the slide toe (McCulloch, 1966). Only one such essentially subaqueous slide has been reported from damaging Puget Sound earthquakes. This was the collapse of a sandspit near Olympia during the 1949 earthquake (Murphy and Ulrich, 1951), and it apparently did not cause a damaging wave.

Among the more likely sites for subaqueous earthquake-triggered ground failure, deltas have apparently not failed during historic Puget Sound earthquakes. The massive collapse of the Nisqually delta (University of Washington Department of Geology, 1970) apparently occurred prehistorically and may or may not have been quake-triggered. Historic slides from the Puyallup delta, such as occurred in 1943 (University of Washington, Department of Oceanography, 1953) apparently have not been earthquake-triggered.

Other subaqueous deposits that are potentially capable of mobilization by earthquakes front many of the shoreline bluffs of the Puget Lowland. These deposits, eroded during the development of the adjacent bluffs and wave-cut terraces, are now poised on submarine slopes below tidal level. In some areas they are quite extensive and may locally be thick enough to experience massive failure during seismic shaking (M.L. Holmes and R.E. Sylwester, personal communication, 1988). Major failures of such material could cause destructive water waves as well as disrupt submarine cables or sewer outfalls.

Landslides impounding water

Landslides into narrow valleys commonly dam streams. Such landslide dams may fail catastrophically when overtopped by the impounded lake, creating "waves", "walls of water", and/or flooding for great distances downstream. Concerns about the hazards of such an event necessitated quick action by the U.S. Army Corps of Engineers following both the 1959 Hebgen, Montana, earthquake and the 1980 earthquake and accompanying eruption of Mount St. Helens. Both events created major landslide dams, requiring prompt action to develop drainage structures capable of controlling or preventing overtopping of the dam.

Seiches

Seiches, or mass oscillations of enclosed or semi-enclosed bodies of water, may be triggered directly by earthquake vibrations. These seiches are caused by the land surface waves of the quake and may occur far from the epicenter. Seiche amplitude is dependent on the amplitude of earthquake surface waves and their similarity to the natural periods of oscillation of a particular body of water (Houston, 1979). Seiches may also occur when a body of water is abruptly tilted by the same tectonic deformation that caused the accompanying quake. Such seiches accompanied the August 1959 magnitude 7.1 Hebgen Lake earthquake near Yellowstone Park. This shallow (10 - 12 km) earthquake was accompanied by extensive surface faulting and ground elevation changes as great as 19 feet (Murphy and Brazee, 1964). It caused seiches on Hebgen Lake, in the epicentral area, that repeatedly overtopped the impounding earthfill dam (Stermitz, 1964).

Long-period surface waves from a large earthquake can travel great distances. The 1964 Alaska earthquake generated seiches on 15 bodies of water in Washington State, 17 in Oregon, many in the U.S. Gulf States and others as far away as Australia (McGarr and Vorhis, 1968). Most of these were too small to be detected except on sensitive recording water level gages. The seiches on Lake Union in Washington were large enough to cause minor damage to pleasure craft, houseboats, and floats along the shore, and jostled two U.S. Coast and Geodetic Survey ships (Wilson and Torum 1972). The 1949 Queen Charlotte Islands quake generated seiches in Lake Washington and Lake Union, as well as at least two lakes in eastern Washington. Bead Lake north of Newport and Clear Lake near Cheney were reported to have had "strong wave action .... pulling boats loose from docks and leaving many fish on beaches" (Murphy and Ulrich, 1951, p. 28). Other seiches have been reported as long ago as 1891 when "Lake Washington .... was lashed into a foam, and the water rolled onto the beach .... eight feet above the present state" (Bradford, 1935, p. 142). There no doubt have been others that have gone unreported.

Historic earthquakes in Washington and Oregon apparently have not developed significant long-period surface waves or been accompanied by vertical displacement at the surface. However, Atwater (this volume) suggests that coastal Washington has experienced repeated abrupt subsidence, the last such event as recently as 300 years ago. As mentioned earlier, Hebenstreit's computor model predicts just such motion. In addition, there is a surface fault with 3.5 meters (11 feet) of movement (mostly vertical) about 5 km

(3 mi) NE of Cushman Dam in the Olympic Peninsula. This fault apparently experienced its major movement about 1,240 years ago (Wilson and others, 1979). Either type of faulting could be accompanied by long-period surface waves or surface tilting, both potential intitiators of seiches.

SUMMARY

The Pacific Northwest includes many settings with potential for destructive water waves. Earthquakes, both distant and local, significantly increase the potential for triggering such waves. The written history of the region is too short to define what is geologically "normal", as indicated by the recent catastrophic eruption of Mount St. Helens.

The accumulating evidence for subduction earthquakes along the Pacific coast suggests that the area could be subject to seismic activity more capable of triggering the whole spectrum of water waves than historic earthquakes have been. Thus, it behooves local governments, emergency planners, and individuals to recognize water waves as an important component of earthquake hazard.

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SEISMIC HAZARD FROM INTRAPLATE EARTHQUAKES IN THE PUGET SOUND REGION

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Although much attention has been focused on the possibility of a large subduction earthquake, the known hazard due to moderate sized intraplate earthquakes along the Puget-Willamette depression must not be neglected. There is much uncertainty about the possible source location, source sizes, and existence of subduction earthquakes. None have been documented from instrumental data. On the other hand, several moderate to large subcrustal earthquakes have occurred since the availability of adequate instrumental data. Rasmussen and others have estimated a mean return period of 110 years for magnitude 7.0 earthquakes and 330 years for magnitude 7.5 earthquakes for the Puget Sound region. The central and south Puget Sound region seems to be a particularly active source region for such earthquakes. We know this region is capable of generating earthquakes in the magnitude range 7.0 to 7.5 at depths of 50 to 60 km beneath major population centers of western Washington.

Until very recently, the cause of these subcrustal earthquakes was basically unknown except that they were generally believed to lie within the subducted plate. Recent progress in understanding the structure of the subducted plate may provide clues as to why the southern Puget Sound region is an important source area. A recently postulated arch in the subducted plate plunging gently to the east has its southern limb near the source zone. Bending stresses induced as the plate adjusts to this arch structure in the process of subduction may contribute to the localization of seismic hazard in south Puget Sound. If such a model is correct, then we can expect a higher incidence of damaging earthquakes in this region relative to other parts of the Puget-Willamette trough. Further observational and theoretical work must be done in modeling the details of plate structure and stress within this zone to fully understand the earthquake hazard.

POTENTIALLY DAMAGING WAVES ASSOCIATED WITH EARTHQUAKES, COASTAL WASHINGTON

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POTENTIALLY DAMAGING WAVES

Low-lying coastal areas are subject to inundation by several kinds of waves; some of the most damaging are waves associated with tectonic events, i.e., seiches and tsunamis. Other damaging waves include storm surges and unusually high tides. In evaluating earthquake hazard and risk in the present, we are concerned with predicting the behavior of tsunamis and seiches; in attempting to reconstruct past events, we are concerned with distinguishing the effects of seiches and tsunamis from the effects of storms and unusually high tides.

In addition, it would be useful to distinguish among the effects or record of a) seiches, periodic sloshing in a basin, commonly started by sudden ground motion, also by ground shaking; b) far-travelled tsunamis generated by distant tectonic displacements, e.g., in Japan or Alaska, or by submarine slope failure (commonly associated with earthquakes), or by major volcanic explosions (e.g., Krakatau); and c) tsunamis generated by local tectonic displacements, i.e., great-subduction earthquakes in the Cascadia subduction zone. Cases (a) and (c) will involve local ground motion, potentially both regional subsidence or uplift and ground shaking. Regional subsidence will make the coast more susceptible to damaging waves. Also, case (a) could occur with virtually no warning time; in case (c), only tens of minutes would be available to prepare for the incoming wave, whereas in case (b), there would be a few hours before the wave arrived.

DISTINGUISHING THE RECORD OF DAMAGING WAVES

Atwater (1987) has used postulated tsunami-generated sand layers as one of his most persuasive arguments for past great-subduction earthquakes in the Pacific Northwest. The stratigraphic evidence tends to support his hypothesis--these fine-grained sand layers are found above and only above rapidly drowned, nearly supratidal marsh deposits of Holocene age. The one he (and we) have studied in most detail is a maximum of 10 cms thick, tends to thin and disappear upstream, and comprises planar-laminated sand, in most cases as couplets with mud (Reinhart and Bourgeois, 1987). The planar lamination indicates that these sediments were deposited from suspension.

Our goal is to identify the depositional mechanism for these sandy layers, by rigorous sedimentological analysis. In the process, we will develop models for distinguishing deposits of various damaging, large waves in coastal areas. Possible mechanisms considered include: a) deposition by river flooding, which we have eliminated based on several lines of evidence (Reinhart and Bourgeois, 1987); b) deposition during a storm surge, potentially coinciding with spring high tides; c) deposition from seiching generated by subsidence due to a local rupture; and d) deposition by earthquake-generated tsunami waves--these tsunamis could be locally generated (at the Cascadia subduction zone) or far-travelled. Each of these processes is well enough understood to make some predictions regarding the characteristics of the deposit.

Deposition by storm surge. The sand layers in Holocene estuarine sequences in coastal Washington and Oregon are found deposited above peats associated with nearly supratidal flats (e.g., Atwater, 1987); these areas are commonly submerged during storms, particularly when the storms are associated with high tides, or spring high tides. The source of the sand would be the sandy tidal flats of the estuary, i.e., the same source as that for a tsunamigenic wave. Thus distinguishing a layer deposited by a storm surge requires modeling the waves generated by these two processes and considering their ability to tansport sand some distance from its source. By modeling the storm surge, we should also be able to predict the thickness and sedimentary structures of a storm surge deposit. If the water is shallow enough, and the wind-generated waves large enough, boundary shear stresses high enough to generate planar lamination could be reached. As the storm wanes, however, we would expect to see wave-generated (symmetrical) ripples within the deposit.

Deposition by a seiche. A small rupture along a local fault, or a great rupture in the Cascadia subduction zone, could generate local subsidence on the scale of a meter, and this subsidence would generate a wave in Willapa Bay (for example) which could be reflected both across and along the bay. This wave would also erode and redeposit sand from the sandy tidal flats and redeposit this sand at higher elevations. Hence we must consider the behavior of a seiche generated under such conditions and predict the microstratigraphy it would produce. The height of the seiche would be on the same scale as the amount of subsidence and (given an average depth of 5 m, a gross estimate), would travel at a velocity of on the order of 5-7 m/sec. Given bay width and length (=seiche wavelength) on a scale of 10-20 km, the seiche would have a period on the order of 1000-4000 sec, and the particle velocity would be approximately 1/10th of the wave velocity, or 50-70 cm/sec. This velocity is sufficient to produce shear stresses and hence turbulent diffusion coefficients capable of suspending sand throughout the water column; but in fact it is also sufficient to generate high shear stresses on the bottom of the bay, which in addition because of its shallowness would dissipate the seiche within one or two periods. This crude analysis predicts that a maximum of two laminae (probably only one) could be deposited on the marsh by a seiche; a more rigorous analysis, in conjunction with structural and stratigraphic studies, would serve to rule out (or support) the seiche depositional mechanism.

Deposition from a tsunami (locally or distally generated): The wave or waves genrated by a tsunami typically have heights in shallow water of meters (locally to 10s of m) and periods of on the scale of 10s of min to an hour. As they approach the coast they will generate a surge similar to a storm surge except on a shorter time scale and typically with greater amplitude; thus sustained unidirectional velocities and boundary shear stresses are greater than in a storm surge or (true) tidal wave, and it is expected that these surges could transport sand in suspension for greater distances than could a storm surge or tidal wave. As with the storm surge and seiche, the source for this sand would be the sandy tidal flats, so distinguishing these deposits requires us to model the process and predict the grain size, thickness and sedimentary structures that could be generated during such an event. Once we understand the relationship between a tsunami surge and its resulting deopsits, we can postdict and predict the behavior of a given tsunami which has attacked or will attack the coast. Although this methodology probably will not distnguish a locally generated tsunami from a distally generated one, the stratigraphic context of the sand layers should reveal whether or not their deposition approximately coincided with rapid subsidence. Also, the geographic extent of the layer, and the magnitude of the postulated tsunami, may help to determine the scale of the postulated rupture in the Cascadia subduction zone, and hence the magnitude of the associated earthquake.

VERIFICATION OF SEDIMENTOLOGIC INTERPRETATION BY USE OF KNOWN TSUNAMIGENIC DEPOSITS

The sedimentologic and fluid-mechanical approach we are taking provides a powerful technique with which to test the tsunami hypothesis. However, the depositional model produced from this technique must be verified by observing known tsunami deposits and by applying the model to them. In spite of the historically recent great-subduction-earthquake-generated tsunamis affecting the coastal lands of Japan (1944, 1946), Chile (1960) and Alaska (1964), as well as coasts more distant to the earthquake, little is known about the sedimentologic characteristics of these deposits (if, indeed, sediment was deposited); and to our knowledge, there exists no sedimentological model of a tsunami deposit.

We have proposed to examine sediments known to have been deposited by a tsunami associated with a great-subduction earthquake. The objectives of this work are: 1) to provide a physical description of the microstratigraphy, geometry and distribution of sediments deposited by a known tsunami, and 2) to verify the techniques we are using in our work in the Pacific Northwest. Four localities have been considered for this work: Alaska; Crescent City, CA; Japan; and Chile. Our criteria for choosing a field area were:

1) a documented record of co-seismic subsidence (satisfied in Alaska, Japan, Chile),

2) the existence of estuarine environments that experienced such subsidence (Alaska, Japan, Chile esp.),

3) a record of the number of tsunami waves, their wave heights (amplitudes), periods (i.e., time separating each wave arrival), angle of arrival, and wave speed (Alaska, Crescent City, Japan, Chile), and

4) a documented account of tsunamigenic sedimentation and its location (Chile).

In our search for tsunamigenic deposits, we have found that only central Chile, site of the 1960 earthquake of Mw 9.5, can provide a documented account of tsunamigenic sedimentation (Wright and Mella, 1963). Although there are some differences between the size and geometry of Chilean estuaries and Willapa Bay, the overall setting of the two coasts is similar, and the application of generalized expresssions of physical sediment-transport should provide good results.

PREDICTED RESULTS

Our study is testing a key corollary of the great-earthquake hypothesis for the Pacific Northwest. In the course of testing the tsunami hypothesis, we will learn much about the hydraulics of surges from which the sand layers settled. This study will also represent the first detailed description and analysis of known tsunami-generated deposits, thus having potential application in paleoseismic studies in other tsunami-susceptible regions. If we confirm that the sand layers in coastal Washington (and Oregon) were deposited by tsunamis, then we will have obtained estimates of the velocites and run-up heights attained by Holocene tsunamis from great Cascadia earthquakes. Such information would have great value to land-use and emergency-management officials, and would also find application in the calibration of mathematical models of tsunami run-up.

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EARTHQUAKE-INDUCED GROUND FAILURE IN WESTERN WASHINGTON

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INTRODUCTION

Ground failure is generally regarded as a permanent disruption of geologic materials at the ground surface. For this paper, we will consider earthquake-induced ground failure to include: (1) slope failures (landslides) on moderate to steep slopes, (2) surface disruption or settlement due to soil liquefaction, and (3) minor surface cracking. These types of earthquake-induced ground failure destroy or damage residential and industrial structures and transportation facilities; in addition, earthquake-induced landslides have caused great numbers of casualties and severe negative impacts on agricultural and forest lands and on the quality of water in rivers and streams.

Several catastrophic examples of earthquake-induced ground failure can be cited. In 1920, as many as 100,000 people were killed by earthquake-triggered loess landslides in Gansu Province, China (Close and McCormick, 1922; Varnes, 1978). In 1949, a M 7.5 earthquake in the Tien Shan Mountains of Soviet Tadzhikistan triggered a series of massive slides and debris flows that buried some 33 population centers, killing from 12,000 (Jaroff, 1977) to 20,000 (Wesson and Wesson, 1975) residents. Youd (1978) estimated that ground failure caused 60 percent of the $300 million total damage from the 1964 Alaska earthquake. Ground-failure (primarily due to liquefaction) damage from the 1964 Niigata, Japan, earthquake was estimated at $800 million (Lee and others, 1977). In 1970, a M 7.75 quake off the coast of Peru triggered a debris avalanche on the slopes of Mount Huascaran in the Cordillera Blanca, burying the towns of Yungay and Ranrahirca and killing more than 18,000 people (Plafker and others, 1971). In March 1987, landslides (and associated floods) triggered by a M 6.9 earthquake in eastern Ecuador killed an estimated 1,000-2,000 people; destruction of 16 miles of the TransEcuadorian oil pipeline by these landslides and floods resulted in economic losses totaling about $1 billion (Crespo and others, 1987).

Ground failures due to historic earthquakes in western Washington have resulted in only a few deaths, but have caused significant damage over large areas (Hopper, 1981; Keefer, 1983; Grant, 1986). The 1949 Olympia earthquake scattered ground failures over an area of approximately 11,000 mi^2 (fig. 1), and the 1965 Seattle-Tacoma earthquake triggered ground failures within an area of about 8,000 mi^2 (fig. 2).

This paper discusses the types and distribution of ground failure that have occurred due to historic earthquakes in western Washington, with emphasis on landslides and on ground failures resulting from liquefaction, which are the types that have caused the greatest amounts of damage. In addition, it briefly reviews studies planned by U.S. Geological Survey scientists and engineers relating to earthquake-induced ground failure in the area.

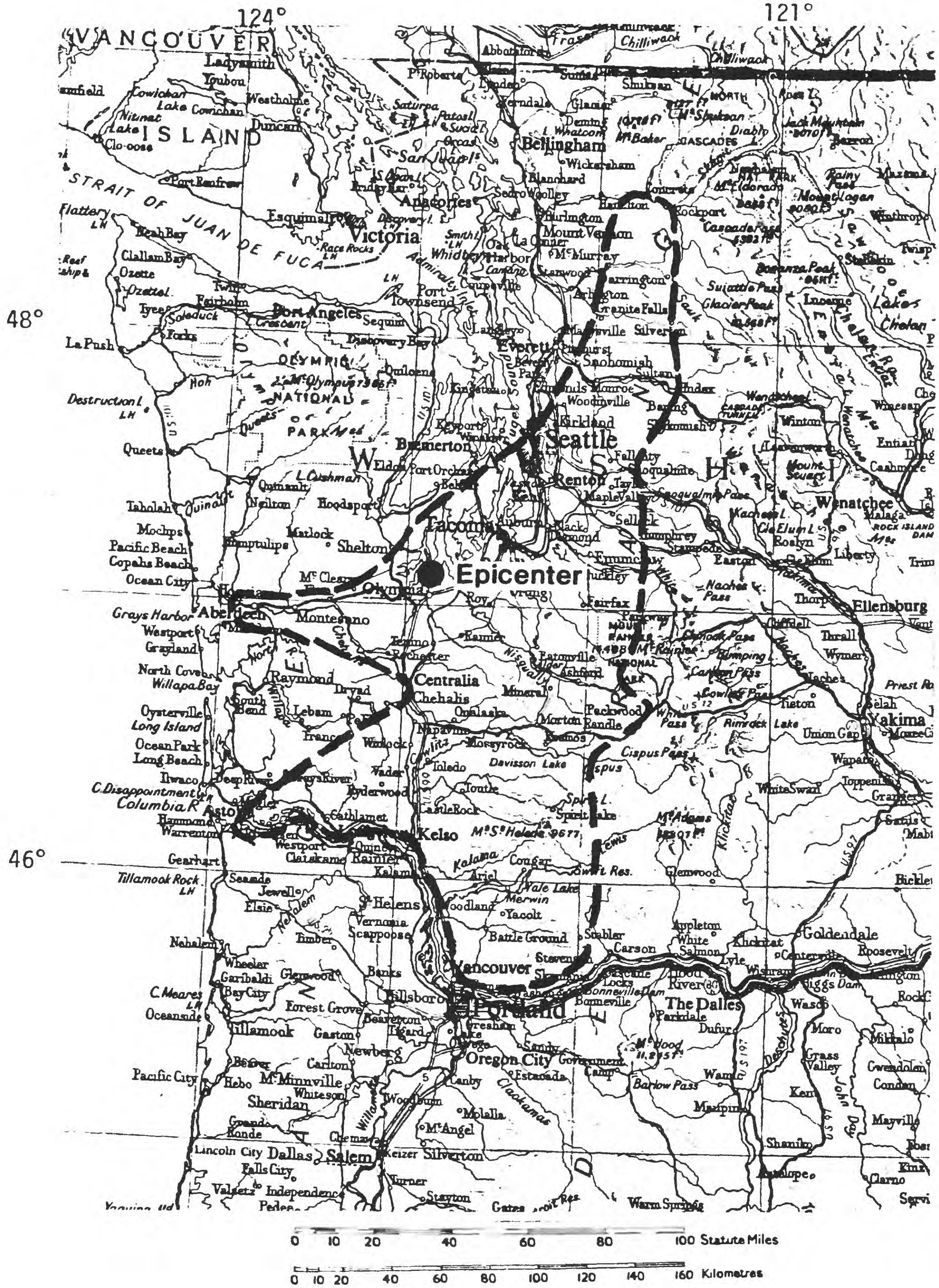

Figure 1. Area within which ground failures were reported for the April 13, 1949, Olympia earthquake (modified from Keefer, 1983).

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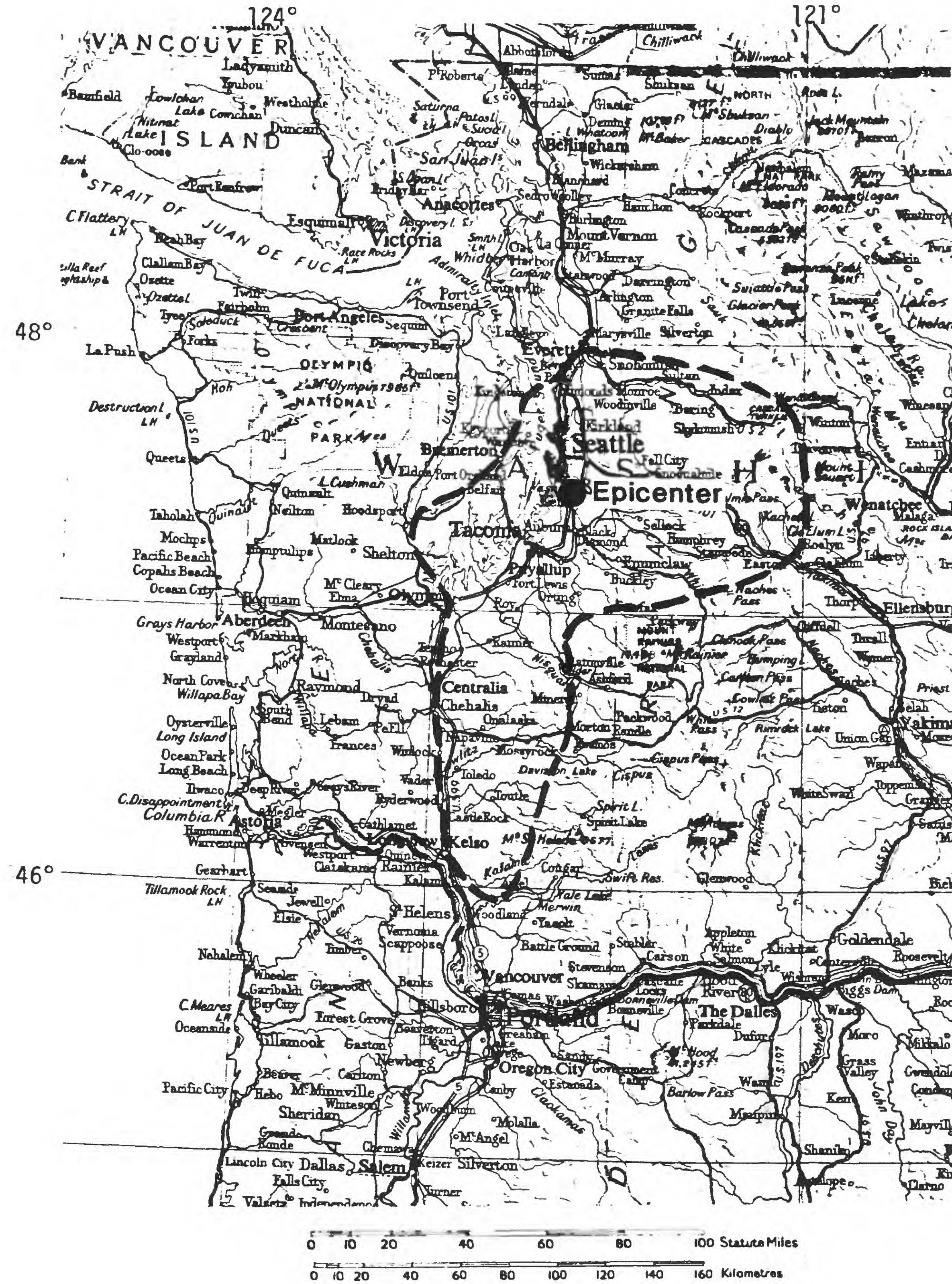

Figure 2. Area within which ground failures were reported for the April 29, 1965, Seattle-Tacoma earthquake (modified from Keefer, 1983).

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SLOPE FAILURES (LANDSLIDES)

Keefer (1984) has documented data on slope failures caused by 40 major earthquakes in many parts of the world. His studies have shown that the most abundant types of earthquake-induced landslides have been rock falls and soil and rock slides. The greatest losses of life have been due to rock avalanches, rapid soil flows, and rock falls. According to Keefer's study the smallest earthquakes that cause specific types of landslides are as follows: (1) M 4.0: rock falls, rock slides, soil falls, and disrupted soil slides; (2) M 4.5: soil slumps and soil block slides; (3) M 5.0: rock slumps, rock block slides, slow earthflows, soil lateral spreads, rapid soil flows, and subaqeous landslides; (4) M 6.0: rock avalanches; and (5) M 6.5: soil avalanches.

As noted by Noson and others (in press), 14 earthquakes triggered landslides in the State of Washington between 1872 and 1980. The greatest landslide activity was recorded as a result of the M 7.1 Olympia earthquake of April, 13, 1949, which had a focal depth of 40 miles (Nuttli, 1952). Landslides occurred as far as 110 miles from the epicenter (Keefer, 1983). The largest landslide (volume: about 650,000 yd^3) occurred in a section of sand and gravel that overlies clay in a bluff forming the eastern shore of the Tacoma Narrows (fig. 3). Many smaller landslides occurred from Seattle south to Portland. Although Keefer's (1983) review of published accounts noted a total of only 23 landslides triggered by the 1949 earthquake, current studies by the authors indicate that the number of landslides was considerably under-reported at the time of the quake. In the Cascade Range, these slope failures consisted primarily of rock falls and rock slides. In the Puget Trough (lowlands from Puget Sound to the Willamette Valley of northern Oregon), numerous minor soil and rock slides and slumps occurred. Many of these occurred in fills and cuts situated in highway and railroad corridors. These failures were particularly common where the corridors were located along the shores of rivers or lakes. Sidehill embankments often failed at the contacts with their foundation slopes. Downslope movement in such failures ranged from only a few inches to tens of feet. Most of the failed embankments were brought back to grade by maintenance crews soon after the earthquake.

The 1965 M 6.5 Seattle-Tacoma earthquake caused significant landslide activity in the Puget Sound area. Utilizing published accounts, Keefer (1983) noted 24 individual landslides located as far as 60 miles from the epicenter. As was the case for the 1949 earthquake, recent study by the authors indicates that landslide occurrences were significantly under-reported at the time of the quake. There were no large landslides, such as the 1949 Tacoma Narrows slide, but there were many small slips and slumps. As was the case for the 1949 earthquake, slope failures in fills and cuts of transportation corridors were common (figs. 4 and 5).

Much of the damage related to the 1980 eruption of Mount St. Helens was caused by a rockslide/debris avalanche (fig. 6) triggered by a M 5 earthquake associated with the eruption. This 0.62 mi^3 landslide (the world's largest historic landslide) swept some 14 mi down the valley of the North Fork Toutle River, destroying public and private buildings, State Highway 504, U.S. Forest Service and logging company roads, and several bridges (Schuster, 1983).

Figure 3. The April 16, 1949, landslide at the Tacoma Narrows. This landslide is considered to have been triggered by the Olympia earthquake, which occurred 3 days before the slide (Vogel, 1949). (Photograph by permission of Associated Press.)

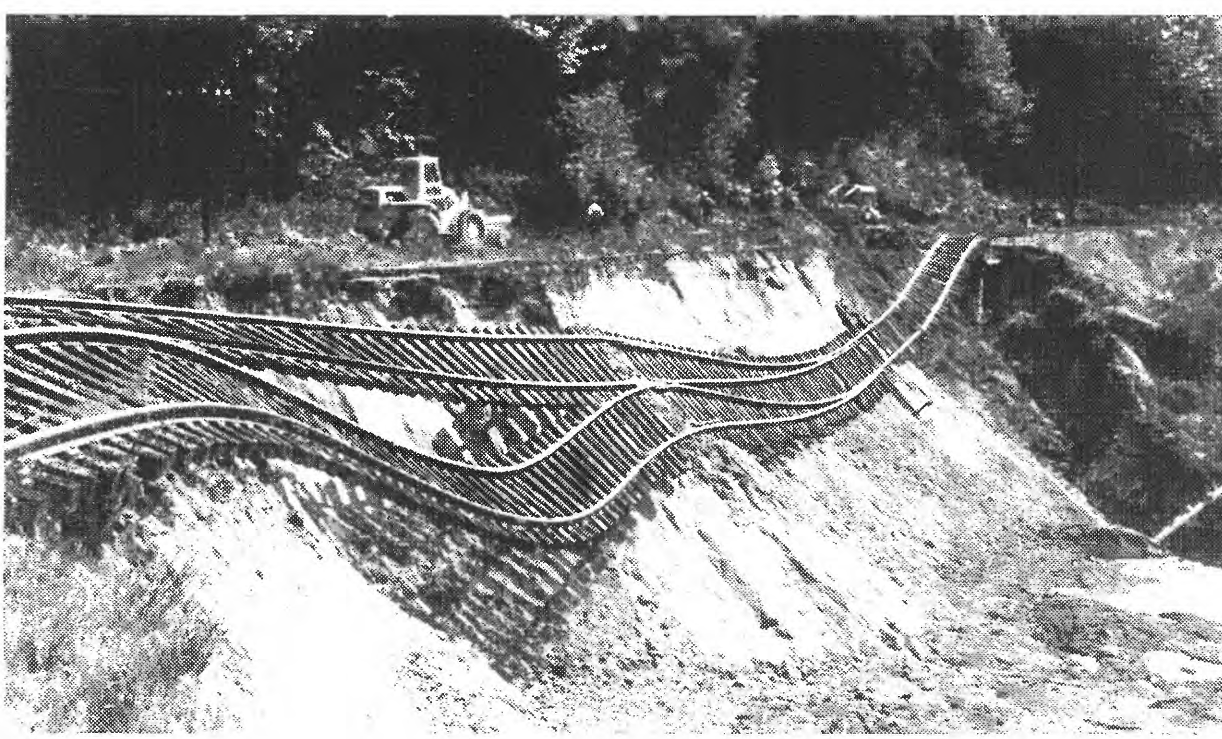

Figure 4. Damage to Union Pacific Railroad tracks in Olympia due to the 1965 Seattle-Tacoma earthquake. (Photograph by G. W. Thorsen, Washington Department of Natural Resources, Division of Geology and Earth Resources.)

Figure 5. Damage to Deschutes Parkway, Olympia, due to the 1965 Seattle-Tacoma earthquake. The Parkway was constructed on granular fill placed on tidal-flat muds which are now within the limits of Capitol Lake; failure was probably due to liquefaction. (Photograph by G. W. Thorsen, Washington Department of Natural Resources, Division of Geology and Earth Resources.)

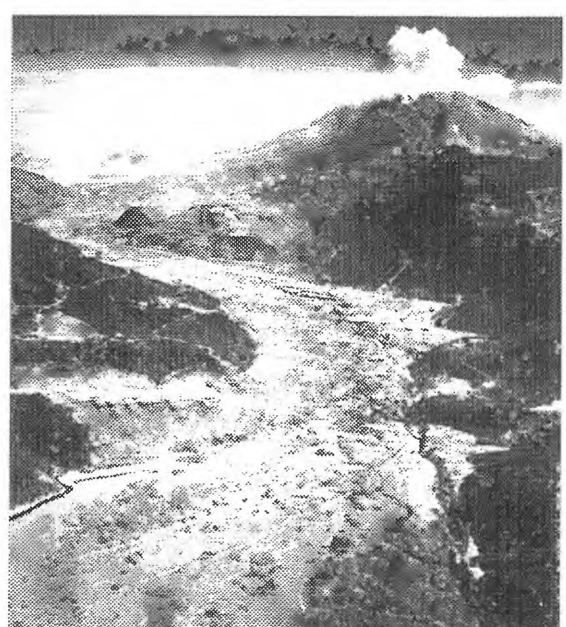

Figure 6. Debris avalanche in the upper valley of the North Fork Toutle River. This landslide was triggered by a M 5 earthquake associated with the May 1980 eruption of Mount St. Helens. (Photograph by R. M. Krimmel, U.S. Geological Survey.)

Most of the landslides triggered by the 1949 and 1965 earthquakes occurred in areas of low population density. Because of increased residential development of hillside slopes in western Washington since 1965, significant losses due to earthquake-induced slope failures can be expected from future earthquakes in the area (Grant, 1986). This will be particularly true for earthquakes of greater magnitude, shallower focus, or longer duration than those that occurred in 1949 and 1965. In addition, greater earthquake-induced slope-failure activity is to be expected when the quakes occur at times of the year when heavy, prolonged precipitation or melting snow results in exceptionally high ground-water levels and saturated soils.

GROUND FAILURE ASSOCIATED WITH LIQUEFACTION

As related to earthquakes, liquefaction is the process by which saturated cohesionless soils change from a solid state to a liquefied state as a consequence of dynamic loading that increases pore pressures and reduces effective stress (Youd, 1978). Liquefaction by itself is not ground failure; however, the liquefaction process results in almost total reduction of shear strength. This reduction can result in ground failure of several types; the most common are: (1) lateral spreads, (2) flow failures, (3) ground settlement, and (4) loss of bearing capacity. As noted above, the first two are, in effect, varieties of landslides, in that they occur on slopes due to reduction of shear strength.

Lateral spreads due to earthquakes involve lateral dispacement of large surficial blocks of soil as a result of liquefaction in subsurface layers (Committee on Earthquake Engineering, 1985). They generally develop on very gentle slopes (most commonly between 0.3° and 3°) and move toward a free face, such as an incised stream channel. Lateral displacements range up to several feet, and, in particularly susceptible conditions, to several tens of feet, accompanied by ground cracking and differential vertical dispacement (Youd, 1978). Lateral spreads often disrupt the foundations of buildings or other structures, rupture pipelines and other utilities in the failure mass, and compress engineering structures crossing the toes of the failures.

Flow failures are liquefaction-caused landslides that develop in loose saturated sands or silts on natural or man-made slopes greater than 3° (Committee on Earthquake Engineering, 1985). Flows may consist of completely liquefied soils, or of blocks of intact material riding on layers of liquefied soil. They often displace large masses of material for many tens of feet at velocities ranging up to tens of miles per hour.

Densification and ground settlement of saturated sediments are commonly associated with and enhanced by liquefaction. Several classic examples of ground settlement caused by seismic shaking occurred in saturated sediments along the coast of Alaska due to the 1964 earthquake; at Portage, Alaska, settlement lowered the ground surface sufficiently so that houses and highway and railroad grades were indundated at high tide (Committee on Earthquake Engineering, 1985). The 1949 Olympia earthquake caused structural damage to buildings on the Duwamish Flat in south Seattle due to settlement of saturated sediments (U.S. Army Corps of Engineers, 1949).

Sand boils often form at the surface during ground settlement. Although sand boils are not strictly a form of ground failure because alone they do not cause ground deformation, they provide diagnostic evidence of elevated pore-water pressure at depth and indication that liquefaction has occurred (Committee on Earthquake Engineering, 1985). Sand boils occurred at several locations in western Washington during the 1949 and 1965 earthquakes. Of particular interest were 1949 sand boils on the flood plain of the Chehalis River about 1 mi southwest of Centralia; spouts of sand and water reached heights of several feet immediately after the earthquake (T. Dorn, Centralia, Washington, personal commun., 1988).

Loss of bearing capacity occurs when the soil supporting a building or other structure liquefies and loses strength. This process results in large soil deformations under load, allowing the structures to settle and tip. An outstanding example of loss of bearing capacity due to seismic activity resulted from the the 1964 earthquake at Niigata, Japan, where spectacular bearing failures occurred at the Kwangishicho apartment complex; several four-story buildings tipped as much as 60 degrees (Committee on Earthquake Engineering, 1985). Minor destabilization of structures founded on saturated sediments occurred in the Seattle area in the 1949 and 1965 earthquakes.

MINOR CRACKING

Minor cracking of the ground surface independent of the above types of ground failure is noted after nearly all major earthquakes. Such cracks seldom cause significant damage. They were noted in many places in western Washington following the 1949 and 1965 earthquakes.

PLANNED U.S. GEOLOGICAL SURVEY RESEARCH ON EARTHQUAKE-INDUCED GROUND FAILURE IN WESTERN WASHINGTON

Ground-failure studies planned for western Washington by U.S. Geological Survey scientists and engineers deal with records and effects of seismicity for three different time frames: (1) prehistoric time, (2) historic time, and (3) the future. The object of each of these categories of study is to aid in prediction of future seismic activity and/or to provide additional insight into the characteristics and effects of ground failure from future earthquakes. The specific objectives of these three research components are as follows:

(1) To identify major paleoseismic events in western Washington by means of the stratigraphic record of earthquake-induced liquefaction and landslides, and to determine the dates of prehistoric ground failure using applicable Quaternary-dating techniques. The search for liquefaction-disturbed strata will focus on the Holocene stratigraphic record, which is mainly concentrated on the valley floors of large rivers. The estuaries of these rivers are the areas that have been most susceptible to liquefaction-caused ground failure during Holocene time. Study of earthquake-induced landslides will be less constrained geographically than the study of features due to paleoliquefaction. The principal requisites for selecting landslides for study are that they be: (a) earthquake-induced, (b) amenable to dating by ^{14}C, lichonemetry, or other suitable Quaternary-dating techniques, and (c) relatively accessible.

(2) To define the distribution and characteristics of historic (1872 and later) earthquake-induced ground failure (with emphasis on landslides and liquefaction-associated ground failure) in western Washington as a step in better understanding what types of ground failure have occurred due to prehistoric earthquakes and what types can be expected in the future. Information obtained on historic ground failure will also be of value in further defining the characteristics of historic earthquakes in the area.

(3) To produce susceptibility maps for landslides and liquefaction-associated ground failure for selected metropolitan areas of western Washington. Geographic Information Systems (GIS) techniques will be utilized in this effort. The need for such mapping is clearly indicated by the occurence in the Puget Sound region of numerous earthquake-induced ground failures related to the 1949 and 1965 earthquakes. Initially, data will be collected on the distribution and character of earthquake-induced ground failures as indicated in the above study plans. Subsequently, this information will be combined with other data on geology, hydrology, and topography, and will be manipulated using GIS technology to produce high-quality earthquake-induced ground-failure susceptibility maps.

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EPISODIC TECTONIC SUBSIDENCE OF LATE HOLOCENE SALT MARSHES IN OREGON: CLEAR EVIDENCE OF ABRUPT STRAIN RELEASE AND GRADUAL STRAIN ACCUMULATION IN THE SOUTHERN CASCADIA MARGIN DURING THE LAST 3,500 YEARS

By

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Multiple Buried Marsh Horizons in Oregon Bays and Estuaries

Coastal marshes from northern, central and southern Oregon have been cored to 6 m depth to establish late-Holocene records of relative sea level and associated coastal neotectonics. Multiple buried marsh horizons (4-6 in number) have been identified in Netarts Bay (45.5 ^{o} latitude), Nestucca Bay (45.2 ^{o} latitude), Alsea Bay (44.4 ^{o} latitude) and South Slough, Coos Bay (43.3 ^{o} latitude). The marsh horizons, 10 cm to 1 m thick, have been traced laterally (over 1 km in distance) within individual estuarine systems by stratigraphic correlation of marsh and sediment burial sequences. Burial sequences are generally observed to include 1) vertically rooted or rhizome rich muds grading upward to peaty sediments (marsh layer) which are overlain by 2) barren sands or muds which commonly grade upwards to finely laminated or bioturbated muds (sediment burial layer). Fresh water diatom assemblages (high-marsh) in some buried marsh deposits are consistently overlain by brackish water diatom assemblages, confirming marsh subsidence and subsequent burial by tidal flat muds. Contacts between marsh layers and overlying burial layers are typically sharp, indicating abrupt subsidence. However, some widely traced contacts are clearly gradational (see later section). Sediment capping layers on top of some buried marsh horizons range from 20 cm to less than 1 cm in thickness and often include internal laminations of sand or mud. The sediment capping layers are wide spread in the lagoonal marsh system of Netarts Bay but are less well developed in fluvially influenced marsh systems of Nestucca and Alsea Bays. Ages of buried marsh surfaces have been estimated by radio-carbon dating of peats in Netarts Bay and indicate approximate ages of local subsidence events:

Surface	Depth (MSL)	Calibrated Age (yrs BP)
1st Buried marsh top	0.7	350+-60
2nd Buried marsh top	1.5	1220+-60
3rd Buried marsh top	1.7	1640+-80
4th Buried marsh top	2.2	1760+-60
5th Buried marsh top	4.4	3170+-90
6th Buried marsh top	5.3	3290+-100

Comparitive Salt Marsh Stratigraphies From Subduction and Transform Margins

In an effort to constrain the tectonic mechanisms of coastal marsh subsidence observed in the southern Cascadia Margin we have performed comparison studies of marsh stratigraphy from the San Andreas transform margin near Point Reyes, California (38.2 ^{o} latitude). Marsh cores (9) taken in Tomales Bay (formed within the San Andreas fault zone) contained a maximum of 6 buried marsh horizons extending to a depth of 5 m below the modern marsh surface. However, unlike the buried marsh layers of the Cascadia Subduction zone, the Tomales Bay buried marshes 1) are not widely correlated within the basin, 2) do not have sharp upper contacts with overlying sediments and 3) do not have distinctive sediment capping layers on top of the buried marshes even though sand is abundant within the upper basin. Burial of the Tomales Bay marshes appears to have occured by incremental subsidence. The preserved marsh layers and intervening sediments in Tomales Bay show no sign of liquefaction or severe disturbance even though the San Francisco earthquake of 1906 was centered near Tomales Bay.

As a control to the study of marsh sequences in the seismically active San Andreas fault zone, an investigation of marsh development was also undertaken in the Schooner Bay arm of Drakes Estero, located about 5 km due west of the fault zone. Uninterrupted peat accumulation was observed in cores to 8 m depth from this tectonically stable setting on the Salinian Block. Episodic tectonic subsidence in the northern California transform margin is limited to the transform fault zone itself. Significantly, the continuous marsh development in the tectonically stable Drakes Estero also demonstrates that marsh burial by potential fluctuations in eustatic sea-level did not occur in late Holocene time. Since marshes of the Schooner Bay arm have developed in a sediment starved, micro-tidal environment they should have been particularly sensitive to any fluctuations in eustatic sea level that might have influenced marsh development on the U.S. west coast.

The results of the northern California studies are significant in that they demonstrate a southern boundary to the abrupt subsidence style of marsh burial seen in Oregon and Washinton. In addition, the lack of severe sediment disturbance in the seismically active San Andreas fault zone demonstrates that marsh and sediment disruption are not neccessarily produced by catastrophic earthquakes. Little or no disruption of marsh or sediment burial sequences are observed in abruptly subsided deposits of coastal marshes in the southern Cascadia Margin. The lack of sediment disruption in the marsh records of the Cascadia Margin does not argue against recent seismic activity in this subduction zone.

Discrimination of Flood and Tectonic Events in Coastal Marsh Records

Regional climatic mechanisms of potential marsh burial have been investigated on a preliminary basis in endmember marsh systems of the southern Cascadia margin. Flood overbank deposition provides a means by which marsh burial could possibly occur independently of tectonic subsidence in fluvially dominated estuaries of the southern Cascadia Margin. In an effort to identify potential marsh burial by flood deposition, several cores (4-5 m depth) were taken in a flood plain-estuarine marsh of the Little Nestucca River in northern Oregon. Several prominant sand and/or gravel layers 10-30 cm in thickness were observed in an upstream flood plain core site, indicating abundant sand supply to the downstream marsh system. A series of 3-5 buried marsh layers were observed in two core sites 0.5-0.75 km downstream of the upper flood plain site. Although this riverine-marsh environment should have been influenced by major flood events and associated sand supply there are no sand layers associated with the buried marshes or with overlying burial sequences. The buried marshes (10-30 cm thick) have sharp upper contacts and are buried by laminated muds 20-100 cm in thickness.

To test the flood hypothesis more rigorously, a total of 10 marsh cores were taken to depths of 4-7 m in the fluvially dominated upper reaches of Alsea Bay in central Oregon. Several buried marsh layers (10-30 cm thick) are preserved in the upper 3 m of this marsh system and two of the buried marshes are capped by sand layers. Two orientated core transects, both normal and parallel to the major estuarine-riverine channel, showed no evidence of increasing sand layer thickness (1-5 cm thick) with increasing proximity to the channel margin or with increasing distance upstream. A thourough search for evidence of the 1964 flood, estimated to have exceeded the 100 yr flood level for this drainage system, showed no evidence of marsh burial or sand accumulation within the modern marsh. Preliminary indications of the marsh studies in Nestucca and Alsea Bays suggest that mash burial by riverine floods have not occured during late Holocene time in these fluvially dominated basins.

Temporal Transitions Between Strain Release and Strain Accumulation

While most of the buried marsh sequences we have observed in the southern Cascadia margin have sharp upper contacts (peat-sediment transitions < 1 cm thickness) some buried marshes show gradational contacts (peat-sediment transitions > 5 cm thickness). One such contact at about 4.4 m depth (MSL) is laterally persistent in Netarts Bay, northern Oregon, as the 5th buried marsh layer (see previous section). This gradual subsidence event (3,170+-90 yrs BP) occurs very shortly after an abrupt subsidence event (3290+-100 yrs BP) but long before the next subsidence event (an abrupt subsidence at 2,040+- 70 yrs BP). Two independent measures of the transition from marsh to tidal flat deposits have been performed on this gradational contact in different core sites. Both dry-weight loss on ignition (a measure of the abundance of peaty material) and a diatom indices of salinity (freshwater assemblage=high marsh, brackish assemblage=low marsh or tidal flat) are shown for one core site below.

Depth m (MSL)	Loss on Ignition (% Org)	Diatom Salinity
3.60	5	Brackish
3.96	7	Brackish
4.20	8	Brackish=Fresh
4.33	12	Fresh>Brackish
4.36	24	Fresh
4.40	28	Fresh

The more common events of marsh burial by abrupt subsidence in Oregon are clearly related to tectonic strain release while the events of gradual marsh burial appear to be related to tectonic strain accumulation. Interestingly, the transition between the two modes of subsidence (rapid strain release and gradual strain accumulation) can occur over very brief intervals (less than 300 years). Additonal evidence of recent subsidence by strain accumulation might be provided by some recent marshes (Netarts Bay and South Slough) which have well defined erosional scarps 0.5-1m in height. The most recent marshes in Alsea Bay and Nestucca Bay have relatively sharp bases (dense rhizome mats over barren sediment) and have prograded over high-energy tidal flats (sand) that have not previously maintained significant marsh development. The unusually broad coverage of these most recent marshes suggest an initial period of coastal emergence by strain accumulation or by strain release. Finally, close spaced couplets of thin marsh layers of similar age might indicate a futher complexity of tectonic movement. Such sequences are observed in Netarts Bay and possibly indicate abrupt subsidence (marsh burial) followed by emergence (rapid marsh progradation). Additional stratigraphic studies of submergent and emergent marsh sequences in the southern Cascadia Margin are needed to establish the complex tectonic cycles of strain accumulation and strain release that have ocurred along this active-margin during late Holocene time.

ANOMALOUS SUBDUCTION AND THE ORIGINS OF STRESSES AT CASCADIA: A REVIEW

By

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ABSTRACT *This framework paper on the seismicity and tectonics at the Cascadian plate system indicates that the primary regional stress is northerly compression, even though the Juan de Fuca plate generally is thought to be subducting N50°E. New and existing earthquake focal mechanism data show that this compression is pervasive throughout the Gorda-Juan de Fuca-Explorer plate system and much of the adjoining section of North American plate. Modeling, using a discrete element code, shows that this north-trending compression is due to the Pacific plate being driven into the Gorda block and Juan de Fuca plate (at the Mendocino and Blanco fracture zones), causing compression of the offshore plate system northwards into the 45° W-trending coast of Vancouver Island. The modeling requires strong coupling at the subduction interface, to permit this north-trending compression to be transferred into the overriding plate. Several independent lines of evidence indicate that the Cascadian subduction interface is locked and that subduction is not occurring aseismically. The absolute velocity of the Juan de Fuca plate has slowed by as least 60% over the last 6.5 m.y. (Riddihough, 1984). The great buoyancy of the young, subducted plate may cause great resistance to subduction and may explain this slowing and why the Explorer subplate and the south Gorda block recently have moved independently from the main Juan de Fuca plate. Moreover, the slowing subduction will allow increased warming and density decrease of the subducted plate. The corresponding decrease of the slab pull force will contribute to further slowing of the Juan de Fuca plate. For major earthquakes within the plate subducted beneath Puget Sound, focal mechanisms indicate extensional stresses that trend downdip. This extension is consistent with stresses, due to the slab pull force of the more deeply subducted plate, that typically are observed in other subducted plates. The slab pull force acting at a locked interface thrust zone is shown to be a likely cause of the geodetically-observed warping and northeast-trending compression along the Cascadia coast. The shallow stresses at the Cascadia province primarily are a superposition of stresses resulting from the action of the Pacific plate on the Gorda-Juan de Fuca-Explorer plate system upon stresses resulting from the slab pull force of the subducted plate. The observed fragmentation of the offshore Juan de Fuca plate, the slowing of subduction of the Juan de Fuca plate, and the strong influence of the Pacific plate's motion in causing stresses at the Cascadia plate system suggest that in-plate driving forces are diminishing and that a geologically long-term cessation of subduction at Cascadia is in progress. The potential exists for M7.5 - 8.0 subduction earthquakes to occur at segments of the subduction boundary at Washington and less frequently so at segments of the subduction boundary at Oregon. The northward compression in the Cascadia plate system*

appears to have caused large, crustal earthquakes in the regions of Vancouver and northern California, and may be capable of causing large earthquakes also in and offshore of Washington and Oregon.

INTRODUCTION

The Washington-Oregon trench is filled with 1-2 km of terrigenous deposits (Scholl, 1974; von Huene and Kulm, 1973), and the presence of this shallow trench reflects subduction of young oceanic lithosphere (Heaton and Hartzell, 1986). Although active volcanism at the Cascade volcanic chain indicates subducted plate at least to depths of about 100 km (Isacks and Barazangi, 1977), most of the subducted lithosphere lacks earthquakes (Weaver and Michaelson, 1985; Weaver and Baker, 1988). This subducted plate and the horizontal Gorda-Juan de Fuca-Explorer plate system (seaward of the trench) are remnants of the Farallon plate, which formerly underthrust much of western North America (Atwater, 1970). This offshore plate system is sandwiched between the San Andreas and Queen Charlotte transform fault systems, with the northwestward motion of the Pacific plate causing right-lateral shear on each transform fault.

The plate motion history of the Juan de Fuca remnant is preserved in its pattern of magnetic anomaly reversals (Raff and Mason, 1961; Vine, 1968; Peter and Lattimore, 1969; Elvers et al., 1973). The changes in shape of the anomalies (fanning and pseudofaults) in the Juan de Fuca plate allow detailed reconstructions of this plate's recent motions (Hey, 1977; Riddihough, 1984; Wilson et al., 1984; Nishimura et al., 1984). Riddihough's reconstructions of the absolute motions of the Juan de Fuca plate system show how it has been slowing down and fragmenting over the last 6.5 m.y., while maintaining a northeasterly subduction direction (Figure 1). This absolute velocity of the Juan de Fuca plate is the same as the velocity of this plate into the mantle. The convergence rate between the Juan de Fuca plate and the overriding North American plate is the vector sum of their individual absolute velocities; this convergence is a factor in determining both the seismic coupling between plates and the characteristic maximum earthquake at the plate interface. However, the absolute velocity of the Juan de Fuca plate reflects the in-plate driving forces for that plate's motion, and determines that plate's contribution to coupling at the plate interface. At 6.5 m.y.B.P. the absolute rate of the Juan de Fuca plate was about 45 km/my (4.5 cm/yr). By 2.5 m.y.B.P. and 0.5 m.y.B.P. the absolute rates had slowed to about 25 km/my and 17 km/my, respectively. Extrapolation of the slowing of the Juan de Fuca plate to the present gives an absolute motion of about 15 km/my. Similarly, Nishimura et al. (1984) find the most recent absolute motion of the Juan de Fuca plate to be 10-20 km/my. Thus the absolute motion of the Juan de Fuca plate has slowed by about 60% over the interval 6.5-0.5 m.y.B.P., to become one of the slowest moving plates on Earth.

At 1.5 million years ago the absolute pole of the Juan de Fuca plate was in northern California, indicating slower plate convergence at Oregon than at Washington State (Riddihough, 1984). The southeast corner of the Gorda block is the Mendocino triple junction. This triple junction is moving northward, as the San Andreas fault is lengthened and as the Juan de Fuca plate system is reorganized. The Explorer subplate and the Gorda block began to act independently of the Juan de Fuca plate at about 4 and 2.5 m.y. ago, respectively (Riddihough, 1984). These recent plate motions at Cascadia indicate that the subduction of the Juan de Fuca plate is anomalously complicated. Magnetic anomaly lineations cannot resolve plate motions for the last 500,000 years. Because of the abrupt changes in shape of the Juan de Fuca plate and the abrupt movements of this plate's pole (Riddihough, 1984), it may invalid to extrapolate the plate motions from 500,000 years ago to the present. Thus the use of geomagnetic anomaly data to make inferences on present-day details of subduction of the Gorda-Juan de Fuca- Explorer plate system must be corroborated from recent geologic, tectonic, and seismic data.

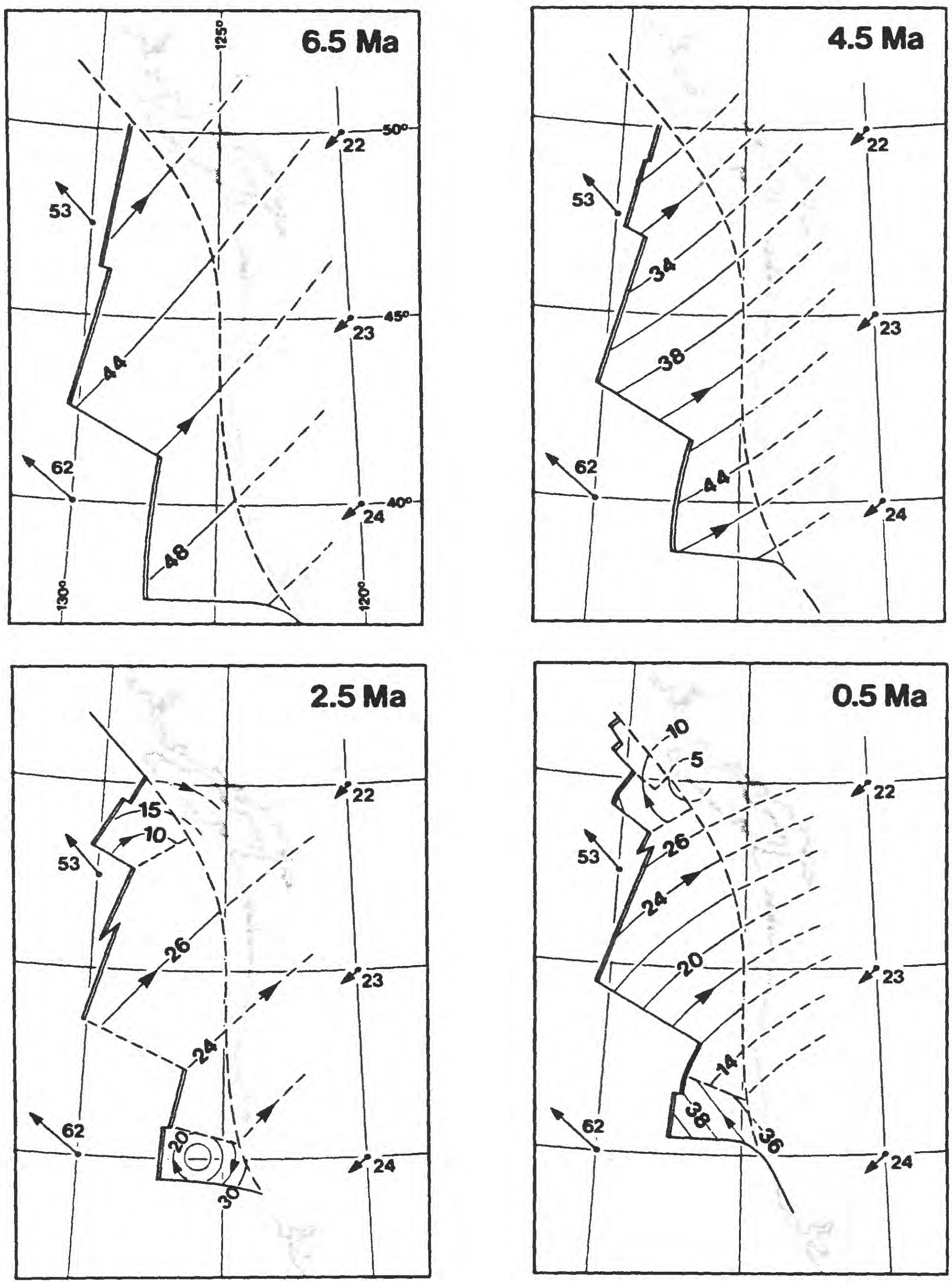

Figure 1. Evolution of absolute motions (km/my) of the Juan de Fuca plate over the last 6.5 m.y., determined from detailed analysis of geomagnetic anomalies (Riddihough, 1984). This sequence shows the slowing of subduction of the Juan de Fuca plate, the beginnings of independent motions by the Gorda and Explorer subplates, and the recent northwestward jumps of the northern spreading centers. The absolute relative plate motions for the 0.5 m.y.B.P. frame are the latest plate motions that are resolvable from geomagnetic anomaly data.

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POTENTIAL FOR A GREAT EARTHQUAKE AT THE CASCADIA SUBDUCTION ZONE

Based on analogies with subduction zones that appear to be similar to the Cascadia subduction zone or on geodetic and seismicity data at the Cascadia subduction zone, numerous workers argue that the Juan de Fuca plate continues to subduct the North American plate (Ando and Balazs, 1979; Rogers, 1979; Savage et al., 1981; Heaton and Kanamori, 1984; Taber and Smith, 1985; Weaver and Michaelson, 1985; Baker and Langston, 1987). The age of the Juan de Fuca plate at the trench is a very young 8-10 m.y.B.P. Subduction of relatively young oceanic lithosphere often is associated with great earthquakes (Ruff and Kanamori, 1980). This implies that plate convergence and subduction at Cascadia may be accompanied by great earthquakes.

A global summary of the characteristic maximum earthquake for various subduction zones vs. both the convergence rate and the age of the subducting oceanic lithosphere is shown by Figure 2 (adapted from Ruff and Kanamori, 1980). This figure shows a strong inverse relationship between the age of subducting oceanic lithosphere and the characteristic maximum earthquake. This implies that the properties of the subducting oceanic lithosphere dominate over those of the overriding plate in determining the size of the characteristic maximum earthquake. The characteristic maximum earthquakes for various subduction zones have been related to the sizes of the slab pull and ridge push forces, which are the main driving forces of oceanic plate motions (Spence, 1987). The sizes of these forces are related directly to the ages of oceanic lithospheres. For a given subduction zone, the ridge push force, due to landward increasing density gradients of oceanic lithosphere, generally is considerably smaller than the slab pull force, due to the negative buoyancy of subducted plate (Forsyth and Uyeda, 1975; Carlson, 1983). This effect increases for increasing age of oceanic lithosphere. At an interface thrust zone the decrease in coupling due to the slab pull is more significant than the increase in coupling due to both the ridge push force and the seaward advance of the overriding plate. However, the slab pull force generally is so much larger than the ridge push force that it dominates over the ridge push force in loading stresses that cause subduction zone earthquakes (Spence, 1987).

In Figure 2 the slowing of the convergence rate between the Juan de Fuca and North American plates is shown with convergence rate data for other subduction zones. Because the absolute velocity of the North American plate has remained at about 2.2 cm/yr this slowing convergence at Cascadia entirely is due to the slowing of the absolute velocity of the Juan de Fuca plate (Riddihough, 1984). This implies a corresponding gradual decrease in the in-plate driving forces of the Juan de Fuca plate, particularly a decrease of the slab pull force of the subducted Juan de Fuca plate. Riddihough (1984) estimates that the area of the Juan de Fuca plate has decreased by about 50% in the last 7 m.y. The increasing buoyancy of younger plate entering the subduction zone not only will decrease the slab pull force of subducted plate but also should increase the resistance to subduction at the shallow interface. Both these factors would tend to slow the absolute velocity of the Juan de Fuca plate.

Great earthquakes at southern Chile, Colombia, Mexico, and SW Japan, associated with subducting oceanic lithosphere of about the same age as the Juan de Fuca plate (see Figure 2), have fostered suggestions that the Cascadia subduction zone has the potential for producing great earthquakes (Heaton and Kanamori, 1984; Heaton and Hartzell, 1986 and 1987). However, the subduction setting at Cascadia has significant differences from the subduction settings for those great earthquakes. The M_W 9.5, 1960 Chile earthquake began at an interface bounding 25 m.y.-old oceanic plate, and ruptured into interface bounding oceanic plate <4 m.y. old (Spence, 1987). The absolute velocities for subducting oceanic plates at the Colombia (Kanamori and McNally, 1982) and Chile source zones are several times greater than for the Juan de Fuca plate (Minster et al., 1974), implying much stronger slab pull forces at Colombia

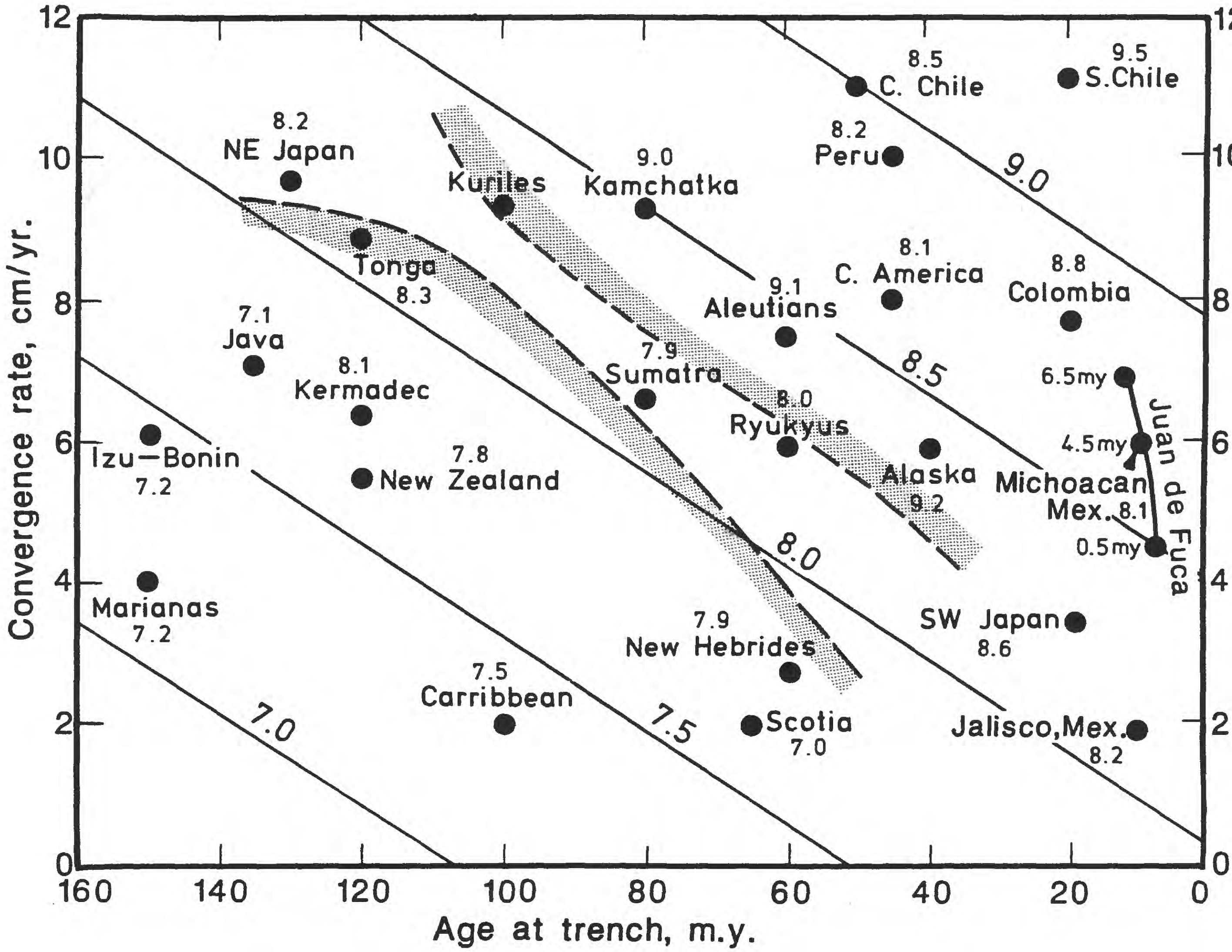

Figure 2. Characteristic maximum earthquake, M_W, for most subduction zones, plotted as functions of convergence rate and age of subducted plate (adapted from Ruff and Kanamori, 1980). Lower right hand corner shows the slowing of convergence of the Juan de Fuca and North American plates; this slowing entirely is due to the 60% slowing of the absloute motion of the Juan de Fuca plate over the last 6.5 Ma. Above upper dashed line are youngest plates, which show strongest coupling at interface thrust zones (due to weak slab pull forces and the resistance to bending by the subducting plate) and which are associated with the seaward advance of overriding plate. Below lower dashed line are oldest plates, which show weakest coupling at shallow, interface thrust zones (because of strong slab pull forces) and which are associated with marginal basin development (Garfunkel et al., 1986).

and Chile. The SW Japan source zone is near an arc-arc intersection and interaction between subducted slabs causes lateral stretching of the Philippine Sea plate (Ukawa, 1982), much unlike deformation in the subducted Juan de Fuca plate. The 1985 Michoacan, Mexico earthquake ruptured the anomalous contact with the subducting Orozco fracture zone (Klitgord and Mammerickx, 1982; Eissler et al., 1986; McNally et al., 1986). The 1932 Jalisco, Mexico earthquake occurred at the Rivera plate, which has only about 1/3 the area of the Juan de Fuca plate (Singh et al, 1985). Here the oceanic lithosphere is about 9 m.y. old and the convergence rate is only about 2 cm/yr. The Jalisco source perhaps is the closest analog to possible seismic subduction at Cascadia. In general each source zone for great earthquakes that has been termed analogous with Cascadia has its own very unique properties that make the nature of stress accumulation there different from stress accumulation at Cascadia.

Stresses near plate interfaces at subduction zones typically show compression in the direction of plate convergence (Nakamura and Uyeda, 1980). Geodetic studies indicate that the coast from Vancouver Island to south-central Washington is subject to NE-SW compression (Savage et al., 1981), consistent with deformation at a locked subduction interface. The focal mechanisms of earthquakes within the subducted Juan de Fuca plate, beneath or downdip of the interface thrust zone of northwest Washington, generally have T-axes that are downdip [Table 1; Figure 3], also consistent with a locked interface thrust zone (Spence, 1987). However, there is a total lack of thrust-faulting earthquakes at the subduction interface of northern Washington (Taber and Smith, 1985). Understanding the tectonic framework at Cascadia is further complicated by focal mechanisms of many earthquakes in the Gorda block and near Vancouver having N-S-trending axes of greatest compressive stress (Bolt et al., 1968; Rogers, 1979; Hyndman and Weichert, 1983) [Figure 3]. The focal mechanisms of many shallow, crustal earthquakes in the Puget Sound depression also have N-S-trending axes of greatest compressive stress (Crosson, 1972 and 1983; Weaver and Smith, 1983). There is debate on whether earthquakes in the St. Helens seismic zone (in the overriding plate) have P-axes parallel to the theoretical direction of plate convergence (Weaver and Smith, 1983), or these earthquakes are due to reactivation of pre-existing faults by the regional northerly compression (Ma, 1988). Thus much of the shallow stress at Cascadia is inconsistent with the stresses typically observed at subduction zones.

Recent work by Atwater (1987) suggests that coseismic subsidence of the Washington coast is the explanation for several sudden burials of coastal estaurine vegetation over the last 5000 years. This implies that the presently observed uplift and landward tilt of the Washington-Oregon coast (Ando and Balazs, 1979; Savage et al., 1981; Reilinger and Adams, 1982; Riddihough, 1982; Adams, 1984) is due to stress accumulation between large or great subduction earthquakes. This tilt is opposite to that often observed when stress is accumulating at locked subduction interfaces at Japan (Shimazaki, 1974) and thus the Cascadian tilt data need to be reconciled with the Japan tilt data and the observed Cascadian NE-SW compression.

The objective of this paper is to evaluate the ridge push and slab pull forces at the Cascadia subduction zone, and to understand the interaction of the Gorda-Juan de Fuca-Explorer plate system with the motions of the Pacific and North American plates. In this study, the spatial distribution of regional earthquakes and their focal mechanisms are integrated with known plate driving forces to explain the origin of stresses within the lithospheric plate elements in and around the Cascadia subduction zone, thus more sharply focussing the present debate on the potential for large or great earthquakes to occur at Cascadia.

Figure 3 contains the seismicity and focal mechanism data on which this study primarily is based. Earthquakes are concentrated within the Gorda block, the Explorer subplate, and at the Blanco fracture zone but are sparse within the Juan de Fuca plate and along the coasts of Oregon and Washington. The plotted earthquakes, $m_b \geq 5.1$, are the result of merging catalogs from the U.S. Coast and Geodetic Survey, the International Seismological Centre,

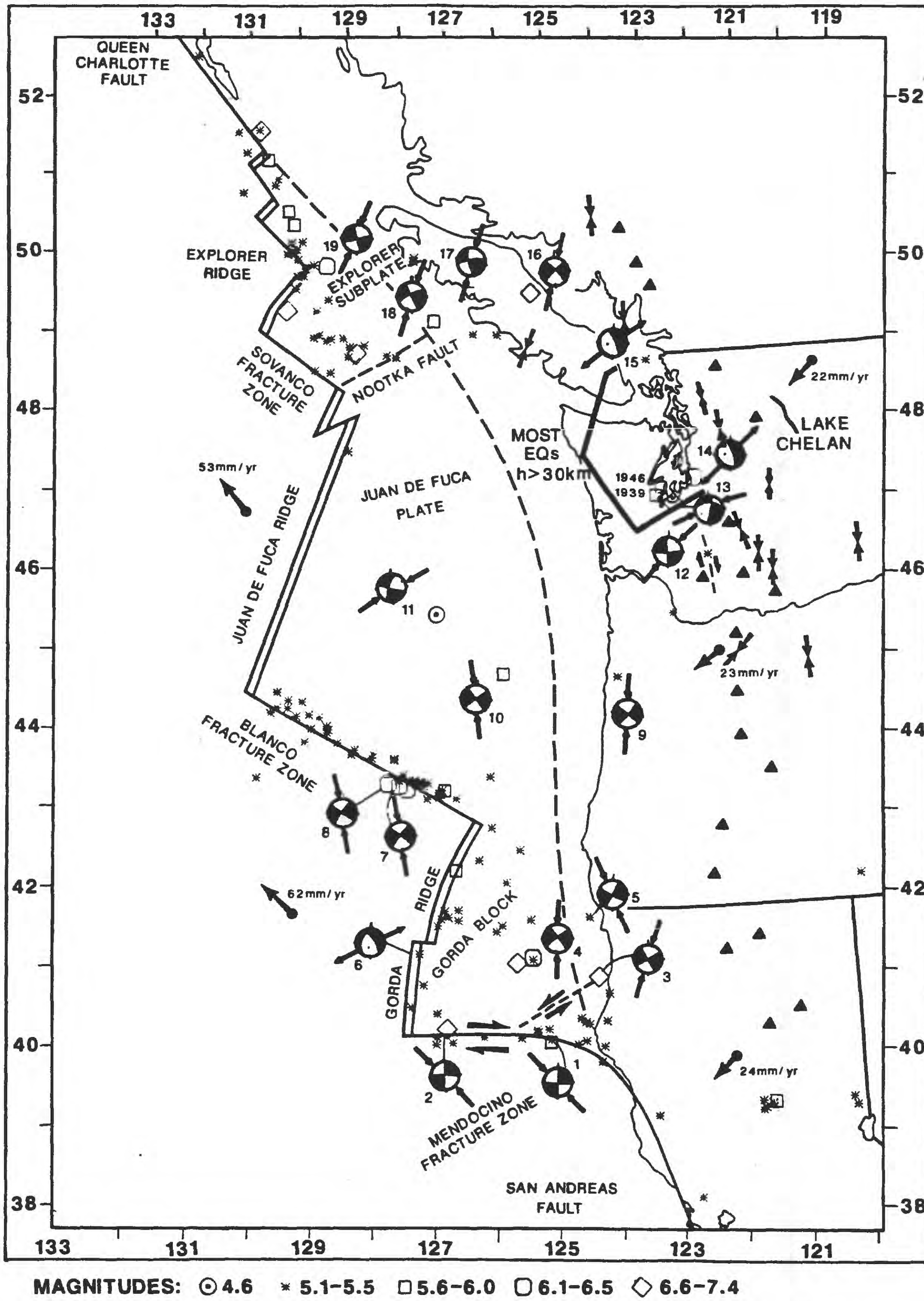

Figure 3. Cascadia seismicity, 1964-June 1986, for earthquakes of magnitude > 5.1. Additional key earthquakes are shown by dates or by focal mechanism solutions for older earthquakes. Focal mechanism solutions correspond to earthquakes in Table 1. For earthquake focal mechanisms, directions of greatest compressional stress indicated by convergent arrows for strike-slip earthquakes; directions of least compressional stress indicated by divergent arrows for normal-faulting earthquakes. Additional data indicating N-S compression in central Washington and east of Vancouver are shown by arrows that meet (Weaver and Smith, 1983; Rogers, 1979; Kim and McCabe, 1984). Most earthquakes deeper than 30 km are within the bracketed zone. Volcanoes indicated by triangles. Geometry of ridges and fracture zones, and absolute plate motions for time frame ending 0.5 m.y. ago are from Riddihough (1984).

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TABLE 1.--Earthquake data for focal mechanisms shown in Figure 3

No.	Location	Time mo/da/19..	Time UT	Magnitude	Latitude °N	Longitude °W	Nodal planes 1 St	1 Dp	1 Sl	2 St	2 Dp	2 Sl	Stress Axes P Tr	P Pl	T Tr	T Pl	References
1.	Mendocino fr. z.	12/20/83	10 41	M_S 5.6 (ISC)[1]	40.33	125.12	1	90	-10	91	80	-180	316	7	46	7	
2.	Mendocino fr. z.	09/10/84	03 14	M_S 6.7 (MOS)[2]	40.50	126.83	278	85	-178	187	88	-5	142	5	233	2	
3.	E. Gorda subplate	11/08/80	10 27	M_S 7.3 (ISC)	41.15	124.30	60	90	-3	150	87	-180	15	2	105	2	
4.	Cent. Gorda subplate	07/06/34	22 48	6.5	41.4	125.4	323	84	-172	232	82	-6	10	188	98	1	Byerly (1938)
5.	Off California-Oregon bdr.	08/23/62	19 29	5.6	41.85	124.3	116	85	180	26	90	-5	341	4	71	4	Bolt et al. (1968)
6.	Gorda ridge	04/18/65	06 33	m_b 5.4 (ISC)	41.44	127.31	327	65	-117	198	36	-45	196	60	77	16	Tobin and Sykes (1968)
7.	Blanco fr. z.	11/03/81	13 47	M_S 6.2 (ISC)[3]	43.55	127.69	218	85	356	308	86	185	173	6	83	1	
8.	Blanco fr. z.	03/13/85	19 34	M_S 6.3 (USGS)	43.51	127.56	302	90	-173	212	83	-360	167	5	77	5	
9.	Coast of Oregon	03/07/63	23 53	5.4	44.88	123.74	318	90	180	48	90	0	3	0	93	0	Bolt et al. (1968)
10.	Cent. Juan de Fuca plate	06/16/73	14 43	m_b 5.8 (ISC) M_S 5.7, (12 obs)	44.98	125.86	300	90	175	30	85	360	345	3	255	3	
11.	Cent. Juan de Fuca plate	12/18/68	13 09	m_b 4.6 (ISC)	45.73	127.10	109	84	-19	201	71	-174	63	18	158	9	

TABLE 1.--Earthquake data for focal mechanisms shown in Figure 3--Continued

No.	Location	Time mo/da/19..	Time UT	Magnitude	Latitude °N	Longitude °W	Nodal planes 1 St	1 Dp	1 Sl	2 St	2 Dp	2 Sl	Stress Axes P Tr	P Pl	T Tr	T Pl	References
12.	So. Washington	02/14/81	06 09	M_L 5.5	46.42	122.09	175	84	-172	84	82	-6	40	10	310	2	Weaver and Smith (1983)
13.	Subducted Juan de Fuca plate (h=54 km)	04/13/49	11 55	M 7.0 (GR)[4]	47.1	122.7	275	45	-10	12	83	-135	244	36	135	24	Nuttli (1952); Baker and Langston (1987)
14.	Subducted Juan de Fuca plate (h=59 km)	04/29/65	15 28	m_b 6.5	47.41	122.29	344	72	-76	125	23	-127	274	61	63	26	Algermissen and Harding (1965); Isacks and Molnar (1971)
15.	Subducted Juan de Fuca plate (h=60 km)	05/16/76	08 35	m_b 5.2 (ISC)	48.92	123.10	336	75	-85	137	16	-108	259	60	61	21	Rogers (1983)
16.	Vancouver I.	06/23/46	17 13	M 7.3 (GR)	49.8	125.3	228	85	-12	319	78	-175	189	12	274	5	Rogers (1979)
17.	Vancouver I.	12/16/57	17 27	6.0	49.8	126.5	248	78	17	154	73	167	21	3	112	20	Rogers (1979)
18.	West of Vancouver I.	07/05/72	10 16	M_S 6.0 (MOS)	49.45	127.18	154	89	163	244	73	1	200	11	108	13	Rogers (1979)
19.	W. Explorer subplate	07/23/72	19 13	M_S 6.5 (MOS)	50.10	129.29	345	90	177	75	87	360	30	2	300	2	

1 International Seismological Commission
2 Moscow Observatory
3 U.S. Geological Survey
4 Gutenberg and Richter (1954)

the U.S. Geological Survey, Oregon State University, The University of Washington, and the Earth Physics Branch, Ottawa. Except as noted, only earthquakes since 1964 are included because earlier earthquakes may be poorly located. Focal mechanism data for the larger and significant earthquakes are included for events back to 1934, and these nineteen focal mechanisms are shown in Figure 3 and in Table 1. Care was exercised only to include reliable focal mechanisms, whose data are not clustered near nodal planes. New focal mechanisms are shown in detail in Figure 4. Assuming that the regional axes of greatest and least compressive stress, σ_1 and σ_3, generally are aligned with the P- and T-axes of earthquake focal mechanism solutions (McKenzie, 1969; Zoback et al., 1987), these nineteen focal mechanisms then reflect much of our present knowledge of stresses at the Cascadia region.

STRESSES in the GORDA, JUAN de FUCA, and EXPLORER LITHOSPHERES

Stresses in and near the Gorda block

Numerous recent geologic studies indicate that the Mendocino triple junction is being driven northward by the Pacific plate (e.g. Fox et al., 1985; Sarna-Wojcicki et al., 1986; Kelsey and Carver, 1988), at a rate comparable to that of the Pacific plate's motion of 58 km/my. This is an 'unstable' triple junction, leading to the creation of new plate boundary at the northwards-extending San Andreas fault (Dickinson and Snyder, 1979). Subducted plate exists both north and south of this triple junction, as described by Jachens and Grisom (1983).

Focal mechanisms 1 and 2 (Figures 3 and 4; Table 1) are for the two largest earthquakes since 1964 on the Mendocino fracture zone and they each are consistent with right-lateral, strike-slip faulting on the Mendocino fracture zone. The axes of greatest compression for these earthquakes nearly are parallel to the absolute motion of the Pacific plate. Focal mechanism studies of small earthquakes at the eastern Mendocino fracture zone include some consistent with the Pacific plate's causing northward compression at that fracture zone (Seeber et al., 1970; Simila et al., 1975).

Within the Gorda block, focal mechanisms for sizeable earthquakes suggest right-lateral, NW-strike-slip faulting (Bolt et al., 1968). Numerous mapped faults in the Gorda block trend north-to-northwest (Kelsey and Carver, 1988), overprinting the north-to-northeast trend of magnetic anomalies (Silver, 1971; Riddihough, 1980). The largest known earthquake in the Gorda block is the 1980, M_S 7.3 strike-slip event (focal mechanism 3 of Figures 3 and 4, and Table 1). Aftershocks of this earthquake trend 150 km southwest from the main shock, nearly to the Mendocino fracture zone (Eaton, 1981). Thus the preferred fault plane for this main shock is left-lateral, strike-slip faulting. Earthquakes 3,4, and 5 are strike-slip events and their axes of greatest compressional stress trend approximately northward. At the Gorda block, the focal mechanisms for earthquakes 1-5 indicate that the mapped faulting and the focal mechanisms for earthquakes 1-5 indicate that the westward component of the Pacific plate's motion is accomodated by right-lateral, strike-slip along the Mendocino fracture zone, and that the northward component of the Pacific plate's motion leads to north-directed compression, with earthquakes occurring on a set of conjugate faults in the Gorda block.

The tectonic character of the Gorda block and its northern boundary are not well-defined. The mapped faulting and high level of seismicity in the Gorda block is consistent with this block being strongly coupled to the overriding North American plate and resisting the northward push from the Pacific plate. Focal mechanisms for several small earthquakes, at depths 30 to 87 km in the subducted Gorda block, show normal-, strike-slip-, and thrust-faulting (Cockerham, 1984; Walter, 1986), unlike deformation in typical subducted plate. It is unknown whether the slab pull force of plate subducted beneath the Gorda block is sufficient to cause further subduction there. The spreading history of the South Gorda ridge has been independent from that of the North Gorda ridge for the last 2-3 m.y. (Riddihough, 1980). At the Gorda ridge,

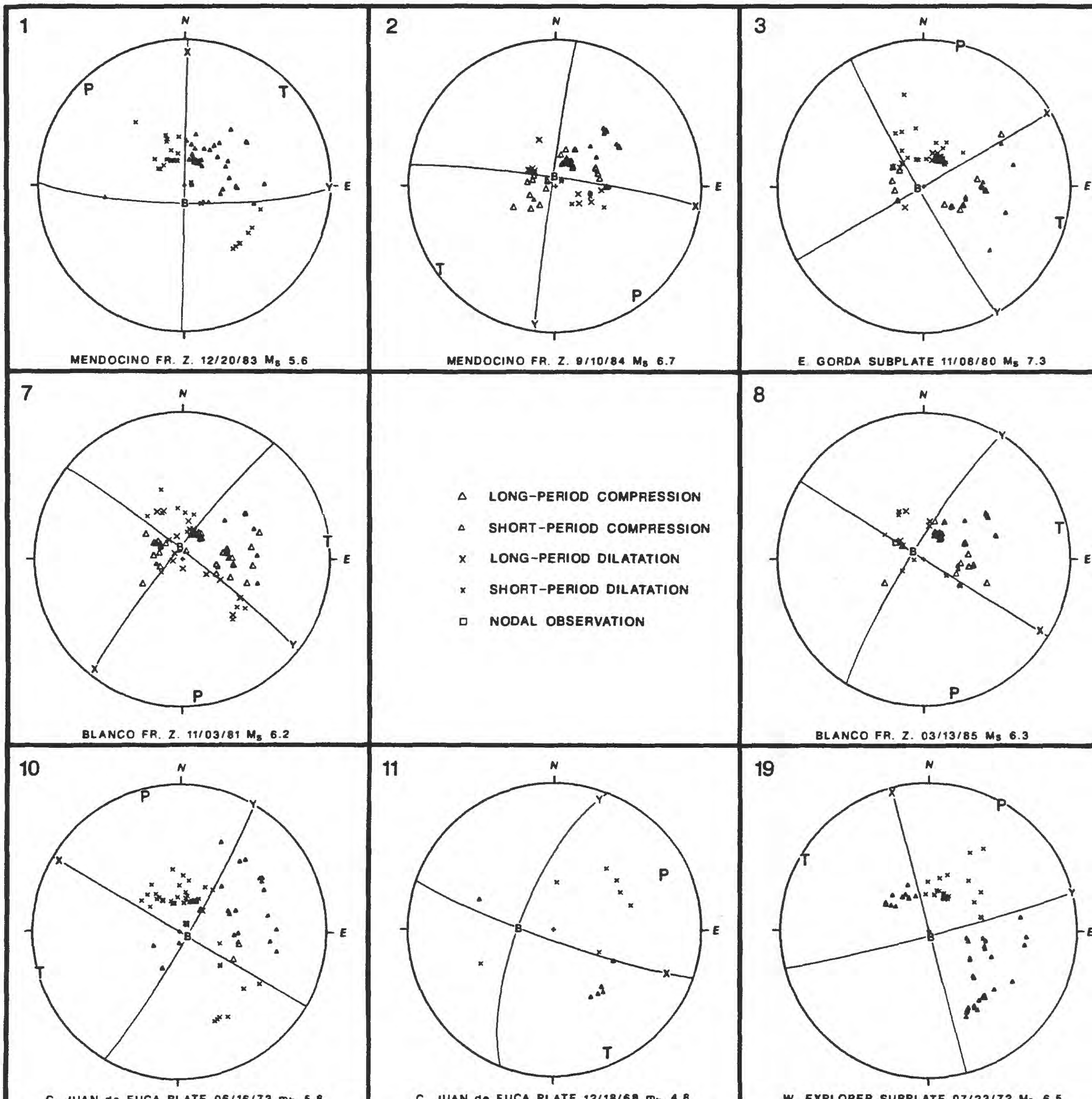

Figure 4. P-wave first motion data for the eight new focal mechanism solutions of this study, plotted on stereographic projections of the lower focal hemispheres. Number in upper left-hand corner of each frame corresponds to that earthquake in Table 1. Shown are nodal planes with the poles of the x- and y-planes, and the pressure (P), tensional (T), and null (B) axes. Except for earthquake 11, these new focal mechanisms indicate a general N-S compression.

in the context of a non-subducting or very slowly-subducting Gorda block, the geologically mapped normal-faulting (Atwater and Mudie, 1968) and a normal-faulting earthquake (focal mechanism 6) would be due to the Gorda ridge's response to the motion of the Pacific plate. The northern boundary of the Gorda block generally is taken to be near the landward extension of the Blanco fracture zone, because of the low seismicity rate south of that extension. However there is no clear tectonic feature that corresponds to a boundary between the Gorda block and the Juan de Fuca plate. The distortion of magnetic anomalies in the Gorda block has been shown to be due to internal deformation there (Wilson, 1986; Stoddard, 1987) and the high seismicity within the Gorda block indicates that this deformation is continuing.

Stresses in the offshore Juan de Fuca plate

Evaluation of stresses within the offshore Juan de Fuca plate is made difficult by the scarcity of earthquakes there, particularly where they would be expected at the trench and interface thrust zone. The Juan de Fuca ridge essentially is aseismic.

The Blanco fracture zone, however, has frequent earthquakes. The Pacific plate has a component of motion into the Blanco fracture zone and this fracture zone is rotated about 15^o clockwise from its expected orthogonality to the Juan de Fuca ridge. The Blanco fracture zone consists of a series of strike-slip faults that are offset by extensional basins (Embley et al., in press). Bolt et al. (1968) found some normal-faulting earthquakes at the Blanco fracture zone, possibly related to these extensional basins. The two largest earthquakes on the Blanco fracture zone in Figure 3 are shown by the nearly identical strike-slip focal mechanisms 7 and 8 (also see Figure 4 and Table 1). The preferred fault planes for these earthquakes strike parallel to the Blanco fracture zone. The P-axes for these mechanisms trend about 35^o north of the Pacific plate's motion vector but are at right angles to the possible motion vector of the Juan de Fuca plate. This implies that the strike-slip faulting on the Blanco fracture zone is caused by the motion of the Pacific plate rather than motion of a subducting Juan de Fuca plate. These large strike-slip earthquakes are concentrated at the Blanco ridge, at the eastern third of the Blanco fracture zone. Iback (1981) interpreted a sediment wedge at the south side of the Blanco ridge as evidence for compression acting across the transform. Thus, the mapped structure and the earthquake focal mechanisms at the Blanco fracture zone indicate that the westward component of the Pacific plate's motion is accomodated by right-lateral, strike-slip faulting and extensional basins, and that the northward component of the Pacific plate's motion leads to compression acting across the Blanco fracture zone.

The only two earthquakes known to be interior to the offshore part of the Juan de Fuca plate are indicated by focal mechanisms 10 and 11 (Figures 3 and 4; Table 1). Focal mechanism 10 is for a m_b 5.8 earthquake in the central Juan de Fuca plate. This 1973 earthquake has a north-trending P-axis. The P-axis of this highly reliable focal mechanism is consistent with the P-axes for most previously discussed focal mechanisms. Focal mechanism 11 is anomalous. It was determined for the smallest earthquake (m_b 4.6) of Figures 3 and 4, because of its important location in the central Juan de Fuca plate. Although this is the least certain mechanism in this study, the P-wave data on which it is based are internally consistent and the P-axis of this earthquake appears to be nearly parallel to the 500,000 yr-old absolute plate motion vector for the Juan de Fuca plate (Riddihough, 1984). While this earthquakes's P-axis could be interpreted as due to plate compression due to the ridge push force (analogous to earthquakes studied by Mendiguren, 1971, and Christensen and Ruff, 1983), this P-axis orientation probably is fortuitous. Bratt et al. (1985) modeled stresses to match the main characteristics of near-ridge earthquakes and concluded that stresses of thermoelastic origin dominate over stresses of ridge push origin in causing earthquakes in oceanic lithosphere younger than 15 m.y. In general, the focal mechanisms of coastal and offshore earthquakes of the Gorda block and the Juan de Fuca plate are inconsistent with subduction of the Juan de Fuca plate but are consistent with stresses originating with the Pacific plate's driving the Mendocino and Blanco fracture zones northward.

Stresses in and near the Explorer subplate

The 15-20 km-wide Nootka fault zone (Hyndman et al., 1979) separates the Explorer subplate from the Juan de Fuca plate (Figures 1 and 3). The southwest boundary of the Explorer subplate is the Sovanco fracture zone. Cowan et al. (1986), using SEABEAM bathymetry data, interpreted the Sovanco fracture zone to be a 15 km-wide zone of right-lateral shear. Since the Explorer subplate has low absolute velocity relative to the overriding plate, the north-stepping jumps of the Explorer ridge and the right-lateral shear of the Sovanco fracture zone must be related to the motion of the adjoining Pacific plate. Hyndman et al. (1979) suggest that the Nootka fault zone has been pushed northwestward along the continental margin, in response to the broad, northward movement of the nearby oceanic plate system.

Although Figure 3 shows numerous large earthquakes in the Explorer subplate, their P-wave first motions generally are so inconsistent that reliable focal mechanism solutions could not be obtained. Such earthquakes include the M_S 6.8 earthquakes of Dec. 20, 1976 and Dec. 17, 1980. Figure 1 indicates the complicated tectonic evolution of the Explorer subplate, showing the recent tendency for sections of the Explorer ridge to jump to the northwest (Davis and Lister, 1977), and the development of new fracture zones. Reconstructions of earlier plate positions (such as by Atwater, 1970) indicate that the Vancouver triple junction essentially was in a fixed position. Riddihough (1984) shows that the Explorer subplate began to act independently of the Juan de Fuca plate at about 4 m.y. ago and that the Explorer subplate's absolute pole of rotation has moved to near that subplate. Thus the Explorer subplate is not strongly subducting (due to in-plate forces) but still may be overridden by the North American plate (Riddihough, 1984). The Explorer subplate's active tectonics (Davis and Riddihough, 1982) and seismicity (Figure 3; Milne et al., 1978; Hyndman et al., 1979) indicate that it is undergoing intensive deformation, primarily due to the influence of the Pacific plate's motion.

NORTH-SOUTH COMPRESSION IN THE OVERRIDING PLATE

Focal mechanisms 16-18 (Figure 3, Table 1) are for the three largest of six shallow earthquakes in the region of Vancouver I. for which Rogers (1979) determined focal mechanism solutions. While these three are strike-slip earthquakes (the largest is the M_S 7.3 event of 1946), two of the smaller earthquakes are thrust events (Rogers, 1979). The average trend of P-axes for all these earthquakes, and for focal mechanism 19 (Figures 3 and 4; Table 1), is just east of north. Thus, in the Vancouver I. region, earthquake focal mechanisms require northward compression that extends well east of the Explorer subplate.

North-trending compression also is the dominant stress in the shallow crust of much of Washington State. Specific data points are shown by convergent arrows in Figure 3, beginning east of Vancouver I., continuing through Puget Sound, across the Cascades and southwards past the Washington-Oregon border. In a comprehensive study of Puget Sound focal mechanisms, Yelin (1982) finds that 19 out of 21 reliable solutions for crustal earthquakes occurring during 1976-1981 had P-axes trending N-S or slightly east of north. The five largest of the earthquakes studied by Yelin (1982) had magnitudes in the range 4.0-4.6. Earthquake 12, at the St. Helens seismic zone, may have been a right-lateral, strike-slip event that resulted from reactivation of a pre-existing fault by north-trending compression (Ma, 1988; cf. Weaver and Smith, 1983).

In the region of the Hanford Site, southern Washington, Kim and McCabe's (1984) hydraulic fracturing data indicate north-south compression, with ratios of maximum compression to vertical stress in the range 2.1-2.7. The location of this data point is the easternmost compression symbol of Figure 3. These high horizontal compression to lithostat ratios suggest a tectonic origin of these stresses. Based on data from a USGS seismic network operated at the Hanford Site, Malone et al. (1975) found that typical earthquakes were very shallow and had thrust-faulting focal mechanisms, with N-trending P-axes. M. Pitt (personal communication, 1986) noted that one Hanford area earthquake with a N-trending P-axis had a focal depth of 28 km.

These data on northerly compression in much of Vancouver and Washington are unlike that expected from active subduction of the Explorer subplate and the Juan de Fuca plate. Similarly, this northerly compression is unlike that associable with the local southwest motion of the North American plate (NE-SW compression is found adjacent to the San Andreas fault and largely is attributed to the southwest motion of the North American plate [Zoback et al., 1987]).

MODELING OF STRESS TRAJECTORIES

This modeling is a test of the hypothesis that the observed northerly compression throughout crustal Cascadia results from the influence of the Pacific and North American plates on the Gorda-Juan de Fuca-Explorer plate system. This modeling also tests whether the subduction interface is strongly coupled or not. These tests are made by comparing the trajectories of greatest compressive stress resulting from two-dimensional, discrete element modelings (MUDEC code) of the Cascadian plate system with the axes of greatest compression observed for earthquakes there.

The input to this modeling is a specification of plate velocity or stress at the eleven boundary elements that are the perimeter of the discrete element mesh shown in Figure 5a. The Juan de Fuca, Gorda, and Explorer ridges are specified to be traction free (zero shear and normal stresses) and the remaining eight boundary elements are specified by the x- and y-components of the absolute velocity of the Pacific or North American plate, as appropriate. The contact between the Juan de Fuca and North American plates is simplified as the midline of the interface thrust zone and is modeled as a joint discontinuity, whose strength is less than that of the surrounding plates. Then the boundary conditions of velocity and stress are propagated iteratively through the corner and edge contacts of the solid continuum mesh. The resulting deformation throughout the mesh is governed by standard equations of elastic deformation and standard yield criteria. This process conserves computational linearity and is continued until a clear result for regional stresses is obtained.

The initial modeling approximated the condition of weak coupling at the subduction interface by assigning the joint shear strengths between 50 and 100 times smaller than that of the surrounding plates, equivalent to yield stresses of 5-10 bars. Also this joint was placed at the trench. The modeled trajectories of greatest compressive stress provided reasonable fits to the P-axes from earthquakes in the Gorda block and near Vancouver. However, the low strength of the joint prevented successful modeling of stress trajectories in the overriding plate. For these trials the modeled vectors of greatest compression in the overriding plate were extremely small and had inconsistent orientations, when compared to the offshore stress trajectories. It is concluded that the condition of weak coupling at the subduction interface at Cascadia does not permit efficient tranfer of north-trending compression into the overriding plate.

The shear strengths used for the joint in the final modeling led to the best fit to the data for the modeled trajectories of greatest compressive stress in the overriding plate. In this modeling, the Juan de Fuca plate is strongly coupled, at the subduction interface, to the overriding plate. The southern and northern halves of the joint were assigned shear strengths of one-third and one-tenth, respectively, of the shear strength of the surrounding plates. These strengths correspond to the stresses that could exist in the time frame between large subduction earthquakes and are comparable to the stress drops generally observed for such earthquakes.

In Figure 5c the approximately north-trending lines chart the final scaled trajectories of greatest compressive stress, and the approximately east-trending lines (with diverging arrows)

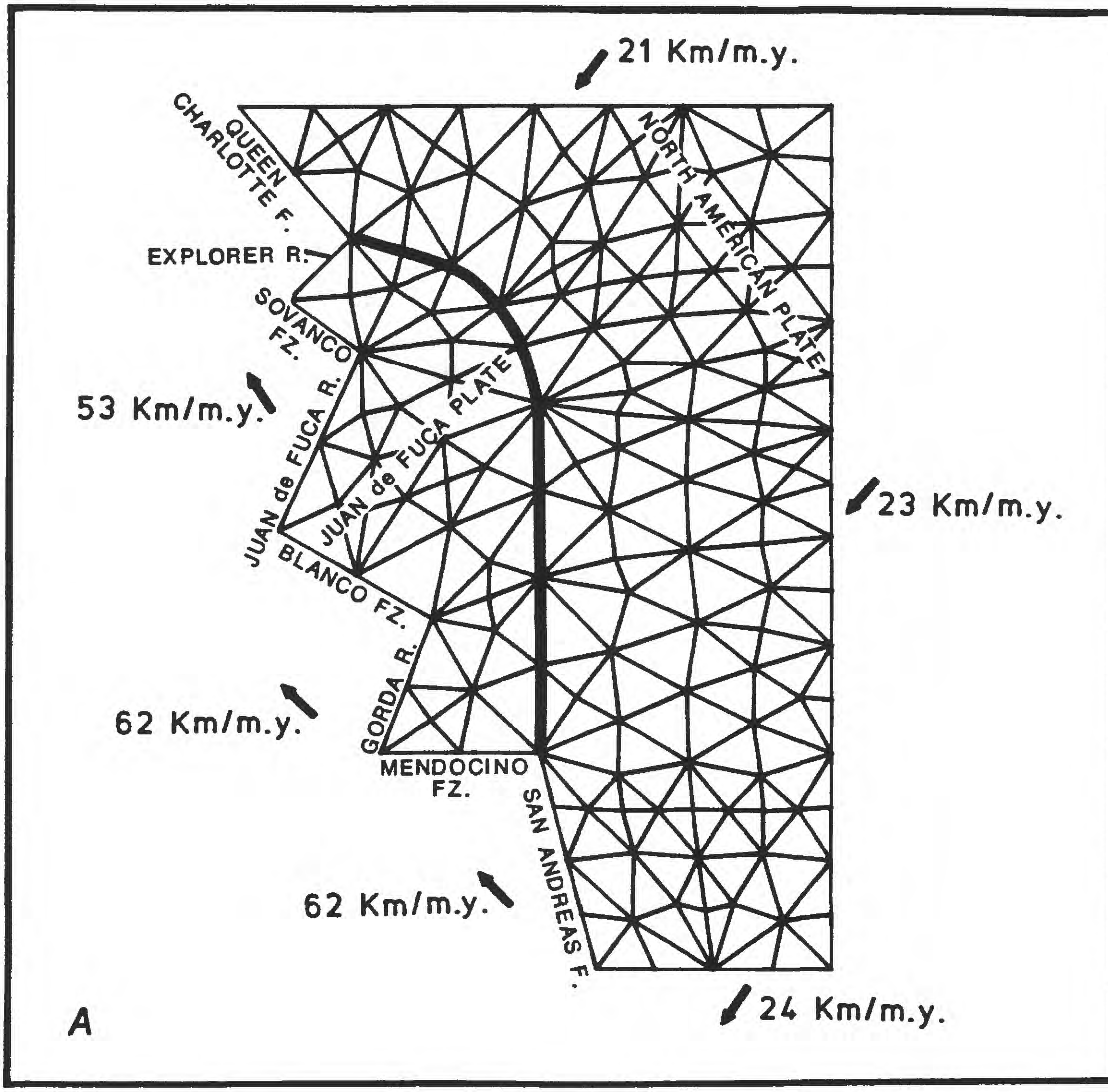

Figure 5. a. Stress and velocity boundary segments and discrete element mesh for the Cascadia plate system. The Gorda, Juan de Fuca, and Explorer ridges are stress-free boundary segments whereas the remaining eight boundary segments are specified by the x- and y-components of the absolute velocity of the bounding plate. The contact between the North American plate and the offshore plate system is represented by the midline of the shallow thrust zone of the subducting plate system.

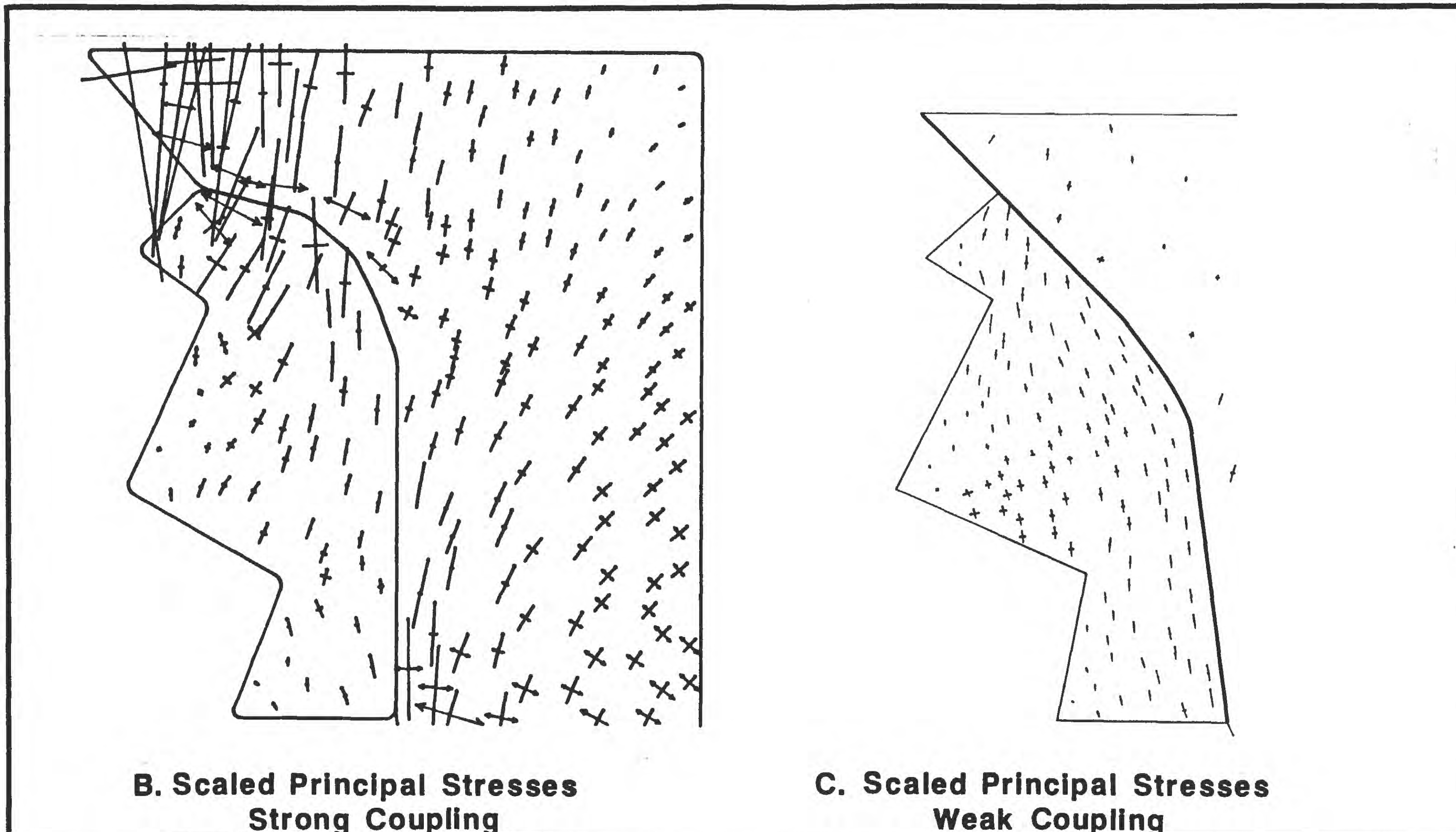

Figure 5b. Scaled greatest and least principal compressive stresses resulting from iterative propagation of boundary conditions through the discrete element mesh; condition of strong coupling between the offshore and continental plates. Approximately north-trending lines describe trajectories of greatest compressive stress; approximately east-trending lines (with diverging arrows) describe trajectories of least compressive stress. 5c. Same as 5b but with condition of weak coupling between the offshore and continental plates. Note lack of stress transferral from the offshore plate system to the continental plate.

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chart the final scaled trajectories of least compressive stress. The trend of the stress trajectories is controlled by the boundary between the offshore (subducting) and overriding plates. The trajectories of greatest compressive stress tend to parallel the contact between the oceanic and continental lithospheres at Oregon and Washington, but at the northwest-trending contact of northern Washington and Vancouver Island the trajectories cross this contact into the overriding plate. Thus the offshore system acts like an element of shear relative to the overriding plate, until blocked by the westward shift of the plate contact at northern Washington and Vancouver Island. The stress trajectories north of Vancouver have been exaggerated by the sharp curve of the joint there. In this modeling, the offshore shear is coupled into the overriding plate and yields predominantly northerly compression there, as observed.

A comparison of the axes of greatest and least compression for the shallow earthquakes of Table 1 (excluding the deeper events, 13-15) with the trajectories of greatest and least compression modeled in Figure 5c shows reasonable agreement. As expected, events 1 and 2 appear to reflect the motion of the Pacific plate at the Mendocine fracture zone, rather than stresses transmitted into the Gorda block. In Figure 6 the final calculated trajectories of greatest compressive stress are superposed on the seismicity and focal mechanism map of Figure 3. These trajectories generally are within about 15° of the axes of compression from the focal mechanisms of shallow earthquakes throughout the entire Cascadia region.

The success of this simple modeling confirms that the motion of the Pacific plate causes the northerly compression in the offshore Cascadian plate system and that this compression is strongly coupled into the overriding plate. The success of this modeling also indicates that the stresses that are implied from nearly all current shallow seismicity at Cascadia arise from sources that are independent of subduction processes there.

STRESSES DUE TO THE SUBDUCTED JUAN de FUCA PLATE

These stresses are due to the negative buoyancy of the subducted Juan de Fuca plate. This negative buoyancy is a function of the penetration depth, thickness, and density contrast of the subducted plate. Vertical sections of seismicity, taken perpendicular to the coast of northern Washington, indicate that subducted oceanic lithosphere penetrates to depths of at least 80 km (Crosson, 1983; Taber and Smith, 1985). Because volcanic arcs at subduction zones are associated with plate subducted to depths of about 100 km (Isacks and Barazangi, 1977; Gill, 1981), the presence of active Cascade volcanoes, from landward of mid-Vancouver (Meager Mt. and Mts. Cayley and Garibaldi) to east of Cape Mendocino (Lassen Peak), indicates that subducted plate extends at least to that depth throughout Cascadia. An inversion of teleseismic P-wave delays at seismic stations in Washington and northern Oregon (Michaelson and Weaver, 1986) shows that the Juan de Fuca plate has subducted to depths of 200-300 km.

Effects of slab pull forces in the subducted Juan de Fuca plate

Figure 7 is an E-W cross-section of seismicity of western Washington, based on results from a high-quality, regional seismograph network (Taber and Smith, 1985). Focal mechanisms for the shallow seismicity beneath Puget Sound reflect N-S compression (Crosson, 1972; Crosson, 1983; Yelin, 1982), transmitted there from the offshore plate stress regime. The deeper, east-dipping trend of seismicity is within the subducted Juan de Fuca plate. The dip of the probable interface thrust zone is about 11°E (Taber and Smith, 1985) and the dip of the deeper plate increases to 20 – 45°E (Taber and Smith, 1985; Michaelson and Weaver, 1986; Weaver and Baker, 1987). The zone of dip increase corresponds to the slab bend feature observed for most subduction zones (Spence). For typical subduction zones, great interface thrust earthquakes generally nucleate just updip of the slab bend and the associated ruptures then then propagate updip and laterally (Ruff and Kanamori, 1983). Downdip from the slab bend, earthquakes generally occur within the subducted plate. Focal mechanisms for earthquakes in the 11°E-dipping Juan de Fuca plate show an average tension axis that is downdip; no mechanisms

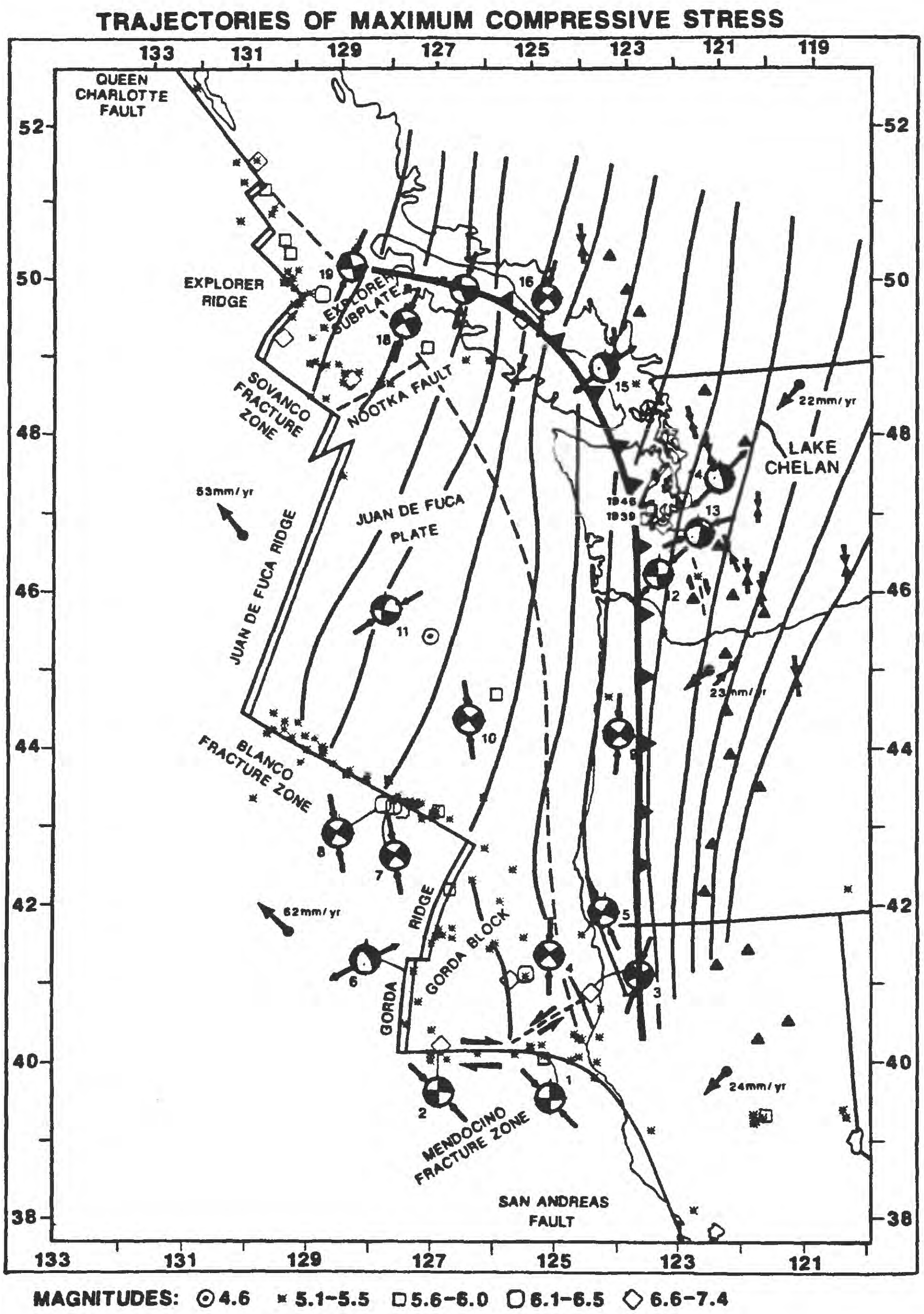

Figure 6. Smoothed modeled trajectories of greatest compressive stress (from fig. 5c) shown on map of earthquake locations and earthquake axes of greatest compressive stress (from fig. 3). There is good agreement between the modeled and observed directions of greatest compressive stress. This agreement implies that the regional stress pattern results from the Pacific plate's collision with the Gorda block and Juan de Fuca plate (at the Mendocino and Blanco fracture zones), the resistance by Vancouver I. to northward movement of the offshore plate system, and strong coupling between the offshore plate system and the North American plate.

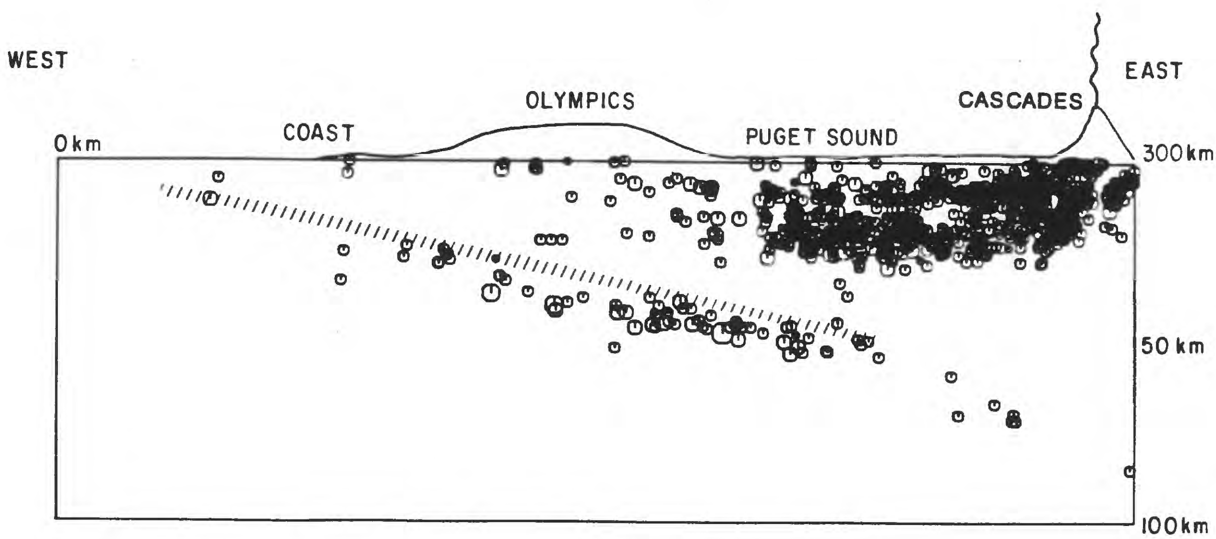

Figure 7. Cross-section of microearthquakes occurring beneath the Olympic Mts., indicated in Figure 3. Larger earthquakes in lower zone have average T-axes downdip, and are probably within subducted Juan de Fuca plate.(Taber and Smith, 1985).

exist that indicate thrusting at the interface thrust zone (Taber and Smith, 1985), which is probably near the hachured zone in Figure 7. It appears that the slab pull force has been transmitted updip past the slab bend to the zone beneath the locked interface thrust zone, giving the downdip tension axes for earthquakes observed by Taber and Smith (1985).

The earthquakes of 1949, (m_b 7.0, h 54 km), 1965 (m_b 6.5, h 59 km), and 1976 (m_b 5.2, h 60 km) (earthquakes 13 - 15 of Table 1 and Figure 3) occurred below the slab bend, downdip of the 11°E-dipping seismicity observed by Taber and Smith (1985) and Weaver and Baker (1988). These large extensional earthquakes, with downdip T-axes, reflect the slab pull force and sinking of more deeply subducted plate, and are interpreted as due to plate extension as the sinking of the Juan de Fuca plate is resisted at a locked interface thrust zone. Rogers (1983) notes other significant earthquakes probably below the slab bend to have occurred east of Victoria, Vancouver in 1909 (magnitude about 6) and at southern Puget Sound in 1946 (magnitude 6.3; Figure 3). Such earthquakes often are observed in other subduction zones (Isacks and Molnar, 1971; Fujita and Kanamori, 1981) but extensional earthquakes those older lithospheres typically extend to depths of 150-190km. Subsets of these downdip-extensional earthquakes appear to be indicative of forthcoming great subduction earthquakes (Spence, 1987; Dmowska and Lovison, 1988).

Velocity-density systematics and slab pull at Cascadia

Indications of the shape of, and P-wave velocity structure within, the subducted Juan de Fuca plate between 45 - 49°N, have been obtained from inversion of teleseismic P-waves that traversed that plate (Michaelson and Weaver, 1986). They suggest that the subducted Juan de Fuca plate is comprised of three sections, extending to depths of 200-300 km. Between 48.5 – 49.0° is a small, steeply-dipping section of plate, whose P-wave velocity is much greater than the surrounding mantle. The central section of plate extends southwards to about 47°N, dips $30 - 45^oE$ and its P-wave velocity is significantly higher than that of the surrounding mantle. The third section section extends southwards from 47°N, dips steeply, and has a P-wave velocity that is only slightly greater than the surrounding mantle. These results on the character of the subducted plate are only general features and are not highly-resolved (C. Weaver, personal communication, 1987), particularly for Oregon where there have been few seismic stations.

Velocity-density systematics, such as Birch's Law, imply that the greater the plate's seismic velocity contrast with the surrounding mantle, the greater the plate's density contrast and thus the greater the plate's slab pull force. The P-wave travel-time studies of Solomon and Butler (1974) and Michaelson and Weaver (1986) show that at Cascadia the subducted plate's P-wave velocity, compared with the surrounding mantle's P-wave velocity, is highest beneath Washington and southern Vancouver. The plate segments subducted there have by far the greatest rate of earthquake occurrence. This level of seismicity is consistent with the observed higher density contrast and implied greater slab pull force for that segment and the condition of a locked interface thrust zone. Conversely, the condition of very few earthquakes in the plate subducted beneath Oregon (Weaver and Baker, 1988) is consistent with the low density contrast observed for the most southern segment, and a small slab pull force there.

The variation of plate densities (and seismicity rates) for the segments of plate subducted beneath Washington and Oregon may be explained by the recent plate motion history of the Juan de Fuca plate (Riddihough, 1984). For the about the last 3 m.y. the absolute and relative poles of rotation of the Juan de Fuca plate have had rapid northward migrations (the absolute pole had moved northward into northern California by 1.5 m.y. ago). The slowest rate of penetration of the Juan de Fuca plate into the mantle is for the southern segment (Figure 1), giving it the greatest time to be warmed by the mantle, with a corresponding decrease in plate density. This decreasing density then leads to a corresponding decrease of the slab pull force, and contributes to the explanation for the continuing slowing of subduction of the southern segment. This in turn should lead to a self-perpetuating slowing of subduction for the remainder of Cascadia.

The boundary between the Cascadian central and southern segments is near 47°N (Michaelson and Weaver, 1986). The seismicity studies of Weaver and Baker (1988) indicate that offsets in dip of the subducted Juan de Fuca plate are smooth, and that the plate is not torn. Analogously, detailed between adjacent and different-dipping segments of the Nazca plate beneath southern Peru indicate that the plate is contorted and stretched (but not torn) by sinking plate forces (Hasegawa and Sacks, 1981; Schneider and Sacks, 1987). Modeling for subducted plates beneath the Apennine and Carpathina arcs only matched the dips of these plates by applying the loads to the negative buoyancies of these plates (Royden and Karner, 1984). Globally, it is clear that the negative buoyancy of a subducting plate is a primary determiner of the dip of subducted plates (Spence, 1987). The 1949, M_S 7.0, left-lateral, strike-slip earthquake is near the boundary of the southern and central segments of the Juan de Fuca plate (Baker and Langston, 1987). The 54-km focal depth for this earthquake clearly places it within the subducting plate (earthquake 13 of Figure 3 and Table 1). The T-axis trends southeast and dips parallel to the downdip trend of local seismicity (Weaver and Baker, 1988). This suggests that the 1949 earthquake is caused by the slab pull force, similar to most other earthquakes in this depth range, worldwide. Baker and Langston (1987) interpreted the E-W-trending, left-lateral, strike-slip faulting of the 1949 earthquake as evidence for downdip motion of the southern segment. However, there is virtually no independent evidence for differential downdip motion of the southern segment. An alternate explanation for the 1949 earthquake appeals to the greater density of the central segment. A preferential seaward sinking of the more dense central segment could produce a couple near the boundary between the central and southern segments that causes the east-trending, left-lateral shear observed for the 1949 earthquake.

SLAB PULL AS THE PRIMARY CAUSE OF TILT AND STRAIN AT SUBDUCTION ZONES

Crustal strains across the Strait of Juan de Fuca and in the Olympic Mts., determined from geodetic measurements, show low but significant compression parallel to the theoretical direction of plate convergence (Savage et al., 1981; Lisowski et al., 1987). Contraction parallel to the direction of plate convergence commonly is observed prior to subduction earthquakes along the Pacific coast of Japan (Shimazaki, 1974). Thus the crustal shortening at Cascadia is interpreted as due to the subducted plate's motion being resisted at the locked interface thrust zone.

Oceanward tilting of the Japanese coast (coastal depression) is observed both before and after great interface, thrust earthquakes. Exactly the opposite sense of tilting accompanies the rupture of an interface thrust earthquake (Shimazaki, 1974). The elastic coupling of the subducting plate to the overriding plate (which produces a 'drag') causes the preseismic and postseismic oceanward tilting, whereas rebound of the overriding plate causes the coseismic landward tilting (coastal uplift). At the coast of Washington and Oregon, there are many observations of landward tilt (coastal uplift with some inland depression). Precise leveling over a 70-year period shows a landward tilt of western Washington (Ando and Balazs, 1979). Reilinger and Adams (1982) used leveling routes that extended south through Oregon and found landward tilt for the entire zone. These short-term rates of tilt substantially are the same as rates of tilt over the last 100,000-500,000 years, indicated by uplift of coastal marine terraces (Reilinger and Adams, 1982; Adams, 1984). Because coastal uplift at Japan accompanies subduction earthquakes, Ando and Balasz (1979) interpreted the coastal uplift in the absence of subduction earthquakes at Cascadia as implying aseismic subduction there.

Partially successful modelings of tilt observations at Japan have been achieved by Savage (1983) and Thatcher and Rundle (1984), who assumed steady-state preseismic and postseismic slip of the subducted plate along a shallow, subduction interface with a fixed dip of 30°. The results of such modeling for Japanese earthquakes possibly could be improved by incorporating the more realistic dip of about 10° for the interface thrust zone and plate dip of about 50° just downdip of the lower tip of the locked interface (Hasegawa et al., 1978; Yoshii, 1979; Kawakatsu and Seno, 1983) and by including some vertical deformation just downdip of the slab bend (Kato, 1979). Kato's (1979) results not only fit deformation above the interface thrust zone but also fit the vertical deformation observed inland. Kato's results imply that the slab pull load applied at the downdip tip of an interface thrust zone will have one component delivered through the stress-guide of subducted plate, causing localized compression at a locked interface thrust zone, and a second component producing a downward moment on the oceanic plate at the slab bend, causing depression centered above the slab bend.

If the slab pull force, acting through the slab bend, is the primary cause of vertical deformation in the region of a locked interface thrust zone, then the distance from the slab bend to the oceanic trench physically is more meaningful than the distance from the coast to the oceanic trench. Figure 8 shows six well-defined seismicity cross-sections, aligned at the downdip tips of the interface thrust zones (equivalently, at the updip ends of the slab bends). The slab pull force, F_{SP}, is indicated in Figure 8, with one component parallel to the plate, $F_{\|}$, and the other component perpendicular to the plate's surface, F_N. The $F_{\|}$ is guided updip in the plate (leading to the extensional earthquakes in Figure 7) and causes compression in the overriding plate.

The numbers on four of the sections in Figure 8 are beneath the corresponding coasts. This shows that the coasts of Peru and NE Japan are landward of their slab bends, whereas the coasts of Cascadia and C. Chile are seaward of their slab bends. Spence (1987) noted that the seaward propagation of slab bends and the downdip mass transfer that occurs at slab bends should lead to surface depressions above those features. At the Olympic Mountains section of Cascadia, the slab bend is at the transition from the shallow, 11°E-dipping thrust (Figure 7) to the deeper, 20 – 45°E-dipping plate. South of the Olympic Mountains the slab bend is smoothly shifted westward and then assumes a southerly trend (Weaver and Baker, 1988). The Puget Sound depression (where Ando and Balasz [1979] observed subsidence of 1-2 mm/yr) and its Oregon extension, the Willamette Valley, lie directly above the slab bend of the subducted plate. The Central Valley of C. Chile is above the slab bend there (Kadinsky-Cade, 1985). When slab bends occur offshore, forearc basins actively develop. The Java outer arc and Lombok basins (Hamilton, 1979) are above the corresponding slab bend (profile 5) and the subsiding deep-sea terrace off NE Japan (von Huene et al., 1978) is above the slab bend there (profile 3). The Lima basin, offshore of central Peru, is above the local slab bend (Langer and Spence, in press), and has subsided >1100 m within the last 0.93-0.98 m.y. (Kulm et al., 1981). The long-term subsidence rate for Puget Sound is similar to that of the Lima basin. This paragraph has shown that active subsidence occurs above the slab bend feature of subducting plates. The slab bend feature is a response to the summed slab pull force of deeper plate and is a continually developing feature (Spence, 1987). The downdip mass transfer at a continually-developing slab bend is an explanation for the surface subsidence above a slab bend.

Figure 9 is a schematic showing a downward bending moment applied to the subducted Juan de Fuca plate at the downdip end of the interface thrust zone beneath the Olympics. This vertical moment would be analogous to the downward bending moment that causes plate bending beneath an oceanic trench (Chapple and Forsyth, 1979; Caldwell et al., 1976). Updip of a slab bend, analogous to the rise occurring seaward of an oceanic trench, the bending plate should have an upward flexure. In Figure 9, the upward flexure of this bending beam is scaled to correspond to the observed vertical deformation at western Washington. This model qualitatively explains the depression at the Puget Sound region and the uplift at the

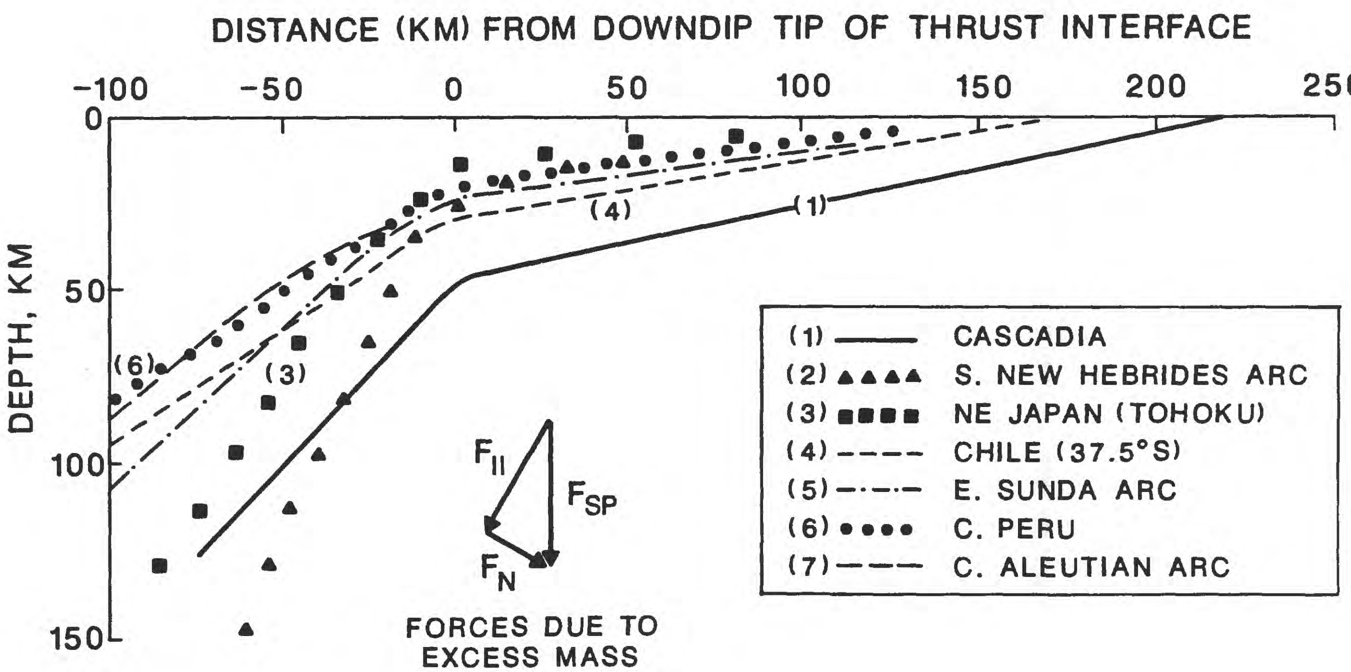

Figure 8. Cross-sections of well-resolved plate dips, plotted as distance from downdip end of interface thrust zone (equivalently, near updip end of slab bend), positive to trench. Numbers on profiles correspond to positions of coasts. Distance from slab bend to Washington trench is anomalously large. Inset shows slab pull force, F_{SP}, the component parallel to subducted plate, $F_{\parallel}$, and the component normal to subducted slab, F_N. These components of the slab pull force cause stress to accumulate at the shallow, interface thrust zone and lead to the strain and vertical deformation observed at the surface. Data sources for profiles are (1) Taber and Smith, 1985; Michaelson and Weaver, 1986; (2) Coudert al., 1981; (3) Hasegawa et al., 1978; (4) Kadinsky-Cade (5) Spence, 1986; (6) Langer and Spence (in press); (7) Hauksson, 1985.

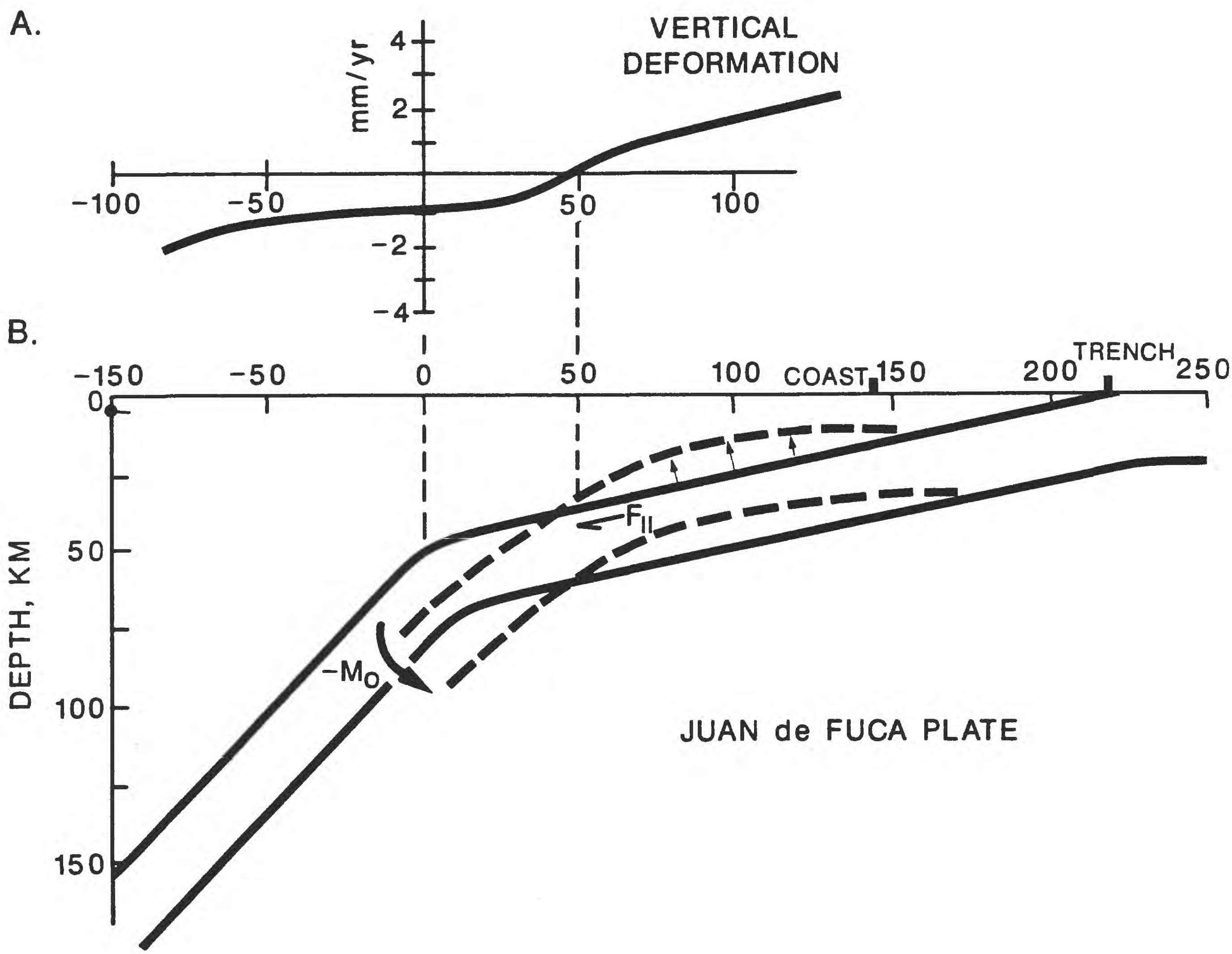

Figure 9. A. Observed vertical deformation above subducted Juan de Fuca plate (Reilinger and Adams, 1982). Surface depression is above slab bend zone, whereas surface uplift is above upwardly flexed plate. Plate flexure in (B) is drawn to align with observed vertical deformation. B. Solid line is top surface of Juan de Fuca plate at western Washington. Bending moment $(-M_o)$ due to slab pull force is applied at downdip tip of interface thrust zone, causing plate flexure as shown. $F_{||}$ is the component of the slab pull force that is transmitted through the subducted plate but is resisted at the interface contact (see inset in Figure 8).

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Washington coast for a strongly coupled interface. As mentioned, Ando and Balazs (1979) combined the observations of landward tilt in Japan being associated with the coseismic phase of subduction at Japan and lack of interface thrust earthquakes at Cascadia, to interpret the Washington tilt data as reflecting aseismic subduction. However, Figures 8 and 9 show that because the slab bend is landward of the Cascadian coast but is seaward of the Japanese coast that, for a given part of the earthquake cycle at these two locations, coastal uplift and depression should be exactly out of phase. Thus the coastal uplift at Cascadia is analogous to the preseismic or postseismic coastal depression at Japan, and is consistent with a locked interface thrust zone at Cascadia. This interpretation supports Atwater's (1987) interpretation of coseismic subsidence at Cascadia.

DISCUSSION

A factor that complicates evaluation of subduction processes at Cascadia is the pervasive north-trending compression caused by the motion of the Pacific plate. This compression may lead to increased earthquake activity within the horizontal Juan de Fuca plate, and ultimatly, further fragmentation and northward motion of these plate fragments. A more complete and systematic survey of stresses in and offshore of Vancouver, Washington, and Oregon is important to better define the regional stress field.

Seismic or aseismic subduction at Cascadia?

Figure 2 indicates that seismic coupling at an interface thrust zone is inversely related to the age of the subducting oceanic plate. Because the Juan de Fuca plate is one of the youngest oceanic plates at a subduction zone it is implied that the seismic coupling at the Cascadia subduction zone is very great (Ruff and Kanamori, 1980: Spence, 1987). Of the seven sections in Figure 8, the greatest downdip extent of interface thrust zone is that beneath Washington's Olympic Mountains. This relates to the buoyancy of the young plate subducted beneath Washington and implies high resistance to subduction. However, Kanamori and Astiz (1985), using data from subduction of young oceanic lithosphere at Mexico, tentatively concluded that the majority of slip at the Cascadia subduction zone is aseismic. This is consistent with Ando and Balazs' (1979) interpretation of geodetic data to imply aseismic subduction at Cascadia. The observation that the Gorda block subducts very slowly or actually has ceased subducting implies that subduction there is greatly resisted and this circumstance is a regional analog to contradict the hypothesis that subduction at the remainder of Cascadia is occurring aseismically. The normal-faulting earthquakes within the subducted Juan de Fuca plate (Table 1; Taber and Smith, 1985) suggest that the sinking plate is pulling against a locked subduction interface (Spence, 1987). Strain data at western Washington and southwestern British Columbia that show crustal shortening about parallel to the theoretical direction of plate convergence, (Savage et al., 1981; Lisowski et al., 1987) and observed shortening across the coast of Oregon (Adams, 1984) both indicate a substantially locked interface thrust zone. The data of Atwater (1987), showing sudden coastal subsidences, were explained earlier by preseismic bending of the locked, shallow plate interface. Finally, the discrete modeling done in an earlier section only leads to satisfactory matching of the northerly compression throughout Washington and Vancouver by imposing a strong coupling at the shallow, subduction interface.

Subduction that is nearly aseismic, with only small-to-moderate interface thrust earthquakes, usually is associated with very old oceanic lithosphere. A good example exists for the eastern Sunda arc, where subducting oceanic lithosphere is about 145 m.y. old. The great slab pull force of this very old plate largely has decoupled the local interface thrust zone and much of this slab pull force is transmitted updip to cause normal-faulting earthquakes near the eastern Sunda trench (Spence, 1986). If the interface thrust zone at Cascadia were decoupled, then we should observe normal-faulting earthquakes near the Washington-Oregon trench. No such earthquakes are known. The arguments of this section indicate that aseismic subduction is not significant at the Cascadia subduction zone and that the interface thrust zone essentially is locked.

Holocene subduction earthquakes at Cascadia

The works of Atwater (1987) and Atwater et al. (1988) show that, in the last 5,000 years, there have been several sudden burials of coastal vegetation at western Washington. These studies suggest that the burials likely are due to coseismic subsidence associated with great subduction zone earthquakes, and the studies seem to be able to discount other possible explanations such as major storm surges, tsunamis from distant sources, or sudden compaction due to large, crustal earthquakes. The finding of a regional coherence of Cascadian burial events and a systematic timing of these burials would help substantiate Atwater's hypothesis. The model presented in this paper supports the hypothesis of coseismic coastal subsidence associated with a subduction earthquake at Washington. The model also predicts uplifts in Puget Sound that correspond in space and time to the inferred coastal depressions.

The studies of sudden subsidences are complicated by the uncertainty in ^{14}C dating of about ± 70 years. For example (assuming an earthquake origin of the sudden subsidences), an apparent regional coherence for a burial event 300 years ago over the coastal zone 43° - 49°N could not distinguish, on the basis of ^{14}C dating, between one M $\sim$ 9 earthquake and four M $\sim$ 8 earthquakes that occurred over a span of 100 years.

This discussion is hypothetical because no instrumentally-recorded earthquakes, of any magnitude, are known to have occurred at Cascadia's subduction interface (Taber and Smith, 1985; Heaton and Hartzell, 1986). Assuming that subduction earthquakes do occur at Cascadia, the absence of interface earthquakes is most simply explained as there being a great time remaining to the end of the present earthquake cycle and that present stresses at the subduction interface are insufficient to produce even small interface earthquakes.

What are some probable characteristics of subduction earthquakes at Cascadia? Because globally there are no examples where an entire subduction zone has ruptured with a single earthquake, it seems unlikely that the entire Cascadia zone would rupture with a single earthquake, of M $\sim$ 9. Subduction zones typically are comprised of segments, each of which has characteristic physical properties that determine the repeat time for the segment. The independence of motions of the Gorda block and the Explorer subplate indicate that the corresponding plate contacts are segments of the Cascadia subduction zone. There are at least four other likely segments at the Cascadia subduction zone. The two northernmost of these, 47.0 - 48.5°N and 48.5 - 49.0°N (Riddihough, 1984; Michaelson and Weaver, 1986), have the greatest seismicity within the subducted plate and the subducted plate segments have characteristic densities and dips. The interval 45.0 - 47.0°N has a lower, but significant, in-plate seismicity rate (Weaver and Baker, 1988) and this subducted plate segment has characteristic density and dip (Michaelson and Weaver, 1986). Finally, the interval 43.0 - 45.0°N, which extends to the northern end of the Gorda block, has a very low seismicity rate within the subducted plate. These six segments may have independent and characteristic repeat times for subduction earthquakes. Occasional subduction earthquakes could rupture two or more segments, as has been observed in other subduction zones. Based on analogy with other subduction earthquakes, earthquakes at these segments would initiate just updip of the slab bend (beneath Puget Sound and Willamette Valley), with sudden displacements extending updip past the coast.

Figure 1 shows that at 0.5 m.y. ago the absolute motion of the northern end of the Juan de Fuca plate was about twice that of the southern end of this plate. Moreover, the 60% slowing of subduction of the Juan de Fuca plate over the last 6.5 m.y. suggests that the time between successive earthquakes at a plate segment must be increasing. Given the complicated recent subduction history at Cascadia it is possible that the subduction rate beneath southern Oregon has slowed further still. The extremely low level of seismicity within the subducted portions of the two most southern segments (Gorda block and 43°-45°N) suggests that subduction nearly may have ceased there. The plate segments beneath northern Washington and southern Vancouver (47.0 - 49.0°N) have the highest density contrast and the greatest slab pull force. Thus the Cascadian slab pull forces should provide a clockwise torque to the subducting Juan de Fuca plate. The factors mentioned here may contribute to independent repeat times for earthquakes at the Cascadian plate segments.

The northerly compression throughout much of Cascadia is superposed on the shallow stresses resulting from the slab pull force. During a Cascadian interface thrust earthquake (when the interface momentarily is decoupled) it is likely that the dip-slip motion will be accompanied by right-lateral translation of the corresponding segment of the offshore plate system.

Seaward motion of both the Gorda-Juan de Fuca-Explorer plate system and the subducted Juan de Fuca plate

The Juan de Fuca ridge now is moving westward in the absolute/hot spot reference frame at about the same speed as the North American plate (R. Riddihough, written communication, 1987). Seaward propagation of the Juan de Fuca spreading centers is required to explain the pseudofaults and pattern of magnetic anomalies there (Hey, 1977; Wilson et al., 1984). The tectonic characteristics of the Gorda block indicates that it is very strongly coupled to the North American plate. Such translation of the Juan de Fuca plate system can occur without a buildup of southwestward compression because the west side of this plate system continually is unloaded due to the Pacific plate's pulling away from the west side of the Cascadian spreading centers.

The F_N component of the slab pull force tends to make the subducted plate propagate seaward (Garfunkel et al., 1986; Carlson and Melia, 1984) and, in the case of Casdadia, helps the subducted Juan de Fuca plate retain its dip even though the North American plate is moving southwestward. If the subducted plate were sinking seaward faster than the rate of advance of the North American plate (with the volcanic arc accompanying the westward propagation of the subducted plate), then sufficient conditions exist for the opening of a back-arc basin. Carlson and Hart (1987) describe how mantle flow, resulting from rapidly changing convergence rates of the Farallon plate system over the last 18 my, may have led to the volcanic flows of the Oregon Plateau and also suggest possibly similar histories for the Basin and Range province and the Colombia Plateau. The young age of the subducting lithosphere at the Cascadia subduction zone makes it unlike typical subduction zones that exhibit back-arc spreading (Uyeda and Kanamori, 1979; Garfunkel et al., 1986) [see Figure 2]. Carlson and Hart (1987) summarize similarities and differences between the Oregon Plateau and back-arc basins of the Western Pacific. It appears that the young age of Farallon plate subducted beneath Cascadia has led to a form of back-arc development, but less well-developed than associated with the subduction of much older oceanic lithospheres in the Western Pacific.

The Lake Chelan earthquake of December 14, 1872

Historically, this may be the largest earthquake (M ~ 7) to occur in crustal Washington and Oregon, and it is a key earthquake in seismic hazard studies for the U. S. Pacific Northwest (Hopper et al., 1975). The primary aftershocks of the Lake Chelan earthquake continued for about 2-1/2 years and often caused aquifer disturbances at Lake Chelan, implying a shallow focal depth for these earthquakes (Hopper et al., 1988). Rasmussen's (1967) seismic history of Washington indicates numerous felt earthquakes near Lake Chelan. The shallow depth implied for the Lake Chelan earthquake differs from suggested focal depths of about 60 km (Malone and Bor, 1979) and of 100-150 km (Michaelson and Weaver, 1986), who assumed that the 1872 earthquake occurred in the subducted Juan de Fuca plate. Neither the 1949 nor the 1965 earthquakes, the largest known to occur within the subducted Juan de Fuca plate, had extensive aftershock series (Algermissen and Harding, 1965) and, moreover, no microearthquakes are known in the subducted Juan de Fuca plate with depths as great as 100 km (Crosson, 1983; Taber and Smith, 1985). These data, combined with analysis of the intensity attenuation pattern for the main shock (Hopper et al., 1988), indicate a shallow, crustal focal depth, perhaps along the trend of Lake Chelan.

Given that the focal mechanisms of shallow earthquakes (mostly strike-slip) throughout much of Vancouver and Washington have N-trending compression axes and given the high, shallow horizontal stresses in central Washington, also with N-trending compression axes, it is reasonable that the shallow Lake Chelan earthquake occurred on a fault that was actived by this regional north-trending compression.

CONCLUSIONS

The collision of the northwestward-moving Pacific plate with the Mendocino and Blanco fracture zones causes compression in the offshore plate system northwards to Vancouver Island. The northward compression in the offshore plate system is strongly coupled into the overriding plate, causing northward compression there. Virtually all shallow seismicity at Cascadia is due to this north-trending compression, which is independent of subduction processes there. The observed earthquakes and implied high compression indicate significant risk from large crustal earthquakes in both the offshore and overriding plates. Additional sources of lithospheric stress at the Cascadia subduction zone are the slab pull force of subducted Juan de Fuca plate (capable of producing large earthquakes within the subducted plate), the relatively minor 'ridge push' force of the horizontal Juan de Fuca plate, and force due to the southwestward motion of the overriding plate. The stress at any part of the Cascadia subduction zone is a superposition of stresses from these sources. Specific zones within the Cascadia region have distinct modes of deformation, usually because of the proximity of a zone to one of the primary stress sources or to a major resistance to plate movement.

The subducting plate dips at about 11°E for a distance of about 180 – 220 km, and then the plate dip steepens to 20 – 45°E. It is hypothesized that the slab pull force acting at this slab bend causes surface depression above the bend (at Puget Sound and Willamette Valley), and an upwarp of plate that is updip from the bend, leading to coastal uplift. The opposite vertical deformation would accompany a subduction earthquake, consistent with the observations of Atwater (1987). Much evidence indicates that subduction is not occurring aseismically, but probably is accompanied by significant subduction earthquakes. The Cascadian subduction zone is segmented and each segment probably has independent seismic potential.

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IMPLICATIONS OF LATE HOLOCENE SALT-MARSH STRATIGRAPHY FOR EARTHQUAKE RECURRENCE ALONG THE COAST OF SOUTH-CENTERAL OREGON

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INTRODUCTION

Repeated, great plate-interface earthquakes have been postulated for the Cascadia subduction zone in western Washington and Oregon. The best evidence of the coseismic subsidence to be expected near the coast during great earthquakes is found in southwestern Washington where many exposures record repeated episodes of submergence of late Holocene marshes. Atwater and others have used consistent stratigraphic relationships, ^{14}C ages, and plant macrofossils from sequences of interbedded marsh peats and intertidal muds to show that the 6 marsh peats buried in the last 4000 years throughout southwestern Washington were submerged suddenly. The late Holocene estuarine record in the central part of the subduction zone in Oregon is more difficult to interpret; there are very few good exposures, and coring at some sites has produced evidence of a gradual rise of late Holocene sea level while sea level rise appears to be jerky at other sites.

MARSH FORAMINIFERA AS SEA LEVEL INDICATORS

One of our goals is to show if the peats we find interbedded with muds in cores from the central Oregon coast were submerged suddenly (coseismicaly), like those in Washington. Marsh foraminifera are more sensitive to changes in sea level than many marsh plants and are easier to identify in cores. Thus, we have begun to use foraminifera faunas in cores from Oregon marshes to test whether our buried peats represent jerky (repeated coseismic) marsh subsidence. Because no studies of modern marsh foraminifera from the region have been done, one of our first objectives is to show if modern marsh subenvironments at different elevations can be distinguished using foraminifera faunas.

Analyses of samples from surface transects of the first two of five Oregon marshes studied show the same strong correlation between foraminiferal assemblage zones and sea level found in other marshes worldwide. Three (informal) assemblage zones can be recognized in the transects studied so far: a high-marsh zone, an upper-low-marsh zone, and a low-marsh--mud-flat zone. Tide-gauge data are not available for either site, but the distribution of high and low marsh and the position of mean high water can be estimated from macrofloras. The highest samples in each transect, on the upland border, are barren of foraminifera. Samples from the upper part of the high-marsh zone are dominated by *Trochammina macrescens* and *Trochammina inflata* with lesser numbers of *Miliammina fusca* and *Haplophragmoides wilberti*. The percentage of *M. fusca* increases towards the base of the high marsh zone. Where *M. fusca* becomes the dominant species over *T. macrescens*, *T. inflata*, and other species we recognize an upper-low-marsh zone. In both transects this zone includes a 0.5- to 1-m-high, nearly vertical scarp resulting from modern erosion of the low marsh. In the low-marsh--mud-flat zone *M. fusca* and *Ammotium salsum* co-dominate, *Trochammina* is absent, and *Reophax nana* and calcareous species become increasing abundant with decreasing elevation. On the basis of these preliminary analyses, we should be able to identify former sudden changes in sea level of about 0.5-1.0 m in future analyses of cores from Oregon estuaries. Studies incorporating more accurate vertical control and more detailed sampling might be able to resolve significantly smaller changes in sea level.

CHARACTER OF SEA LEVEL RISE INDICATED BY MARSH STRATIGRAPHY

Preliminary coring and study of outcrops at 12 marsh sites in seven tidal inlets yields conflicting evidence for the history of relative sea level along the south-central Oregon coast. Additional radiocarbon dates from most of these sequences are pending.

At sites in the eastern arms of Coos Bay, one probable buried marsh surface is found in the upper 1 m of most cores overlying 4-6 m of uniform mud. In some cores both upper and lower contacts of peaty units are gradational, but in most cores the thickest peat bed has a fairly abrupt upper contact suggesting sudden submergence of a marsh. A spruce root from this buried surface in Shinglehouse Slough was dated at 340 ^{14}C yrBP. One interpretation of this type of marsh sequence is that sediment deposition rates in most tidal inlets have been low during all but the last few hundred years of the late Holocene and that for this reason no evidence (buried marsh surfaces) of earlier sudden submergence events has been preserved. Another interpretation is that no sudden changes in sea level have occurred.

In contrast, at two sites in South Slough in western Coos Bay, cores show 6-8 abruptly buried marsh surfaces that are 0.4-1.2 m apart. Extensive coring in a small marsh along Winchester Creek revealed up to 8 buried marsh surfaces in sections 5-8 m thick. The 4 best-developed surfaces can be correlated across the inlet. The uppermost buried surface has a modern ^{14}C age; it must have been buried by sedimentation following diking of the marsh. Lower surfaces date at 460 (2.2 m) and 2880 (2.8 m) ^{14}C yrBP, indicating highly non-uniform sedimentation rates. A core from Day Creek (described with C. Peterson and M. Darienzo, OSU), 4 km to the north, had a similar sequence of 6 buried surfaces. These sites are near the axis of the South Slough syncline, and tilted marine terraces on the west limb of the syncline document continued late Pleistocene folding of this structure. Thus, the South Slough buried surfaces may record local Holocene coseismic faulting or folding rather than regional deformation of the central Oregon coast during great plate-interface earthquakes. Alternatively, sudden slip on flexure slip faults within the syncline might also occur primarily as a response to large subduction zone earthquakes.

Coring in South Inlet, an arm of the Siuslaw River estuary, shows that 4 m of fairly uniform peat overlies 4 m of mud. This type of marsh sequence suggests that late Holocene relative sea-level rise was gradual with no abrupt changes in the type or rate of sedimentation. Subtle, gradual lithologic changes within the peat section suggest only small, gradual changes in sea level. Abrupt lithologic changes found in some cores farther up the valley of South Inlet probably record stream flood events.

Most cores in the Umpqua River estuary showed peaty beds in the upper 1.5 m of the cores, but the upper and lower contacts of most beds were gradational. Abrupt contacts bounding some units could be due to sudden submergence or flooding. As in Coos Bay, below 1.5 m only muds were found to 7 m depth in the cores. A ^{14}C age of 3.1 ka from a depth of 6 m in one core indicates that the relative rate of sea level rise here is twice the rate in Coos Bay, or that a great deal of differential compaction has taken place in these peat-mud sequences.

A single buried marsh surface was described in outcrop along the Coquille River estuary at a depth of 1.2 m. A small spruce stump rooted in the surface was dated at 290 ^{14}C yrBP. The estuarine muds that bury the surface are overlain by overbank silts deposited by river flooding and by eolian sands derived from dune fields to the west.

Thus, the most recent buried marsh surface, which may date from about 300 yrBP, appears to be fairly widespread along this part of the Oregon coast. Good evidence for earlier submergence events is found only in South Slough. To show whether or not the earlier submergence events found in South Slough have regional extent emphasis in FY88 will be placed on coring less-protected sites in inlets with moderate-size streams. The moderately high sedimentation rates in marshes at these sites should have allowed marshes to develop and be preserved following all major submergence events.

DIFFERENTIAL QUATERNARY UPLIFT OF THE WESTERN OREGON COAST RANGE INDICATED BY RIVER GRADIENT AND RIVER VALLEY SHAPE

By

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INTRODUCTION

The problem under investigation is whether or not river gradient and river valley shape can be used to discern tectonic movement during the Quaternary. If active subductiion is continuing in western Oregon some portions of the Coast Range should experience uplift and other portions subsidence (Spence, in press; Atwater, 1987). On most rivers, gradient decreases and discharge increases downstream. In a graded system, there is a smooth decrease in slope. In a system that is not fully graded, there are sections of the river where the change in slope is irregular, and some environmental or geologic factor may influence the gradient. For example, where a tributary joins the main channel there is usually a sudden decrease in river slope, which is inversely proportional to the increase in discharge from the tributary, although this does not always occur. Where the river bottom crosses a geologic contact or fault, slope changes are usually observed and they are often related to changing resistance across the boundary. River gradients and valley shape can be indicative of the lithology the river flows through. River gradients and valley shape can also indicate uplift or subsidence. Uplift causes flooding upstream and accelerated downcutting downstream. These effects can be observed on the river's profile as a region of relatively low slope followed by a region of high slope. Where the zone of uplift is narrow, a knickpoint forms, but within a broad zone of uplift the river gradient is usually convex. Subsidence causes similar river adjustment, except downcutting is observed upstream and flooding is observed downstream. Subsidence produces a concave profile. Because all these factors may effect the river's profile and valley shape, each must be carefully considered before conclusions can be drawn.

Recent studies using river profile data in coastal South Carolina (Rhea, in press), Arkansas' Ozark Mountains (McKeown, 1988) and central South Dakota have demonstrated the correlation of river gradient anomalies with local or regional uplift. Other investigations in Costa Rica (Wells and others, 1987), Eastern Papua New Guinea (Pain, 1983), the Maryland Piedmont (Costa, 1984), and the laboratory (Ouchi, 1983) concluded that using river profile data helps to identify areas of differential tectonic movement. Maclean (1985) measured different river and valley shape parameters in the Wasatch Range and her conclusions supported the fault segmentation hypothesis. Neim (1976) examined river morphology in the central Oregon Coast Range and determined that although knickpoints and valley shape correlated with lithology, entrenched meanders were not related to either faults or bedrock lithology.

For this study, modern river channel location and elevation data for 22 rivers and tributaries on the coast of Oregon were digitized from $7\frac{1}{2}'$ and 15′ topographic quadrangle maps. River lengths varied from under 25 km to over 350 km. Relief varied from 100 m on some of the shorter tributaries, to over 1600 m on the longer rivers. The ratio of relief to length ranged from .2 to 3.6%. Hypsometric integrals or the ratio of the area below the profile to the area defined by length and height, is a measure of how much of the region has not been erroded; these integrals ranged from 7 to 43%. Changes in river slope and valley shape were compared to regional bedrock mapping (Peck's 1961).

OBSERVATIONS AND INFERENCES

Graphs of river elevation versus length were generated for each river, along with the theoretical profile, which predicts exponentially decreasing slope with length. The exponential decay of each theoretical profile is dependent on the hypsometric integral, and is therefore independent for each river, but the smooth reference profile with constant decay downstream generalizes the profile so that relationships between the theoretical and observed profile for one river can be compared to relationships on another river.

Inflection points and broad convexities were observed on river profiles and were compared to maps showing the locations of tributary junctions and lithologic and structural changes along the rivers' courses. Overall, increased discharge resulted in decreased slope downstream, but there were places where a major tributary joined the main channel and no increase in slope occurred. On several rivers there were increases in slope at tributary junctions, opposite to expectations. Nearly all of the slope irregularities were coincident with geologic contacts and intrusions, such as massive basalts adjacent to estuarine and marine sediments. Generally, inflections occurred as the river flowed from a less resistant formation to a more resistant formation, such as from marine sediments onto a mafic intrusion.

Not all of the anomalous slopes could be explained by changes in stream development or in predicted adjustments to lithologic or structural changes. For example, a steep section of the Siletz River flows through a resistant mafic intrusion, while the river gradient decreases on the more erodable marine sedimentary rocks downstream. There also were areas of slope change that were not associated either with tributary junction or mapped geology.

Other significant observations from the river and valley data included: (1) in the headwaters gradients were very high (in excess of 100 m/km) and valleys were relatively wide, (2) on the middle sections of many rivers there were slope convexities and valleys were relatively narrow and deep, and (3) many rivers ended with slope *increases*. (See examples in following figure.) The slope increases at river mouths may indicate tectonic movement, either subsidence off the coast or uplift farther inland. If base level lowering at the coast is accepted, the flat section upriver could only have been created during a long period of tectonic stability, an unlikely possibility given the tectonic history of the Oregon coast. If, instead, the slope convexities midriver were caused by uplift 50 to 100 km landward of the coast, both the steepening downstream and flattening upstream would be explained. Thus, the convex gradients and steep-sided, V-shaped valleys in the lower third of the river valleys suggest significant rates of uplift in the later Quaternary.

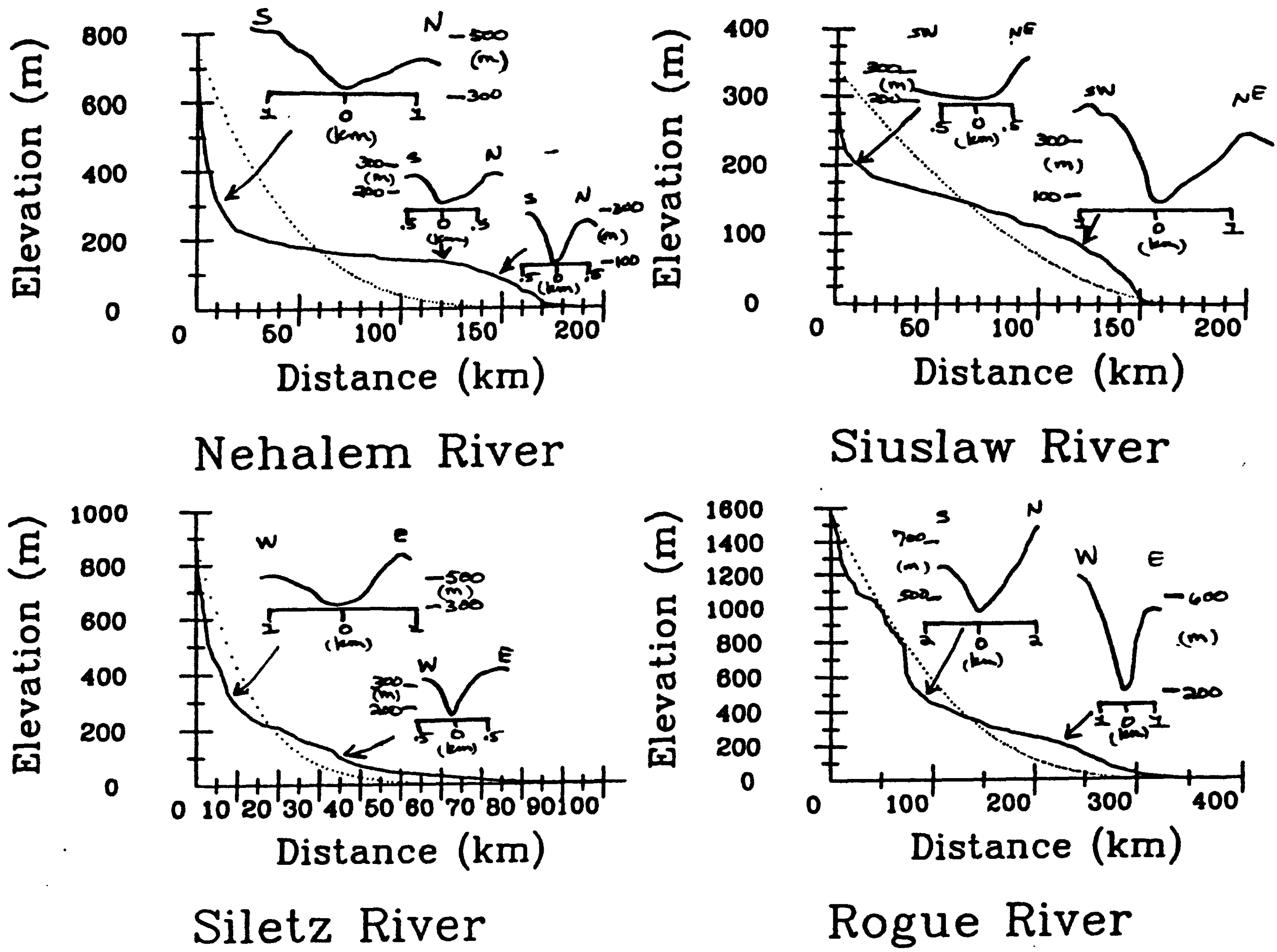

Figure 1. River profiles for four rivers studied in the Oregon Coast Range. Dotted line represents theoretical profile (see text). Valley shapes at several places along river are included, demonstrating entrenching on downstream flat sections of rivers. Convex profiles toward mouths of rivers suggest Quaternary uplift within 50 to 100 km of the coast.

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FLUVIAL TERRACES IN THE OREGON COAST RANGE: PRELIMINARY ASSESSMENT AS INDICATORS OF QUATERNARY DEFORMATION

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INTRODUCTION

The purpose of this study is to evaluate some of the effects of subduction along the Cascadia subduction zone by examining the styles and rates of deformation of Quaternary deposits within the Oregon Coast Range (OCR). Extensive Quaternary deposits are relatively rare in the erosion-dominated OCR; however, fluvial terraces along several Coast Range rivers appear to be well enough preserved for stratigraphic, chronologic, and tectonic analysis. The three rivers examined in this study are the Umpqua River, the Smith River, a main tributary of the Umpqua, and the Siuslaw River. The Umpqua River has its headwaters in the Cascades; both the Smith and Siuslaw Rivers drain the western flank of the central OCR. This abstract will concentrate on the preliminary aspects of this study, including discussions of terrace geomorphology and stratigraphy, and some results of radiocarbon dating.

GEOMORPHOLOGY

The poor preservation of fluvial terraces in most of the OCR reflects the processes that form these features. Most OCR terraces are strath terraces, which are fluvial benches cut into bedrock, covered by a thin veneer of fluvial sediment. This type of terrace is formed by fluvial downcutting in response to changes in base level. In the OCR, these changes are related to eustatic sea level changes and regional uplift. Strath terraces commonly do not form broad platforms along streams, so laterally extensive, paired terraces of this type are rarely preserved. OCR terraces are commonly preserved as scattered unpaired remnants, usually restricted to the insides of meander bends and along wider parts of river valleys, and less commonly in abandoned meander loops. All the rivers examined in this study are flowing in deeply incised valleys, which indicates that uplift of the OCR has been an ongoing, long-term process.

STRATIGRAPHY

Exposures of fluvial terrace sediments along the Umpqua, Smith, and Siuslaw Rivers show a remarkably consistent stratigraphic sequence. They typically consist of a 1-2-m-thick sandy pebble gravel that overlies a cut bedrock bench; this gravel is in turn overlain by a 2-5-m-thick silt or sandy silt. An exception to this sequence is seen in terraces very near the coast, where the sediments generally consist of much thicker deposits of sand and silt. These near-coastal deposits are probably overthickened by trapping of sediment in estuaries during periods of higher sea level. However, several high (>90 m), well exposed fluvial terraces near the coast show a thickened, but stratigraphically similar sequence of silt over gravel over bedrock, suggesting that processes of fluvial terrace formation are similar along the length of Coast Range rivers.

I have interpreted the gravel facies as bedload sediment deposited in channels, and the silt facies as overbank sediment deposited during periodic flooding. The modern river channels are flowing directly on bedrock except in estuarine settings near the coast. Terraces surfaces appear to be reoccupied only rarely by channel deposits, but are frequently reoccupied during seasonal flooding. This is evident because the silt units are remarkably uniform stratigraphically; they are generally massive or weakly stratified, with only minor thin, discontinuous sand and sandy gravel interbeds. Of over 40 exposures examined so far, only one outcrop showed a gravel deposit at the surface of a terrace deposit. Because the modern rivers are flowing directly on bedrock, contemporary uplift of the Coast Range is assumed. This uplift eventually results in raising the surface of the terrace beyond the reach of flood waters, and the terrace surface is abandoned. The massive nature of the silt facies and general lack of buried soils within these deposits suggests that overbank sedimentation occurs at regular intervals at fairly high rates until the terrace surface is abandoned.

PRELIMINARY RESULTS

Umpqua River

Fluvial terraces are intermittently present along the length of the Umpqua River. Terraces are presently being examined from near the mouth of the river near Reedsport to Coles Valley, 160 river kilometers upstream. Terrace remnants vary in height, from the modern floodplain to over 100 m above modern river level. Correlation of these scattered remnants is difficult, but a dating program of radiocarbon and thermoluminescence (TL) analyses is being undertaken in an attempt to identify possible terrace deformation and to calculate rates of downcutting. Several radiocarbon dates have been obtained on charcoal in the lower terraces. Terraces about 13-15 m above river level, 120-130 km upstream are 7-10 ka. A terrace of similar height on Scholfield Slough, 15 km upstream from its confluence with the Umpqua near Reedsport, has a radiocarbon age of >26 ka. This relationship suggests that the coast may be subsiding relative to the inland Coast Range. Alternatively, this relationship may be explained by a decreasing stream gradient and subsequent convergence of terraces as the river approaches base level. Additional radiocarbon and TL dates and terrace profiles will be used to further analyze these problems.

Smith River

The Smith River is a major tributary of the Umpqua River; the confluence of these two rivers is just upstream from the town of Reedsport, about 18 km from the mouth of the Umpqua River. The drainage basin of the Smith River is much smaller than that of the Umpqua River, and is subsequently shorter and has a much steeper gradient than the Umpqua River. Several radiocarbon dates obtained on charcoal indicate that rates of downcutting are substantially faster on the Smith River. A 3 ka terrace surface 47 km upstream from the confluence is about 30 m above river level, whereas a correlative terrace surface 10 km upstream from the confluence is only about 10 m above river level. This relationship again suggests decreasing stream gradients and(or) subsidence near the coast. Additional dates and terrace elevations are pending.

Siuslaw River

Terraces along the Siuslaw River were the subject of studies by Schlicker and Deacon (1974) and Adams (1984). They both concluded that a high terrace surface on the north side of the river showed apparent westward tilt that may have been related to active folding. My studies along the Siuslaw River show that this "surface" is actually several terrace levels that may have been incorrectly mapped as a single surface. Terrace profiles are currently being constructed in order to assess possible deformation. Unfortunately, the only well preserved terrace surfaces along the Siuslaw river are those preserved at great height (80-110 m) above the modern river level. The degree of soil development on these surfaces (several-meter-thick Bt horizons with 2.5 YR colors, complete weathering of in situ gravel clasts) suggests that they may be several hundred thousand years old. This would suggest that these deposits are probably substantially older than the estimate of 100 ka of Adams (1984), and that they are beyond the range of TL dating.

GEOLOGIC FACTORS AND THE REGIONAL EVALUATION OF SITE RESPONSE FOR URBAN SEISMIC HAZARDS STUDIES

By
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Several factors influence the character of earthquake-generated ground shaking at a point on the earth's surface, including distance from the causative fault or seismic source, characteristics of the earthquake source, and geologic conditions within the earth through which the vibratory energy propagates. Certain frequencies of strong shaking may be amplified considerably owing to thin, low-velocity surface layers; the overall spectral level of ground motion may increase as the seismic velocities of near-surface materials decrease and/or as the thickness of the sediments increases (Murphy and Hewlett, 1975; Borcherdt and Gibbs, 1976; Rogers and others, 1979, 1985). Ground shaking wherein the earth is not apparently permanently deformed has caused the greatest losses historically during earthquakes, because the seismic energy radiates over large areas where it encounters numerous works of man. In comparison, other mechanisms by which earthquakes cause damage to structures include direct displacement of the ground surface by a fault and damage that arises from ground failure. If surface faulting occurs immediately beneath a structure, the damage makes for spectacular T.V. footage, but the zone of damage tends to be restricted to the fault zone; hence, surface faulting damages a relatively small number of structures and consequently causes relatively small losses compared to losses caused by ground shaking. Losses from earthquake-generated ground failure (landslide, liquefaction, rockfall,) tend to be of intermediate magnitude in terms of the number of structures that they affect; ground failure tends to be localized, and can be predicted either deterministically or probabilistically by a careful analysis of the earthquake potential of a region and an analysis of the earth materials which comprise the surface and near-subsurface deposits, the topographic relief, and the association between cohesionless deposits and shallow ground water. The topics of surface faulting and ground failure are addressed in concurrent sessions of this workshop; thus, while being important elements to consider, they will not be discussed further, here.

In this short paper, I will discuss ongoing efforts to identify and understand the geologic factors correlated with attenuation or amplification of ground motion in the Puget Sound area and which may enable earth scientists to prepare predictive maps describing the ground shaking hazard in the Pacific northwest and the Puget Sound region.

Hazards Assessment Program

Evaluating the hazards posed by moderate and large earthquakes in the Puget Sound-Portlant areas requires a concerted effort by numerous geologists, geophysicists, engineers, urban planners and elected officials who labor on dozens of related projects. The research program properly includes at least 5 interrelated elements:

1. Collection and synthesis of earth science data;
2. Ground motion modelling;
3. Preparation of loss estimation models;
4. Incorporation of models into information systems;

5. Selection and implementation of hazard mitigation measures.

This paper emphasizes selected aspects of the first two of these 5 elements. Once ground motion models describing the vibratory motions of large earthquakes in terms of the local geology are prepared, predictions addressing how types and classes of man-made structures will respond to those motions are possible. A predictive ground response map also enhances evaluations of ground failure, including landslides, rockfall, and liquefaction-induced soil failures (see, for example, a discussion of liquefaction hazards in the Los Angeles region by Tinsley and others, 1985).

Predicting Ground Response

The least model-dependent ground response maps are produced by combining measurements of ground motions with geological and engineering attributes of the earth materials or substrate beneath the recording instruments. In this way, the data reflect site conditions typical of the map area; the attributes of ground motion expressed in terms of spectral characteristics can be related to attributes of the regional geology. There are several phases to this research which are described in additional detail below.

Initially, one must collect measurements of vibratory ground motion. For best results, these recordings are made simultaneously at many sites including at least one bedrock (reference) site, against which the ground response measured at all other sites is to be compared. Recorded ground motions may reflect a variety of seismic sources, including underground nuclear tests, quarry or mine blasting, as well as real, true-blue earthquakes. The recording instruments should be deployed or sited so as to sample a range of subsurface conditions representative of geologic conditions within a region. The seismic sources which have been used historically in this part of the analysis include actual earthquakes, microtremors (see Kagami and others, 1986), local quarry blasts, and underground nuclear tests occurring at the Nevada Test Site (NTS). Each of these sources can be used separately or inclusively for measuring relative ground response, so long as there are instrumental recordings of each seismic event made at the reference site. However, naturally-occurring earthquakes are difficult to use because their schedules are not advertised in advance and their geographic location will vary in place and time--azimuth-dependent effects are a variable which we desire to eliminate or control in the analysis, so a nuclear test or quarry blast which emanates from the same location is preferred for this purpose and is the source that is most commonly used. Once obtained, the seismic records are each compared to the bedrock or reference site's record of the respective seismic event and the vertical and horizontal components of the ground motion spectra which are attenuated or amplified are determined for each event and site. An example from the Los Angeles region showing the time-histories of ground motion generated by NTS nuclear testing and recorded at eight sites in the Los Angeles region are shown in figure 1, after Rogers and others, (1985). The amplitudes at locations underlain by various types of alluvium are significantly greater than the amplitudes at sites underlain by rock. The reference station is CIT (Old Seismological Lab, of California Institute of Technology).

The second step is to collect geologic and geotechnical engineering data from the sites where the recordings of ground motion were made. These data include measurements of the thickness, type, and physical properties such as density, strength parameters, compressional-wave and shear-wave velocity of the deposits beneath the site, as well as depth to ground water and depth to bedrock. In most cases, these data are not available or may be poorly known because efforts are made to locate the instruments away from the interfering effects of nearby buildings so that the so-called "free-field" ground motion is recorded. The "free-field" recordings are made at a

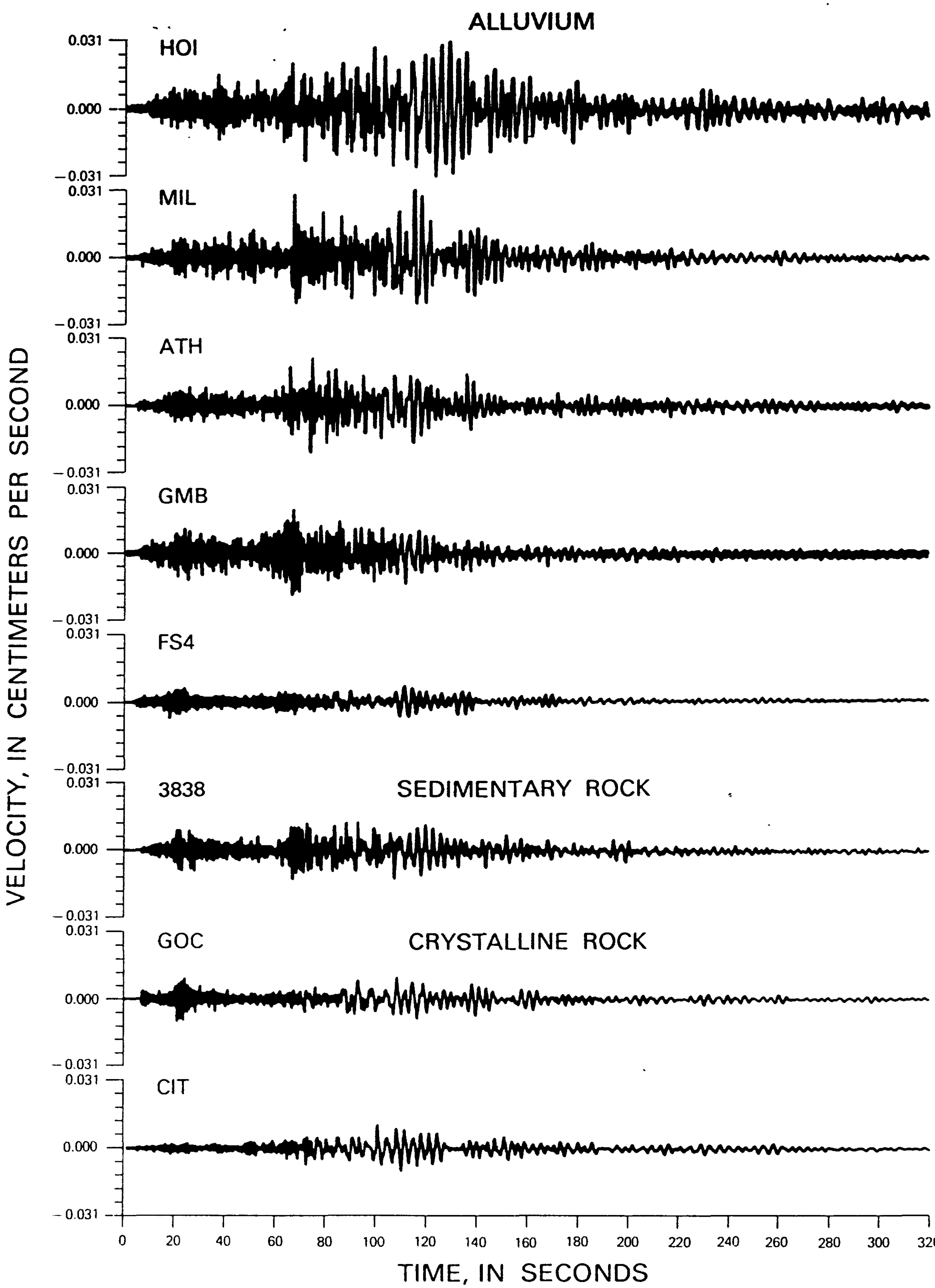

FIGURE 1 —Radial component time-histories of ground motion from a distant underground nuclear explosion in Nevada recorded simultaneously at eight sites in the Los Angeles region and grouped according to the type of geologic materials immediately beneath each recording station. The amplitude levels at locations underlain by alluvium clearly are greater than those at locations underlain by rock. The degree of amplification also appears to be related to the thickness of underlying alluvium: HOI, Holiday Inn, 300 m; MIL, Millikan Library, 372 m; ATH, Athenaeum, 372 m; GMB, Glendale Municipal Building, 120 m; FS4, Fire Station 4, 15 m. GOC, CIT, and 3838 are rock sites.

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distance from the building that exceeds the height of the building. Consequently, geological and geophysical experiments must be conducted (such as seismic refraction and reflection profiles, exploratory drilling and sampling) to determine the properties of the materials.

The third step is to identify those attributes of the geologic units which are associated with the different degrees of seismic response relative to the reference rock site. This is done by forming statistically-determined clusters which group sites having suites of like geotechnical parameters with the spectral characteristics measured at the recording sites.

If the clusters are chosen so that the geologic properties associated with the various degrees of ground motion amplification or attenuation are mappable, maps predicting ground motion can then be prepared and used in loss estimation studies or compared to observed actual earthquake damage or Modified Mercalli or Rossi-Forel intensity levels to check the accuracy of the predictions. In any event, a matrix is easily prepared in which suites of geotechnical properties can be related to given attributes of ground motion spectra, even if a regional map is not formally prepared. Thus, an interested party could refer to the matrix, and on the basis of a suite of physical properties and thickness parameters for a site in question, could quickly determine where in the range of potential site response the suite of parameters was correlated. An example of this approach is that of Rogers and others (1985) in downtown Los Angeles, where maps of a small area were prepared in 3 period-bands ranging from 0.2 to 10 seconds. Although the importance of local geologic conditions on the relative severity of ground shaking has long been recognized, the quantitative prediction of the influence of these conditions on ground shaking employing either empirical or theoretical models is still in a developmental stage. The procedure is shown conceptually in figure 2, after Rogers and others (1985).

Amplification of Seismic Ground Motion

Studies of earthquakes in California, Japan, and Mexico have shown amplification of seismic waves at sites where thick sequences of unconsolidated or semiconsolidated sediments and soil overlie more competent bedrock. Such soft and weak sedimentary deposits, such as San Francisco Bay Mud (an estuarine deposit initially containing more than 50% water) or the recent lacustrine deposits of Lake Bonneville (Great Salt Lake) in Utah typically are characterized by low densities, high void ratios, and low shear-wave velocities. Some examples may be instructive. The 1933 Long Beach, California, earthquake caused more damage in Compton than in Long Beach, a finding that Wood (1933) ascribed to local geologic effects and which Campbell (1976) studied and showed that for a given distance from the Newport-Inglewood fault zone, damage at sites underlain by unconsolidated soils (including the Compton area) was greater than at sites underlain by consolidated middle Pleistocene and late Pleistocene deposits, which underlie much of the City of Long Beach, California. The September 19, 1985 Mexico earthquake did extensive, localized damage hundreds of kilometers from the epicenter in parts of Mexico City underlain by 50+ meters of soft, water-saturated lake deposits. The sedimentary section had a fundamental vibratory period of about 2 seconds; buildings in the range of 15 storeys had a similar period and suffered severe structural damage and collapse, owing to resonance effects. Accelerations were amplified from bedrock levels of 0.04 g on bedrock to 0.2 g, a factor of 5 on the soft soil sites.

The Puget Sound area does not have quite so severe site conditions as Mexico City's; however, the effect of site geology on ground motion is expected to have a considerable influence on levels of damage. The Seattle area, for example, is underlain

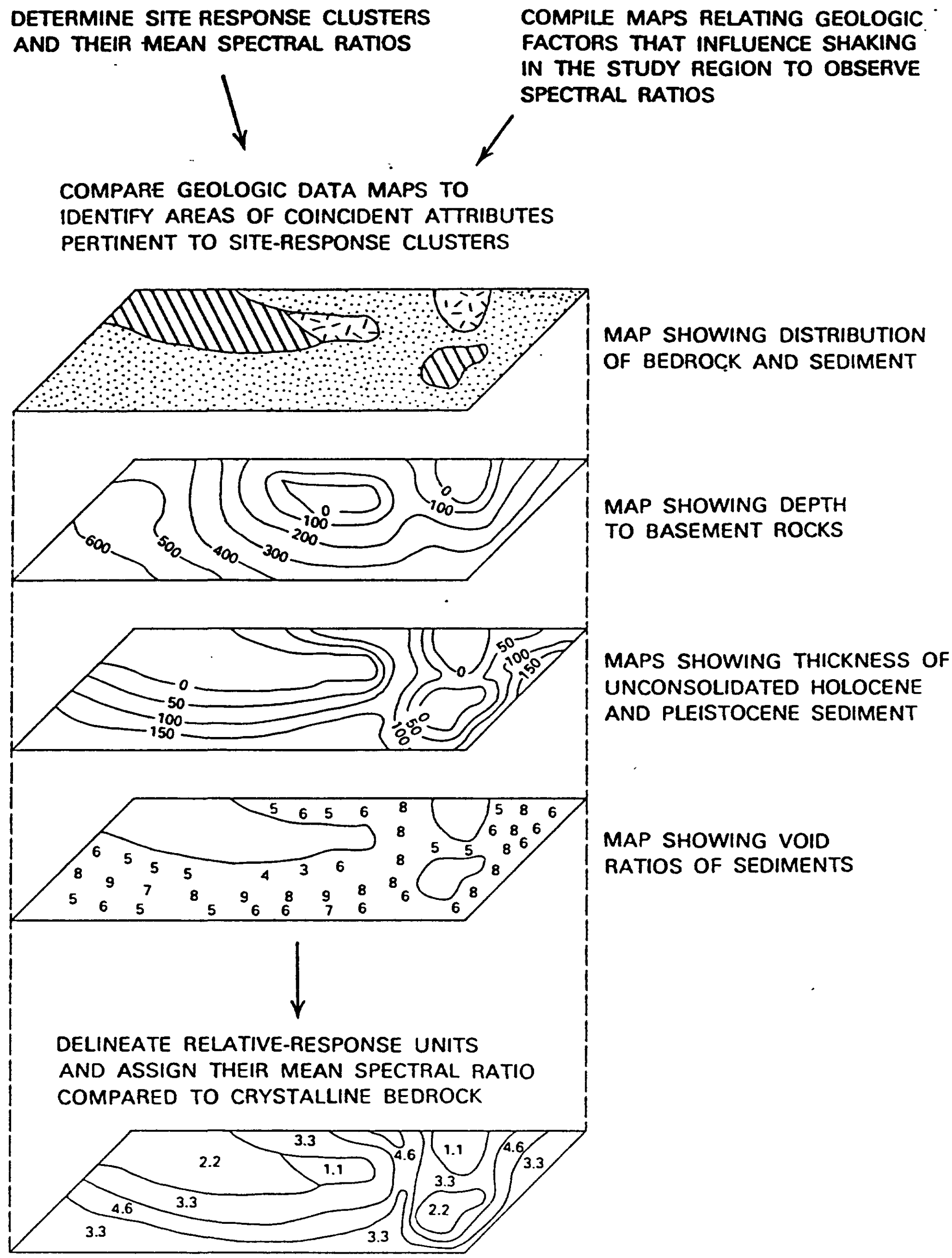

FIGURE 2

Procedure used to construct a predictive relative ground response map after Rogers and others, 1985.

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by glacial till (ice-deposited semiconsolidated mixtures of clay, silt, sand, gravel, cobbles and boulders), post-glacial fluvial deposits, marine and estuarine muds, and fill materials such as sawdust and hydraulically jetted till. The detailed wave-propagation characteristics of these materials is poorly known. Glacial deposits characteristically are heterogeneous deposits in the best of times, so data will have to be obtained from geographically widespread areas and from a large number of sites before ground response maps can be drawn with confidence. Thicknesses of sedimentary deposits above bedrock range from 0 to more than 1 km near Seattle (Yount, 1983). The deposits from the latest (Vachon) glaciation are draped across a pre-glacial terrain which is not likely to be very simple in any stratigraphic context. I suspect that many lithologic contacts especially among the pre-Vachon deposits of the Puget Sound region are likely to have attitudes other than strictly horizontal. The implications for ground response remain to be determined.

Historical Earthquake Effects in the Puget Sound Area

The occurrence of two moderately large earthquakes in the Puget Sound region during the past 40 years, the 1949 Olympia earthquake (M=7.1, Nuttli, 1952) and the 1965 Seattle earthquake (M=6.5, Algermissen and others, 1965), illustrates several complex aspects of ground shaking and the geographic distribution of the damage relative to some of the geologic deposits of area. The prospect of a truly great earthquake occurring on the Cascadia subduction zone (Heaton and Hartzell, 1987; Heaton and Kanamori, 1984; Atwater, 1987) is sobering. The 1949 and 1965 seismic events had rather deep foci of 70 and 60 kilometers, respectively, and, in consequence, seem to have caused shaking damage that was slight (slight by California standards, where focal depths seldom exceed 15 km) compared to the magnitudes of the earthquakes (Algermissen and others, 1965; Mullineaux and others, 1967). The rather great focal distance and the relatively thick sedimentary sections through which the seismic waves were propagated and presumably attenuated are thought to be responsible for the relatively low levels of damage (Langston, 1981; Shakal and Toksoz, 1980). Yet damage to structures was observed to vary greatly over short distances even if the buildings were sited on what were ostensibly lithologically similar geologic deposits, especially for the 1965 event (Algermissen and others, 1965; Yount, 1983).

Yount (1983, p. 268) reviewed the damage patterns of the 1965 earthquake and noted that relatively heavy damage occurred "in the lower Duwamish River area and southern downtown region of Seattle where unconsolidated Holocene alluvium and artificial fill make most of the substrate; but damage was relatively light in the upper Duwamish River Valley just a few kilometers to the south, where similar geologic materials make up the substrate". The most severe residential damage involved brickwork and chimneys and seemed to be concentrated in the West Seattle area, a sector underlain by compact glacial sands and silts; yet the Beacon Hill and Magnolia areas, underlain by similar Pleistocene deposits, suffered little damage. Yount concludes that subsurface geologic conditions are of paramount importance in understanding the ground response characteristics of the Puget Sound region. Initial efforts by the U.S. Geological Survey to study geologic aspects of ground response focus on areas of West Seattle and Olympia (see papers by Kenneth W. King and Arthur C. Tarr, this volume, and figure 3) and will endeavor to discover if heretofore unrecognized differences in site geology can be discerned and used to improve predictions of the effects of earthquake-generated strong ground motion.

Systematic efforts to record ground motion at sites damaged by the historical earthquakes are already underway under the direction of Kenneth King (USGS, Golden, Colorado) and include ground motion recordings, reflection profiles to determine the

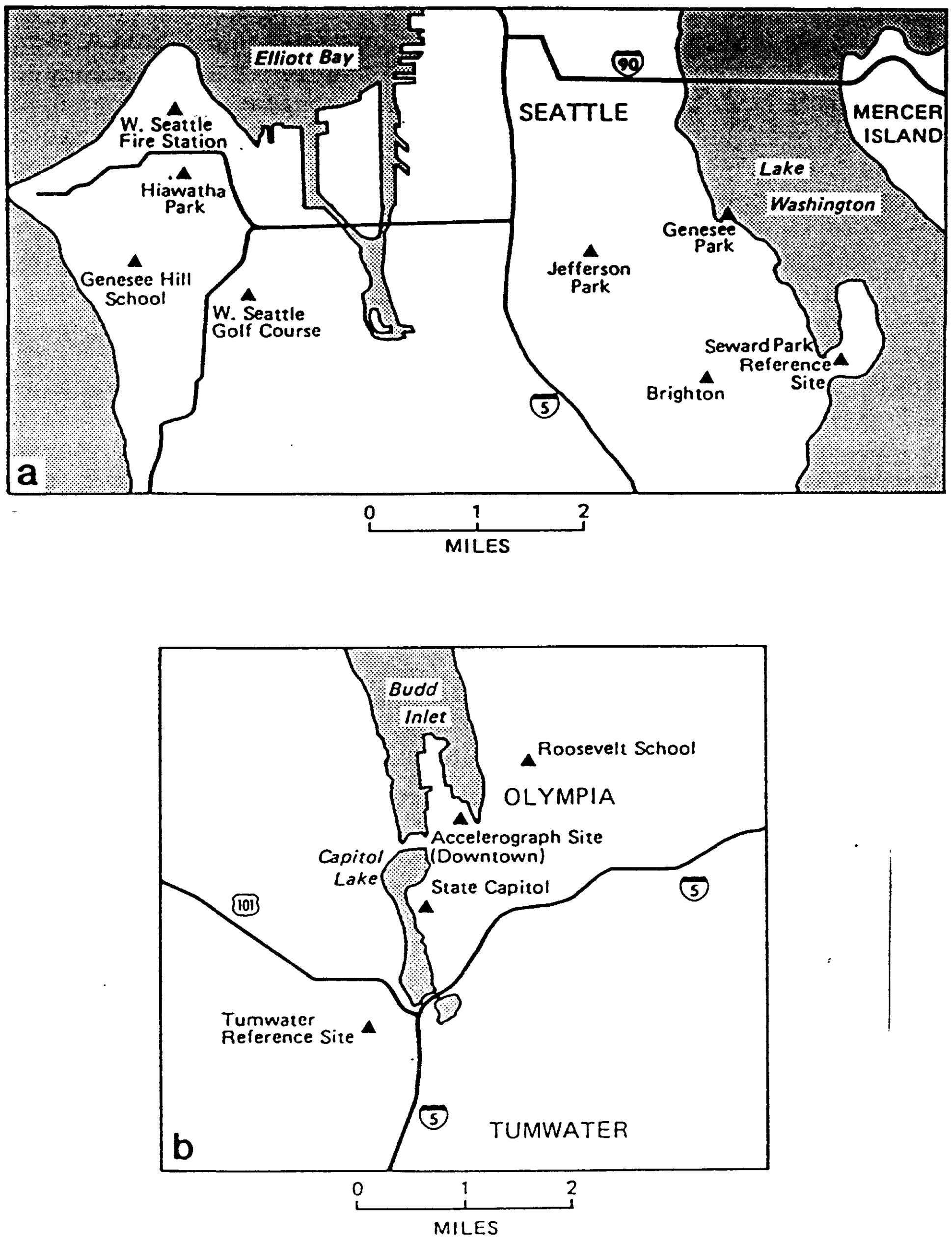

FIGURE 3
Locations of seismic stations comprising part of the array for initial studies in the Seattle and Olympia areas, after Tarr and King, 1987.

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depth to prominent reflectors in the subsurface and depth to rock. A program of exploratory drilling and geotechnical sampling intended to determine the nature of the substrates and assess the degrees of similarity or differences among the subsurface stratigraphic units of the region commences in July, 1988, under the direction of John Tinsley (USGS, Menlo Park). These initial exploratory studies will include down-hole P-wave and S-wave geophysical studies and will commence at 3-4 sites from Genessee Park and downtown Seattle to the West Seattle and Magnolia areas, and additionally at 6-8 sites in the Olympia area; the results of these studies and additional studies during the next several years will contribute to understanding of geologic aspects of ground shaking hazards in the Puget Sound region. The properties and character of Holocene (post-Vachon) alluvium and man-made fill, the presence of and depth to poorly-consolidated sand deposits which are situated within otherwise well-consolidated last-glacial and pre-last-glacial deposits, and the configuration of the bedrock beneath the metro areas are expected to be key geological aspects in the analysis.

The geologic exploration phase is commencing this year, so data are rather sparse. I anticipate making full use of exploratory data obtained for purposes other than studies of ground motion. Initial contacts with geotechnical engineering firms have been encouraging and helpful. Cooperative studies with the USGS Water Resources Division personnel studying the ground water resources in the King County, WA and Olympia, WA areas is underway. Future activities will see expansion of the database to include studies of sites in the Portland, Oregon, area as well as establishing additional recording sites distributed throughout the Puget Sound region. It would be desirable from a statistical standpoint to have as many seismic stations and detailed site studies as possible. I will endeavor to use in the analysis generalized stratigraphic systems such as those derived during water resources investigations in the region. However, the viability of these models for predicting ground response remains to be tested, and will be tested during this study. The pertinent geotechnical data will be incorporated into a database using the geographic information systems software developed and modified by Art Tarr. Hence, the data used in our interpretations might be available for future reference and use by interested researchers. Comments concerning the approach, the methodology, and the local geology in the Seattle and Olympia areas are respectfully solicited.

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FLUVIAL MORPHOLOGY OF THE OREGON COAST

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INTRODUCTION

The purpose of this study is first, to determine the feasibility of using river profile and surrounding topographical relationships to identify where geologic controls exist, and second, to expose regions of current uplift on the Oregon Coast. River course and elevation change for 22 rivers and tributaries on the coast of Oregon were digitized from $7\frac{1}{2}'$ and $15'$ topographic quadrangle maps from the U.S. Geological Survey. Lengths varied from under 25 km to over 350 km. Relief varied from 100 m on some of the shorter tributaries, to over 1600 m on the longer rivers. The ratio of relief to length ranged from .2 to 3.6%. The ratio of the area above the river profile within a rectangle defined by relief and length to that below the profile ranged from 1.33 to 13, with a mean of 3.8. Changes in river slope and valley character were compared to geologic information as presented on Peck's 1961 "Geologic Map of Oregon West of the 121^{st} Meridian", U.S. Geologic Survey Map I-325. Peck's map was the most complete reference for geologic information over the entire Oregon coast, and included sufficient detail along river drainages to explain most of the anomalies on the drainages.

BACKGROUND

A river's natural development is from steep slopes in the headlands, where there is little water volume and erosive capability, to flat slopes at the mouth where water volume, and hence erosive capability, have increased. When the river system is in equilibrium, there will be a smooth transition from the steep head to the flat mouth as the river system balances energy (discharge and elevation change) and work (sediment load and degradation). Where the change in slope is irregular, there may be a change in water discharge (an increase in discharge results in a decrease in slope), lithologic change, or tectonic motion. A change in lithology could be expressed in river course change, a change in meander behavior, a change in valley shape, and change in river slope. Downstream of uplift there is downcutting and increased sinuousity if the uplift rate is slow enough, or entrenched meanders if the rate is too fast. The morphology upstream of an uplifted region resembles an area of subsidence, having flooded channels, bank erosion, and generally flattened slope. Since the river system is always eroding toward equilibrium, tectonic effects are not observed for long periods of time, *unless they are an ongoing process.*

DISCUSSION

River elevation and slope versus length profiles were constructed for 22 rivers. The theoretical profile for each river was also generated, theory anticipating a smooth exponential decrease in slope with length. Abrupt decreases in slope, or inflection points, and broad slope convexities were compared to discharge and geologic changes along the rivers' courses. Overall, increased discharge resulted in decreased slope downstream, but there were places where a major tributary joined the main channel and no increase in slope occurred. On several rivers there were increases in slope at tributary junctions, opposite to expectations. Nearly all of the slope irregularities were coincident with geologic contacts and intrusions, such as massive basalts adjacent to estuarine and marine sediments. Generally, inflections occurred as the river bed encountered a resistant formation within a less resistant formation, such as a mafic intrusion into marine sediments. However, not all of the anomalous slope patterns could be explained. For example, a steep section on Siletz River was through a very resistant mafic intrusion, and the river flattened on the more erodable marine sedimentary rocks. Other factors also influence river behavior, one of those being topographical changes, which is in turn generated from tectonic movement. Therefore, although river changes correlate with geologic changes, causality can be ambiguous.

A more significant observation from the river and valley data was that headwaters were very steep and associated valleys wide, there were slope convexities in the middle sections with associated narrow, deep valleys, and many rivers ended with slope *increases*. (See examples in following figure.) Interpretation of the slope increases at the mouths included tectonic movement either in the form of base level lowering at the coast, or uplift further inland. If base level lowering at the coast is accepted, the flat section upriver could only have been eroded during a long period of tectonic stability, an unlikely possibility given the tectonic history of the Oregon coast. If, instead, the slope convexities midriver were caused by uplift 50 to 100 km landward of the coast, both the steepening downstream and flattening upstream were explained. The uplift must be an ongoing process since these river features are a present landform.

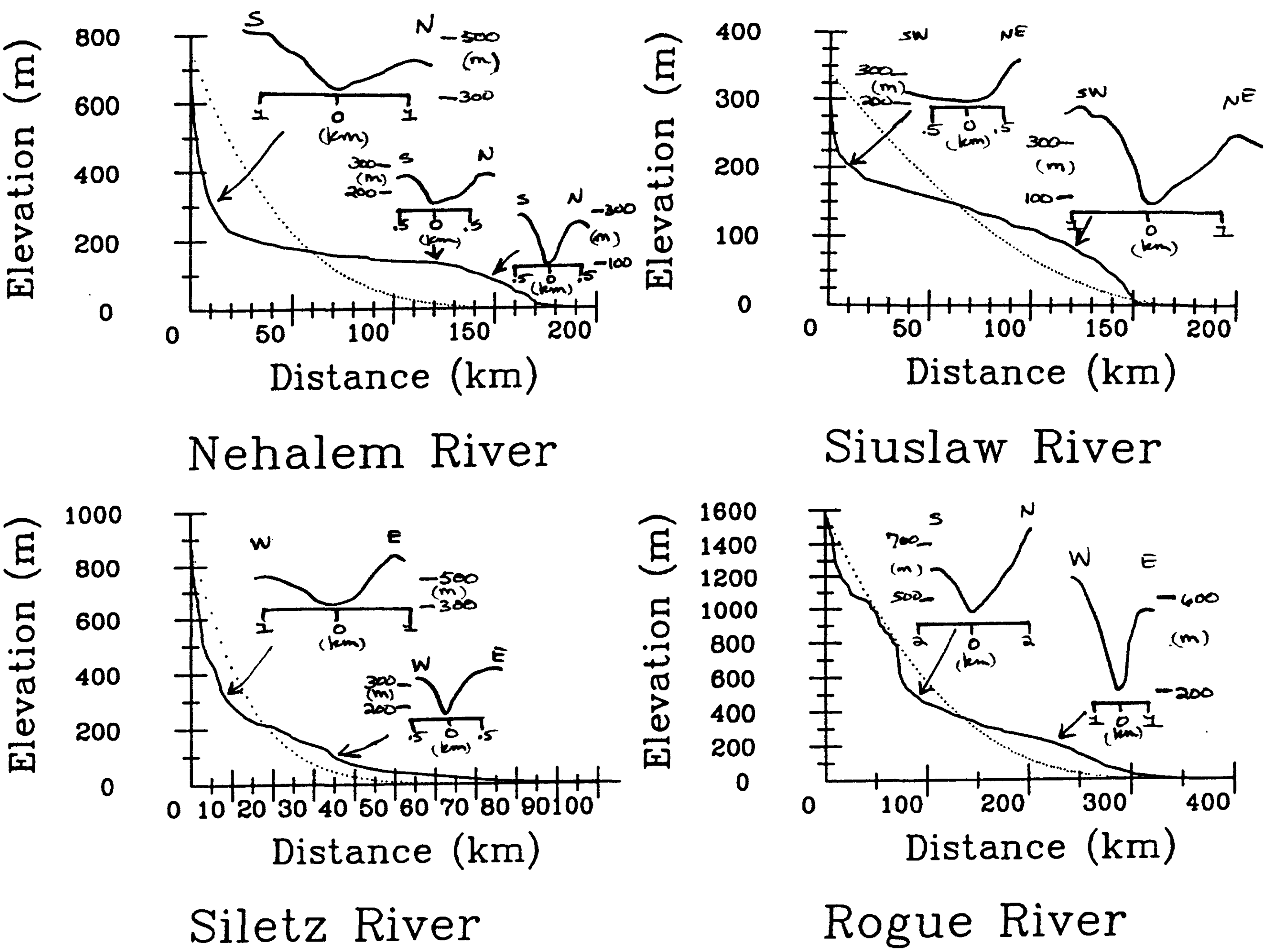

Figure 1. River profiles for four rivers studied on the Oregon Coast. Dotted line represents 'ideal', or theoretical profile. Valley profiles at several places along the river are also included, demonstrating entrenching on downstream flat sections of rivers. Convex profiles toward mouths of rivers suggest ongoing uplift within 50 to 100 km of the coast.

UNCERTAINTIES IN LIQUEFACTION HAZARD ANALYSES

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INTRODUCTION

Major damage and property losses have occurred during earthquakes as a result of liquefaction or lateral spreading of the subsurface soils. These phenomena occur as an indirect result of earthquake ground shaking. Liquefaction is a phenomena in which a loose deposit of sand existing below the water table loses its internal shear strength when subjected to severe earthquake ground motions. Lateral spreading is essentially an extension of the liquefaction concept, applied to conditions of a sloping ground surface. Thus lateral spreading is characterized by the horizontal flow of liquefied soil toward an open channel or an open slope.

Liquefaction or lateral spreading may affect various systems or facilities. Lifeline structures, such as water and sewer lines or gas lines, may be severed as a result of liquefaction or lateral spreading. Liquefaction or lateral spreading may cause movements in bridge abutments which could result in bridge decks being crushed or falling from their supports. Liquefaction may affect buildings by differential foundation settlement which could lead to distress of the superstructure. Finally, liquefaction of submarine slopes may result in tsunami-like waves which may damage coastal facilities similar to damage that occurred in the towns of Seward and Valdez, Alaska, during the 1964 Good Friday earthquake.

The implications of earthquake-induced ground failures may be far reaching. Earthquake-induced ground failures which affect bridges may render these structures inoperative immediately following an earthquake and hinder emergency response teams such as fire fighters and ambulance crews. Liquefaction may also create life threatening situations if differential movements within a building foundation results in a collapse of the structure, injuring its occupants. Furthermore, the effects of liquefaction or lateral spreading may extend far beyond the immediate response to the earthquake and encompass the economic recovery of community, requiring public funds for infrastructure repair and funds from the private sector to repair damaged buildings and plants.

As earthquake-induced ground failures may have a significant impact upon communities in the Pacific Northwest during a future earthquake, the purpose of this paper is to briefly discuss the current state of engineering practice in evaluating these hazards, delineate areas of uncertainty in the analyses, and recommend areas requiring further research studies.

HAZARD ASSESSMENT

There are three major factors which control the occurrence of liquefaction:

- Earthquake severity
- High groundwater table
- Liquefiable soils

All three of the above factors must be simultaneously present for liquefaction to occur. These factors are typically evaluated by geotechnical engineers performing a liquefaction hazard analysis of a building site. Specifically, borings are drilled at the building site for the purposes of foundation design and liquefaction analysis. Liquefaction potential is typically evaluated using simplified procedures which compare the strength of the soil as determined from the site borings with the strengths of soils at other locations which have experienced liquefaction during previous earthquakes. Based upon this empirical assessment, the liquefaction potential of the site is evaluated and appropriate remedial measures are developed.

Aside from individual studies at specific sites, various liquefaction microzonation studies have been performed for other cities in the United States (Power and others, 1982; Roth and Kavazanjian, 1984). The end product of the studies is typically an area map indicating potentially hazardous areas of liquefaction. Research sponsored by the U.S. Geological Survey is currently being conducted to construct similar maps for the Puget Sound area. The major attraction of such microzonation maps is that they may be used by public agencies and others to provide a quick assessment of liquefaction potential over a wide city area. While the specific nature and techniques used in these studies may vary among investigators, the results are typically the same in that areas of fill or most recent alluvial deposits which exist in low-lying areas are assigned the highest liquefaction hazard potential. Areas having low liquefaction potential typically correspond with older and denser sediments that are located above the water table.

Based upon the simplified model of alluvial or fill soils in low-lying areas having the highest liquefaction potential, it would be concluded that major portions of populated areas in the Pacific Northwest would be at risk during an earthquake. Specifically, these would correspond to industrial areas along the Duwamish in Seattle, tide flat areas in Tacoma, the low-lying areas adjacent to the Sound in Olympia, and finally low-lying areas along the Columbia and Willamette Rivers in Portland.

Potential liquefaction within these areas brings up interesting questions affecting public policy. First, should new development be limited in these high risk areas? If buiding is not restricted, then should there be special or standardized studies to define the extent of liquefaction for each new building or should there be standardized procedures for mitigating the occurrence of liquefaction at these locations? Finally, should existing structures which have been designed and constructed without special consideration for liquefaction receive special retrofitting to mitigate this hazard?

UNCERTAINTIES OF ANALYTICAL PROCEDURES

While liquefaction potential is routinely analyzed for building sites in the Pacific Northwest, there are a number of factors or uncertainties which affect the results of the analyses or the recommendations provided by the engineering firms. These factors may be categorized into uncertainties involving earthquake potential in the Pacific Northwest and non-standardized design procedures.

One of the greatest factors affecting liquefaction evaluations conducted for sites in the Pacific Northwest is the uncertainty regarding the largest earthquake which could affect the region. Previously it was believed the largest earthquake that could affect the Puget Sound area would be a magnitude 7.5 event (U.S. Geological Survey, 1975) centered in the Puget Lowland. The magnitude of this postulated earthquake is generally consistent with historical earthquakes, the largest being the magnitude 7.1 Olympia earthquake of April 13, 1949 (SW-AA, 1978). However, research by Heaton and Kanamori (1984) has suggested that larger earthquakes, associated with tectonic subduction off the coast of Washington, could affect western Washington and Oregon. Currently, the U.S.G.S. is sponsoring research to investigate physical evidence for the past occurrence of such a large event (Atwater, 1987).

The potential occurrence of a subduction zone earthquake in the Pacific Northwest would have a major impact upon liquefaction analyses. The potential occurrence of a subduction zone earthquake in the Northwest would imply that current earthquake design standards are too low and should be increased. Therefore, it is first necessary to agree upon the hazard potential of a subduction zone in the Pacific Northwest before any appropriate liquefaction design studies may be accomplished.

The second major area involving uncertainties in liquefaction evaluation focuses upon design standards. Uncertainties or non-standard analytical procedures within this category would include:

- Earthquake recurrence interval
- Liquefaction analysis procedure
- Site assessment
- Remedial treatment
- Retrofitting

Aside from the issue of the potential for a subduction zone earthquake in the Pacific Northwest, liquefaction analyses are also affected by the critiera which establishes the design level earthquakes. Currently there are no standard or accepted guidelines for establishing an earthquake return interval for liquefaction analyses. The U.S. Navy typically uses an earthquake return interval of approximately 200 years for evaluating liquefaction potential of their major facilities. Guidelines from the Applied Technology Council typically recommend a design earthquake having a 500-year recurrence interval for the design of buildings. Therefore, based upon these two different agencies, there is a substantial difference on the definition of a design earthquake. Accordingly, a design earthquake selected for a liquefaction analysis by one agency may indicate unsatisfactory performance whereas an analysis performed using guidelines from another agency would indicate satisfactory site performance.

In addition to discrepancies between agencies in definition of a design earthquake, there are also discrepancies in procedures for evaluating liquefaction potential. Liquefaction potential may be evaluated using empirical procedures which are based upon a correlation of soil properties determined from field testing with sites where liquefaction has occurred in prior earthquakes (Seed and Idriss, 1981) to more analytical procedures involving steady state analysis of soil behavior. Aside from these two techniques, there are a range of other empirical and analytical procedures which are being used in the engineering field. Thus, the analytical procedures for evaluation liquefaction potential may result in significantly different assessments of the liquefaction hazard.

After having analyzed the site for its liquefaction potential, the geotechnical engineer may still exercise some latitude in judgment in evaluating the liquefaction hazard. As an example, a shallow spread footing foundation system would not be appropriate for a building which is located upon near-surface soils which may liquefy. However, this same foundation may provide satisfactory performance if the zone of liquefaction is limited to a relatively thin layer located well below the base of the foundation. Thus, it is obvious there may be a wide range of opinions on site-specific hazard for soil conditions between these extremes.

Another area of non-standarized design procedures involves remedial treatment for addressing liquefaction potential. Remedial schemes for addressing liquefaction potential could include soil densification by a number of different field techniques to supporting the structure on piling which transfers building load below the zone of liquefaction. Thus, attendant with each of these remedial procedures are uncertainties involving the design methodology and the adequacy of the solution.

A final item regarding uncertainties and design standards is the issue of retrofitting existing structures which were originally designed without consideration for potential liquefaction. This represents a major policy issue for public agencies that could affect the life safety and economic well being of a community. This area is further complicated by the fact that many existing structures have experienced major earthquakes in the Pacific Northwest, such as the magnitude 7.1 Olympia earthquake in 1949 without major damage. However, when one considers that the ground accelerations associated with this earthquake, particularly in Seattle, were relatively low (on the order of 0.10 g) and that a large subduction zone earthquake could result in much larger ground accelerations, the argument of past successful performance during prior earthquakes becomes less convincing.

HAZARD REDUCTION

From the above discussion it is clear that there are a number of uncertainties that may affect the determination of liquefaction potential and furthermore the public safety and well being of a community. Some of these factors, such as further research into evaluating the potential of a subduction zone earthquake in the Pacific Northwest, can be directly addressed by scientific research. Other factors regarding non-standardization of analysis techniques or code procedures are less well defined in scientific terms and overlap into areas involving risk and public policy. Many of these items will be addressed in the future years by building officials and design agencies on the local and national levels.

Thus, it is our opinion that the immediate goal to reduce earthquake hazards from liquefaction would be to establish the potential magnitude and recurrence interval for a subduction zone earthquake in the Pacific Northwest. Such research should be substantiated with field evidence of the occurrence of such an event in recent geologic times. Another area of technical research would focus upon the development of liquefaction hazard maps for major metropolitan areas in the Pacific Northwest. The major emphasis on these studies would be to delineate areas of liquefaction on a regional basis. The purpose of these hazard maps would be to aid the public and private sector in land use planning, building development, and planning for disaster response. Specifically, the maps could be used to locate projects out of high seismic risk areas or to plan for high foundation costs for structures located within these areas.

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PRELIMINARY EVIDENCE OF POSSIBLE QUATERNARY FAULTING IN PUGET SOUND, WASHINGTON, FROM A MULTICHANNEL MARINE SEISMIC REFLECTION SURVEY

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INTRODUCTION

A 461-km multichannel marine seismic-reflection survey was conducted in Puget Sound (fig. 1) during April of 1987 to investigate possible Quaternary faulting reported by previous investigators of the region. The survey was designed to image geophysical anomalies outlined by Yount and others (1985) and active Holocene structures described by Gower and others (1985), and to establish a framework for the integration of existing, numerous single-channel seismic-reflection profiles and well-log data into ongoing regional geologic studies.

Although numerous single-channel marine seismic-reflection surveys have been conducted in Puget Sound with good near-surface results (Sylwester, 1971; Wagner and Wiley, 1980), the depth of penetration below water bottom has been limited due to high-frequency attenuation and low-power sources. Therefore, a multichannel system was used for deeper penetration in an effort to augment previous single-channel surveys.

Background information for marine seismic-reflection surveys can be found in Lee and others, 1987 and Shedlock and Harding, 1982. In addition, the results of Quaternary faulting investigations using land seismic-reflection techniques are documented in Shedlock and Harding (1982), Harding and others (1983), Crone and Harding (1984), Skipp and Harding (1985), Harding (1985), Harding (1985b), Harding and Stewart (1986), Whitney and others (1986), Harding and others (1986), and Harding and Barnhard (1987).

DATA ACQUISITION PARAMETERS

Navigation and accurate track-line locations were achieved by using a combination of Loran C and GPS (Global Positioning System). Loran-C positions were recorded on magnetic tape every 5 minutes and corrected using GPS. Position locations were also photographed on the onboard radar screen every 30 minutes and tied to shot-point numbers as a position-location backup.

The energy source was a 15-in^3 watergun. A 24-channel, 150-m-long, hydrophone streamer (6.25-m group spacing) was used and the data were recorded at a 1-ms sample rate. (See figure 1 for track line locations and figure 2 for equipment geometry.) Lines 1 thru 12 were recorded to 2,000 ms with a shot interval of 6.25 m and line 13 was recorded to 1,000 ms; both were processed at 12-fold. Lines 14 and 15 were recorded to 1,000 ms with a shot interval of 3.13 m and processed at 24-fold.

A series of cascading deconvolution programs were used to suppress both the sea-bottom multiples and interbed multiples (pegleg multiples). The deconvolution programs entailed digitizing water depths and applying a spiking deconvolution operator from the water bottom through the section to remove pegleg multiples that were generated in the layers below the water-sediment interface. A gaping deconvolution was then applied with the gap determined

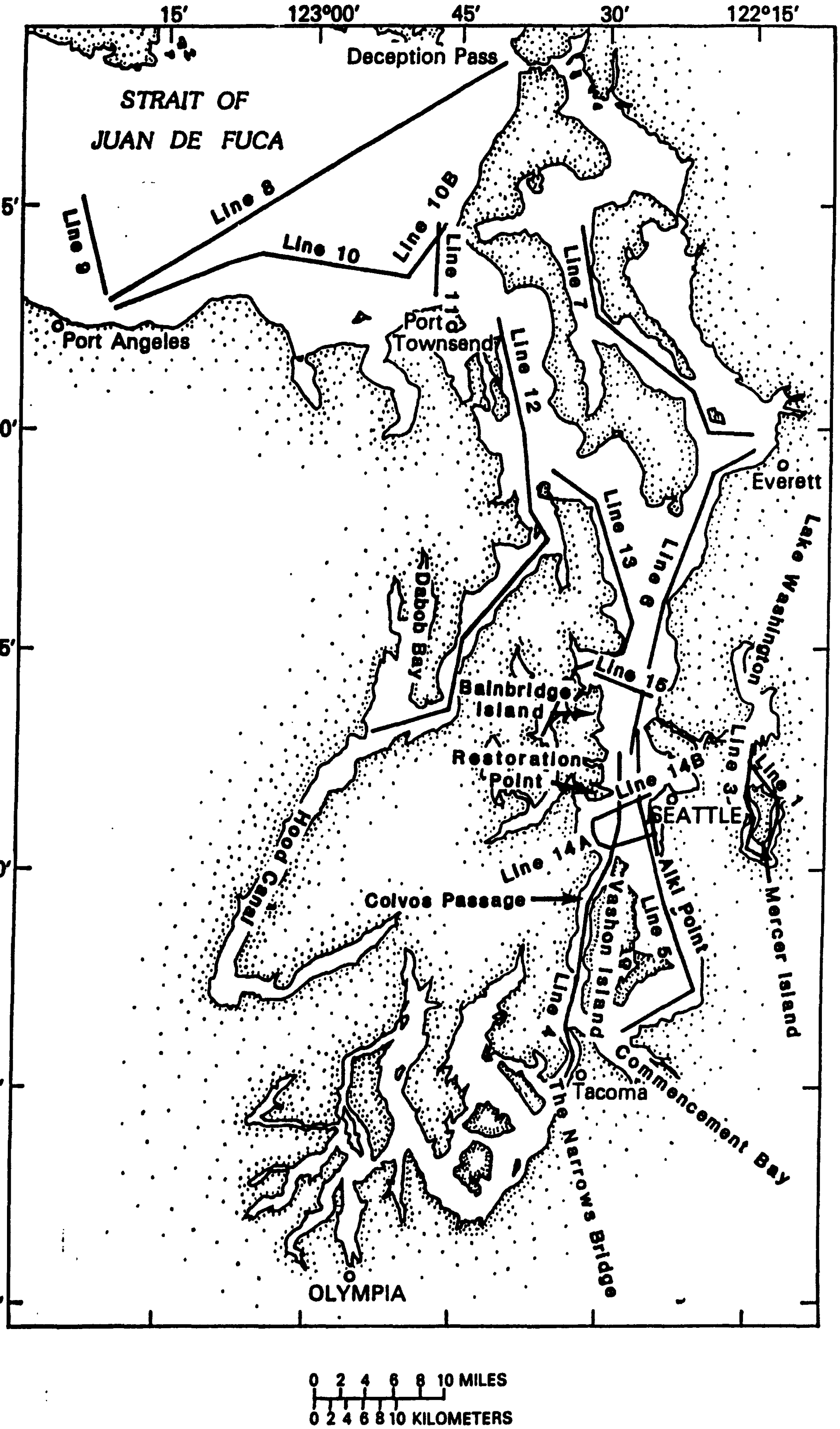

Figure 1.--Map showing track lines and designated numbers for the marine seismic-reflection survey in Puget Sound.

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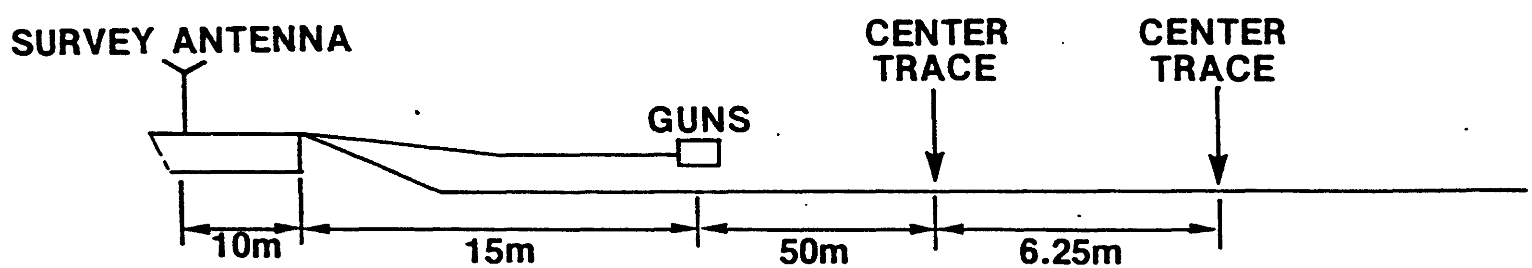

Figure 2.--Diagram illustrating the geometry of seismic survey, including the position of survey antenna, center of first hydrophone group, and spacing of hydrophone groups.

from the depth of water. This suppressed the water-bottom multiple in most places. Other than spectral whitening, a standard marine processing sequence was used.

GEOPHYSICAL ANOMALY TRENDING EAST-WEST ACROSS SEATTLE

The most persistent feature traced along the track lines is an east-west-trending geophysical anomaly underlying Seattle (documented by Yount and others, 1985; Gower and others, 1985). An acoustically transparent zone (that is, no coherent energy return) occurs along the strike of the geophysical anomaly (see fig. 3). At both Restoration Point and at Alki Point (fig. 1), lines 4 and 5) the Tertiary Blakely Formation strikes east-west and dips vertically. The near-vertical dips scattered the reflected energy to points outside the hydrophone array. While close spacing of the geophone groups reduced the effects of spatial aliasing during processing, the short streamer limited the aperture of the receiving system to pick up the steeply dipping Blakely Formation. On Lake Washington (fig. 3), the section is nearly void of seismic energy from CDP 3700 south to about CDP 2800. A strong band of reflectors at 450 ms occurs in the northern part of Lake Washington. This band is flat near the east side of the southern pontoon bridge at CDP 4400 and changes dip at CDP 3950. Without well control in the immediate vicinity, we may only assume that this band of reflectors is coming from the upper part of the Tertiary. This same structure is seen on line 1 on the east side of Mercer Island (fig. 1). Structures seen on the upper parts of the section, between the water bottom to 300 ms, do not appear to correlate with any other lines, indicating that these structures have no great lateral extent.

If the acoustically transparent zone had been an isolated observation (along one line), it could have been attributed to surface conditions; however, this was not the case. A broad band of little or no energy return

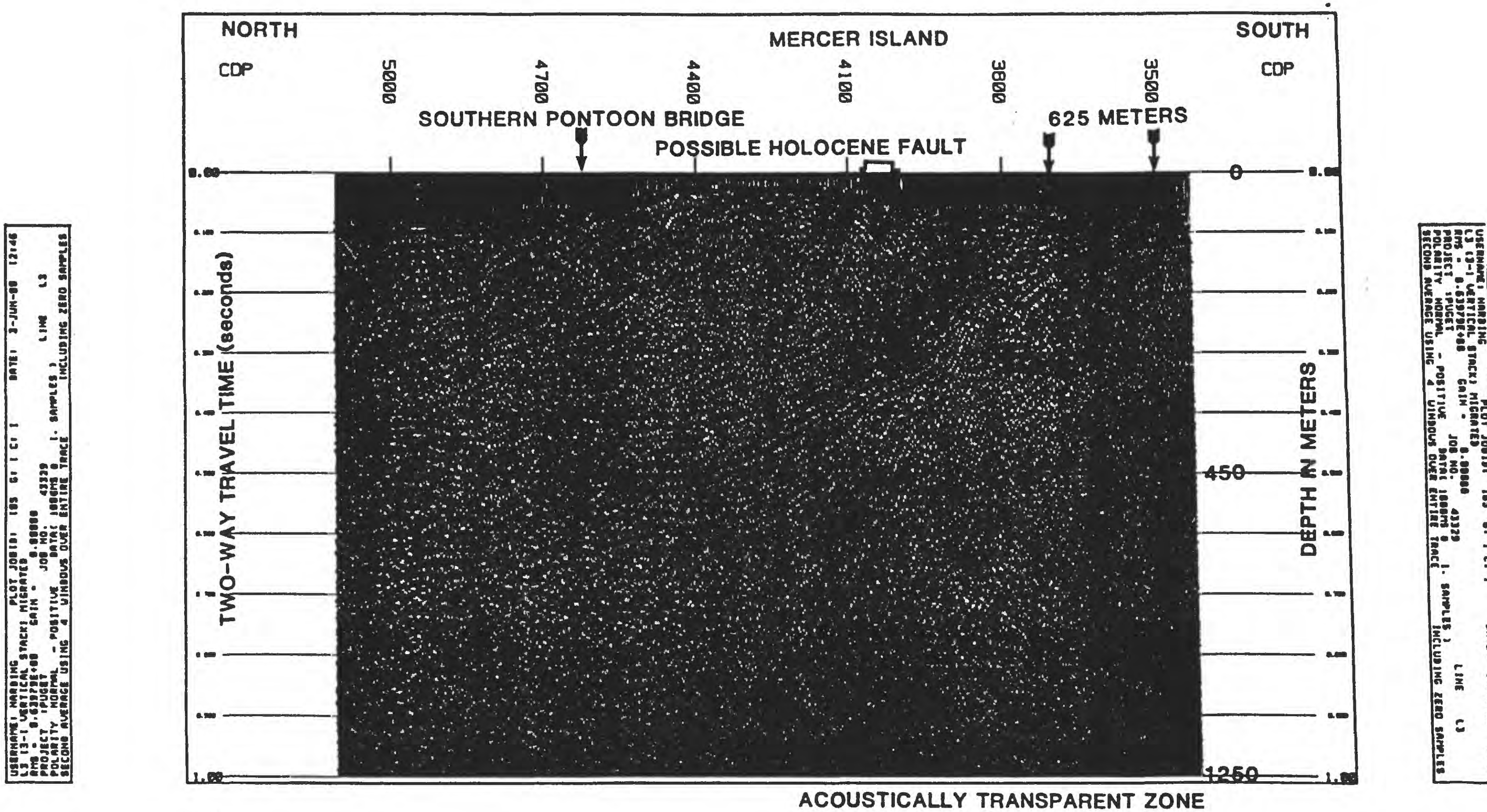

Figure 3.--Migrated seismic-reflection section (line 3, Lake Washington) illustrating acoustically transparent zone across Seattle geophysical anomaly. Figure also shows complex nature of the reflectors on the north flank of the anomaly and possible location of Holocene faulting 200 m south of the southern Pontoon Bridge over Lake Washington.

follows the geophysical anomaly, which is defined by a steep gravity gradient and a linear outcropping of Tertiary rock. The areal extent and persistence of this feature, from Lake Washington (lines 1 and 3) to Alki Point (line 5) and at Restoration Point (line 4), leads us to conclude that this acroustically transparent zone does not have a surficial origin; rather it is due to a deep structure that crosses Seattle and Puget Sound.

Seismic-reflection lines that were run across Lake Washington and off of Bainbridge Island show indications of youthful faulting (fig. 3). If our correlation is reasonable, there is 50 m of vertical displacement of the Tertiary reflector on the south side of the fault. The sediments above the Tertiary reflector also appear to be faulted, indicating a possible Quaternary fault with displacement down to the south. The complex subsurface-faulting pattern hints of a buried flower structure which indicates a strike-slip origin for the this zone. Indications of recent faulting where line 4 crosses the mouth of Blakely Harbor (fig. 1) will be discussed in more detail at a later time.

GEOPHYSICAL ANOMALY IN HOOD CANAL

A geophysical anomaly in Hood Canal (Yount and others, 1985) extends into Dabob Bay and may even extend as far as the land fault at the northern end of Dabob Bay (see figs. 1 and 4). The anomaly is a west-facing 74-m step in the sea-bottom that lies above a steep reflection discontinuity and is coincident with the trace of a fault reported by Gower and others (1985). Tertiary beds dip to the east and cannot be correlated beyond CDP 12,450 (fig. 4). If the sediments near the water bottom at CDP 12,300 are of Tertiary age, vertical displacement on the fault is on the order of 350 m.

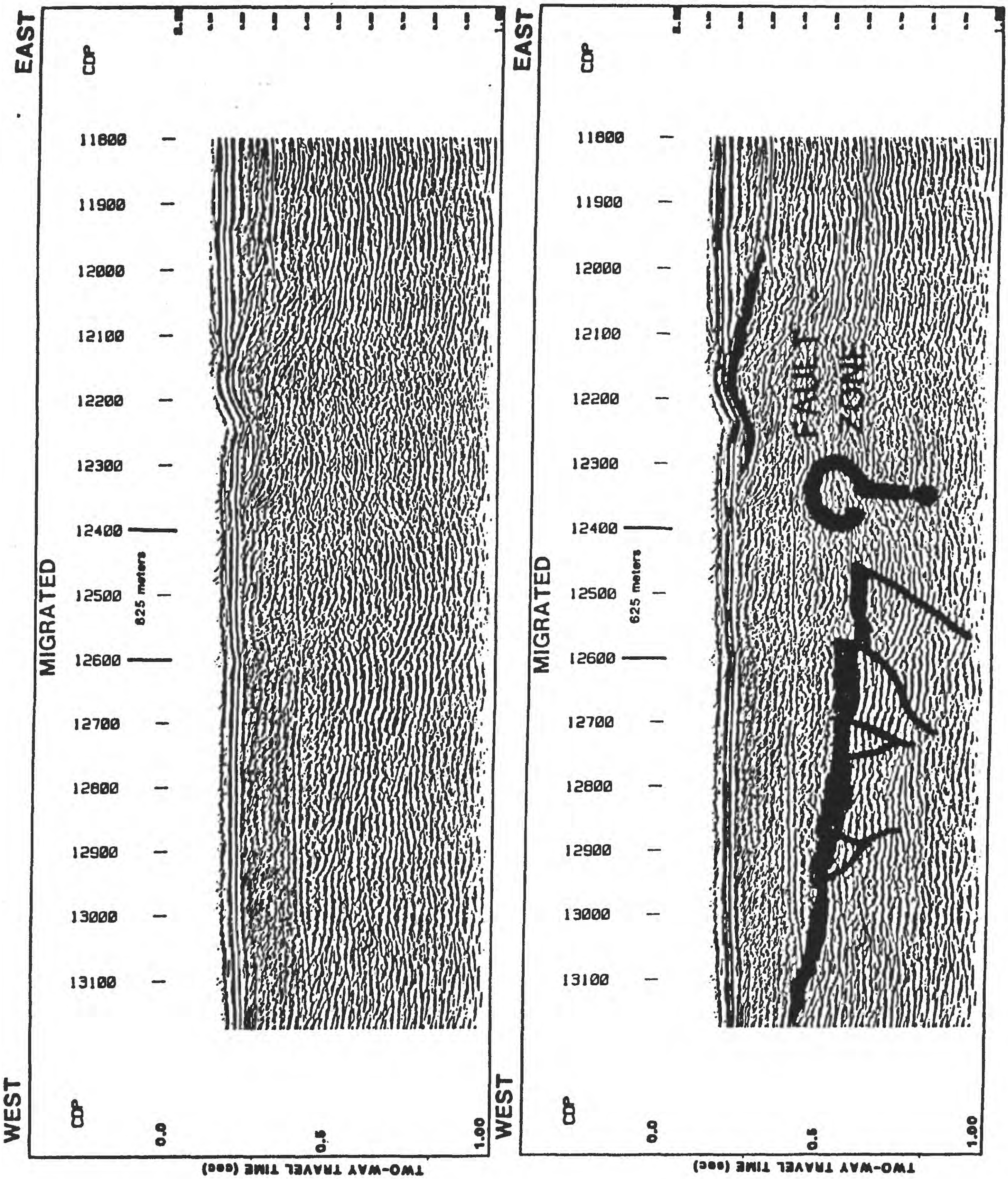

Figure 4.--Migrated seismic-reflection section of the southeastern part of line 12 showing possible fault close to where Hood Canal and Dabob Bay intersect. Interpretation of the seismic section is shown at bottom of figure.

ADMIRALTY INLET FAULT

The Admiralty Inlet fault as mapped by Gower and others (1985) shows a fault extending northwest but not extending into Admiralty Inlet. However, Wagner and Wiley (1980, 1983) do extend this fault northwest through the inlet. Lines 10B and 11 (shown on fig. 1) cross this proposed extension of the fault. Tertiary reflectors on the south ends of these lines can be seen. Although a fault may exist here, its sense of motion is different than indicated by Gower and others (1985). Wagner and Wiley (1980, 1983) show the extension of the fault to be down-to-the-west at the north end and down-to-the-east at the south end of the extension of this fault (Gower and others, 1985). Other faults are present in the Strait of Juan de Fuca and have been mapped by Macleod and others (1977). Our reflection lines have crossed several of these faults. Of these, the only fault having any surface or discernible subsurface expression is the fault described by Macleod and others, 1977), which appears as a large warp on the sea floor (also shown in Wagner and Wiley, 1983) and as a possible reflection discontinuity on line 10. There is a slight bump on the ocean floor on line 8 where this fault is mapped. The other previously mapped faults cannot be seen on the seismic sections.

POSSIBLE FAULTS ASSOCIATED WITH THE SEATTLE GEOPHYSICAL ANOMALY

The largest and steepest step in the sea-floor occurs just off Alki Point in West Seattle (fig. 5). The step reaches a height of 115 m and can be mapped over a distance of at least 1 km as a very steep water-bottom scarp. There are a number of possible explanations other than faulting for such a feature in a submerged glacial terrain. Our case for this step being of fault origin is as follows: (1) The band of reflectors seen on the hanging wall-block (50 ms wide) can be correlated with a similar band found on the footwall block of the fault in the middle of Puget Sound (not shown on fig. 5), implying that these surfaces were once connected. (2) The morphology of the near-surface strata is similar to what would be expected of a reverse fault (fig. 5). The position of the tensile structures as well as the uplifted features have a striking similarity to that shown in the cartoon. A strong reflector (at about 500 ms) is terminated along a proposed fault plane. However, this reflector cannot be seen on the hanging-wall block of the fault (Harding and Barnhard, 1987).

On the west side of Puget Sound near Restoration Point, there are two sea-bottom features coincident with Blakely Harbor which appear to delineate a graben-like structure. The southernmost east-west-trending graben fault may connect with a similar fault mapped by Walden (1967). The northern east-west fault has not been previously mapped. There are indications on the seismic section that these may be faults, but the subsurface seismic-reflection data are sparse. This graben feature is in the middle of the Seattle geophysical anomaly where little seismic energy is returned due to the steeply dipping Blakely Formation. However, there are broken reflectors on the northern step, indicating the sea floor is faulted.

POSSIBLE FAULTS IN COMMENCEMENT BAY

Geophysical studies of Commencement Bay (near Tacoma) indicate that perhaps two faults are present. One fault mapped by Rogers (1970) is also shown by Gower and others (1985), and Yount and others (1985) show a possible east-west-trending fault through Commencement Bay and crossing Vashon Island. Sylwester (1971) maps a similar fault but with a slightly different

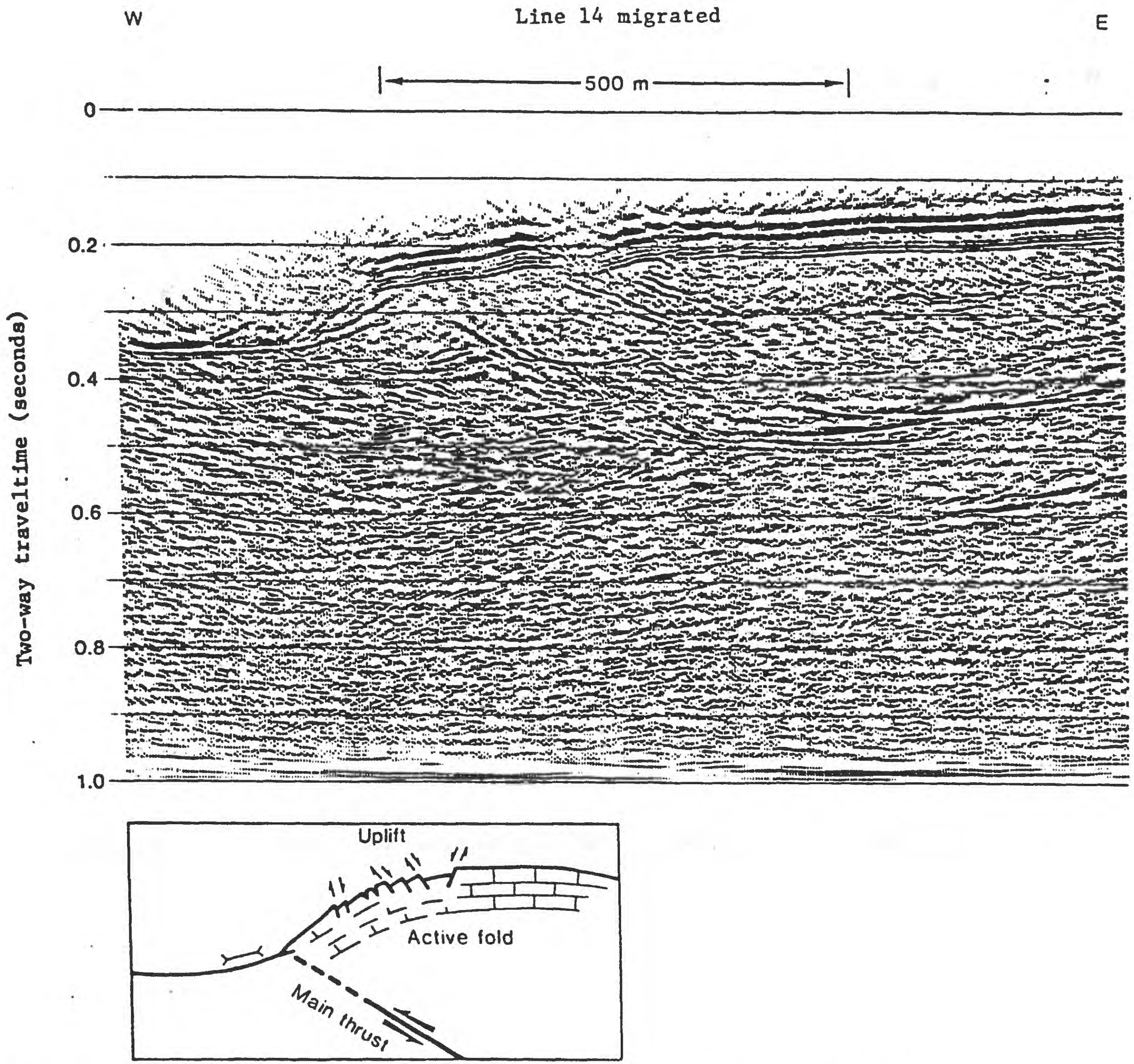

Figure 5.--Migrated seismic-reflection section at east end of line 14B showing a steep scarp off Alki Point that may be interpreted as possible Holocene fault. Cartoon insert showing near-surface effect of a reverse fault is from King and Bailey (1985).

strike (northwest trending) in the same area using single-channel seismic-reflection data. However, neither of these faults could be seen from the seismic data collected in this study.

CLOSING REMARKS

The results of this marine seismic-reflection survey for Puget Sound and the Seattle area are **preliminary**, and further site-specific processing needs are currently being determined. Although the collected data indicate possible Quaternary faults, additional processing is required to better define the nature and extent of the faulting.

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OVERVIEW OF EARTHQUAKE HAZARDS REDUCTION IN PUGET SOUND AND PORTLAND AREAS THROUGH IMPROVED BUILDING PRACTICES

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INTRODUCTION

Any discussion of seismic hazard reduction in building design for the Pacific Northwest region must consider the basic concepts for seismic structural design, how these concepts relate to the regional seismicity, and how they are employed by the local practicing profession. The discussion must also include consideration of the local history, since many variations in practice have occurred over time. Finally, the wide range of building types and ages must be included. This paper will attempt to join these different topics to provide a coherent picture of the existing hazards and the improvements which have been made in recent years. The discussion will focus on the Puget Sound region because it is the most heavily populated area of Western Washington and Oregon and the author is most familiar with this part of the region. However, the general comments should apply to most parts of the general region.

SEISMIC DESIGN CONCEPTS

The primary design concept applied to the seismic design of buildings in the United States is based on the Uniform Building Code and the SEAOC recommendations. With this method, the structure is designed to remain elastic for a modest lateral load distribution. The magnitude of the lateral loads depend upon the regional seismicity, the soil conditions, the importance of the structure, the type of structure, and the dynamic properties of the building. The lateral forces are relatively small, and so this part of the design essentially assures that the structure remains serviceable during small frequent earthquakes. Much larger forces must be expected in a major earthquake, but it is not economical to design most building structures to resist these larger forces. The overall safety of the structure during a major earthquake is assured by using a structural system which is very ductile. The ductility results in much smaller lateral forces at the cost of large permanent deformations of the structure during a major earthquake. The ductility permits the structure to dissipate large quantities of energy, and this dissipated energy dampens the dynamic response. However, it requires that the building be able to sustain large cyclic, inelastic deformations while supporting the gravity loads. The specifications are frequently ambiguous about how the ductility requirement is satisfied, but it is usually met by selection of a well behaved structural system and good connection detailing.

Some variations of the above procedure should be noted. Some structural engineering firms have become proficient at linear elastic dynamic analysis. They obtain an appropriate ground acceleration for their building site, and use linear elastic dynamic analysis methods to generate a response spectra or a time dependent response for the structure. They may use these computed results in several ways. The computed forces and displacements may be examined to verify that the structure can support the gravity loads and sustain the required displacements without yielding and without failure. This method has been used to justify the design and construction of new or unusual structural systems, and it has also been used to justify the use of connections with questionable ductility. The computed linear elastic response is sometimes adjusted to account for inelastic behavior. The computed forces are decreased and the deflections are increased by appropriate ductility factors. The structure must then be designed to remain elastic at these reduced forces and it must also be designed to develop the required ductility. Other variations in the seismic design procedure have been employed. Base isolation is receiving increasing acceptance in the United States. Isolators are inserted between the foundation and the structure. The isolators change the dynamic properties of the structure and sometimes add additional damping to reduce the dynamic response. This method is sometimes proposed as a method which can reduce the design requirements of the basic structure, and more important it may insure the serviceability of the structure even during extreme earthquakes. These later methods are based on rational principles. They clearly have a range of validity, and they have received some acceptance by the profession. There also appears to be some rational concerns with the use of these methods. Some engineers are rationally concerned that these methods may be misused, or that these methods required greater knowledge of seismicity than truly exists. However, these methods clearly have a range of validity, and they have received some acceptance by the profession. The methods also require very specific information related to the earthquake acceleration and relatively sophisticated analysis techniques.

REGIONAL SEISMICITY

A elementary knowledge of the seismicity of the Pacific Northwest region is necessary to evaluate the seismic risk potential. The seismicity of the Puget Sound Region is quite different than the California experience. The earthquakes tend to have a relatively deep focus (typically 15 to 35 miles), and they are associated with local movements at the junction of two major faults rather than movement along a long seismic fault. Portland and other cities outside the Puget Sound Region are more distant from major fault locations. Ground shaking at these locations is sometimes caused by movements along smaller inland faults, and smaller accelerations are usually expected for these cities than for the Puget Sound Region. As a result of these differences, the ground motion expected for a regional earthquake is somewhat different than that expected in California. The lack of long fault lines has led most engineers to believe that the maximum plausible earthquake has a magnitude of approximately 7.5 in the Puget Sound area. The very deep focus of the earthquake tends to attenuate the peak acceleration in ground motion records, but it also tends to modify the predominate period of the acceleration record to that of the soil deposit. Thus, the properties of the soil are extremely important throughout the region.

Three major soil categories may be noted throughout the Pacific Northwest. In the mountains and other isolated locations, bedrock lies at or very near the surface. Large portions of the populated regions have very deep soil deposits over the bedrock. These soil deposits tend to be very stiff and strong due to overconsolidation which occurred in recent glacial periods. The third major category is the very soft recent deposits which can be seen in many deltas and river basins. Probably the majority of the major buildings in the region are situated on the deep glacial deposits, but some significant structures are situated over the softer more recent river deposits. The location of the structure with respect to these deposits may have a large impact on the damage potential for the structure. The deep glacial deposits have fundamental periods in the range of .6 to .8 seconds, and as a result one must expect that buildings of intermediate height (5 to 10 stories) have the greatest potential for severe damage during a major earthquake. Quite different characteristics must be expected in regions over bedrock or more recent soil deposits.

Recent developments in the regional seismicity may further complicate the issue. It has been postulated that a major earthquake with magnitude greater than 8.0 has a small probability of occurrence in the subduction zone off the Pacific Coast. This possibility severely complicates the evaluation of the potential seismic hazard for the region, since the peak acceleration, predominate period and duration of shaking could be very different for such an earthquake.

HISTORY OF SEISMIC DESIGN FOR THE REGION

The first settlers arrived in the Puget Sound region approximately 140 years ago. Seattle was developing into a significant city by the early 1900's. In the early years of recorded history, there is considerable evidence of seismic activity, but there were no provisions for earthquakes in the design of buildings during this period. Many of these buildings are still in service and are regarded as historic structures. Seismic design provisions were introduced in California in the 1930's, and these provisions ultimately became the provisions of the Uniform Building Code. Seattle and the Puget Sound region was considered as Seismic Zone 1 until after the 1949 Olympia Earthquake. This effectively means that no buildings in the region built before 1950 had any consideration of seismic design. After 1950, the city of Seattle adopted the major portions of the Uniform Building Code for engineered structures and the seismic zone rating was upgraded. However, many other cities in the state of Washington did not adopt this specification until the late 1960's, and many buildings were built in these communities during this period.

During this same period, significant changes were occurring within the Uniform Building Code. Strength and stiffness requirements have modified considerably in the past 30 years. Many restrictions have been inserted to assure the ductility of structures and components. The specification has become more rational in that it now considers the soil conditions and importance of the structure. Therefore, many buildings which were designed to satisfy the Uniform Building Code during this period would not meet the present specifications.

Changes have also occurred within the engineering profession during this period. Most structural engineering firms in this region had little if any expertise in structural dynamics as recently as 10 to 20 years ago. Thus, any buildings designed by these firms were designed with code based static design concepts. They did not always understand the importance of ductility nor did they understand the dynamic amplification that can occur with seismic excitations. Some of the buildings designed by these engineers may have potential problems even though they legally and technically satisfied the code at the time of construction. Today nearly all the regional firms have a few engineers who are familiar with the concepts of dynamic response. The major firms in the region usually have one or two people that are highly skilled in this area. These major firms design most of the major buildings, and a number of these recent buildings were designed by alternate design concepts. That is, a linear elastic dynamic analysis may be performed to verify the performance of the structure, or the design forces may be determined by a linear elastic or modified response spectra. Some unusual and daring design concepts were used in some of these buildings. While these firms sometimes use sophisticated elastic analysis concepts, few if any of these firms employ inelastic analysis in their designs. Further, ductility often does not appear to be in the forefront of their thinking. Small or intermediate sized buildings (buildings 10 to 15 stories or less) are frequently designed by smaller engineering firms, and appear to be designed by the usual code based static design methods. One may logically ask if all of these smaller firms have a sound understanding of the unwritten ductility requirements of the code, and if these buildings all satisfy both the spirit and legal requirements of the code. This distinction may be quite important when it is recalled that local soil conditions suggest that these small to intermediate sized buildings are prime candidates for damage during future earthquakes.

The construction methods have also changed during this period. A number of small or intermediate sized buildings were constructed in the region prior to 1950. Most of these buildings have light structural frames with considerable mass contributed by unreinforced masonry, heavy plaster, and ornate architectural fixtures. Some of these buildings are still in service and are in need of renovation. These buildings typically have light structural frames which cannot possibly satisfy the present seismic design code. At the same time, many of these structures have survived two major earthquakes. They probably survived these past earthquakes because of the stiffness and resistance provided by the unreinforced masonry and nonstructural elements. These elements are relatively brittle and design codes do not provide a method for incorporating this strength or for estimating the degree of deterioration. As a result, this causes a serious dilemma to structural engineers, developers, and government agencies. It is generally impractical or even impossible to bring the building up to existing code standards, and the engineer is concerned that he will be legally responsible if a failure occurs with a building that is rehabilitated to less than present design standards. Government agencies are hesitant to assume the responsibility for legal waivers to the existing design provisions. On the other hand, nearly everyone agrees that the buildings are in need of repair, and that seismic upgrading is required. Many of these older buildings are of the intermediate height which is most susceptible to damage in the region. The balance between the opposing concerns is difficult to achieve.

Many buildings built since 1950 have similar problems. They were built with little or no consideration of seismic design or they were built to standards well below those required today. In addition the construction methods changed considerably during this period. Heavy masonry and plaster walls were replaced by light partitions and glass curtain walls. The weight and mass of the structure was reduced dramatically, but the strength and stiffness provided by these non-structural components was well below that found in older structures. The 1965 Puget Sound Earthquake resulted in significant damage to a number of these newer buildings. In addition, these buildings do not have the psychological advantage of having withstood the 1949 Olympia Earthquake. Thus, upgrading of these somewhat newer buildings is also a question of some concern.

Most homes and many other small one story buildings in the regions are built without any engineering design. These buildings are generally wood frame buildings which behave well if they are properly attached to their foundations, have good connection between members, and have chimneys which are reinforced and attached to the building. The building codes usually have minimum requirements for these details. However, the public awareness of the seismic problem in the region is not great, and the inspection requirements for the construction of these small buildings is minimal. As a result, one must suspect that there are a number of potential hazards with these structures.

SEISMIC HAZARD POTENTIAL

This has been a brief and simplified discussion of the seismic design practice in building design in the Pacific Northwest with particular emphasis on the Puget Sound region. The evaluation of the hazard potential is a highly uncertain process because of the many variables and uncertainties involved. However, it appears that a few important observations can be made -

1. The design specifications in the region have changed significantly in the last 25 years. Today they appear to be at a level consistent with other seismic areas of this country. However, many of the buildings in this regions were built with no consideration of seismic design or by standards well below the present level. The appears to be considerable potential for damage in these buildings.

2. The structural engineering profession has become much more aware of the seismic design problem and the special requirements of designing for dynamic loads. Some of the more sophisticated firms use linear elastic dynamic analysis to help them in their designs. Essentially all local firms use linear elastic static analysis methods in their design. There does not appear to be any usage of inelastic response calculations by the local profession. Therefore, it is not clear that the profession is appropriately concerned with inelastic behavior and ductility requirements. It is not clear that some of the new and daring structural designs used in the region are justified with this present state of practice.

3. The many older and substandard buildings raise serious concerns for rehabilitation of buildings in the region. Many of these older buildings are of intermediate size which appear to be most susceptible to damage with local soil conditions. Rehabilitation is needed and required, but the complex technical and legal issues make it difficult to achieve.

4. The present codes and design practice appear to be in line with recent seismic history. This recent history has suggested that the magnitude of the maximum earthquake is limited by local geological conditions. The amplitude of the acceleration, the duration of shaking, and the predominant period of the acceleration record are strongly influenced by the deep focus of these earthquakes and the local soil deposits. However, recent research has suggested that a much larger magnitude earthquake could occur off the Pacific Coast. This much larger earthquake could change the characteristics of ground motion and greatly increase the damage potential for the region.

LAND-USE PLANNING IN THE MITIGATION OF SEISMIC HAZARD

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INTRODUCTION

Geologic hazards can be either ignored, avoided, or prepared for. Land-use planning efforts seek to reject the alternative of ignorance. Of the remaining two choices, "planning" typically has favored avoidance over structural or engineering solutions. Yet the tools and procedures of planning can also be used to identify when and where more active measures should be applied within an existing zoning framework.

In the Puget Sound region, King County has adopted what is probably the most comprehensive code dealing specifically with seismic hazards on a site-by-site basis. The County's "Sensitive Areas Ordinance", adopted in 1979, provided for the delineation of potential seismic hazard areas and the mechanism to require additional site-specific study and design for developments proposed in such areas. The ordinance also adopted equivalent regulations for landslide, erosion, and coal-mine hazard areas in an effort to avoid the worst consequences of development in geologically hazardous areas. The King County Comprehensive Plan, adopted in 1985, reaffirmed the intent of the ordinance in two policies:

"E-308 In areas with severe seismic hazards, special building design and construction measures should be used to minimize the risk of structural damage, fire and injury to occupants, and to prevent post-seismic collapse.

"E-309 Prior to development in severe seismic hazard areas, builders should conduct special studies to evaluate seismic risks and should use appropriate measures to reduce the risks."

From a planning standpoint, the focus of these policies are essentially reactive and reflect the prevailing local attitude towards seismic risk. Developments are conditioned or modified once proposed, but the underlying zoning limitations are not altered as a result of hazard designation. This approach stands in contrast with the treatment afforded other types of geologic hazards, such as landsliding or coal mine subsidence, where the restrictions in many cases are tantamount to a prohibition on any development. Seismic risk in the Puget Sound region is generally perceived as a hazard that can be mitigated by appropriate engineering techniques.

There are several components to any regulatory effort designed to mitigate a geologic hazard. These include:

- --Definition of the hazard;
- --Characterization of a hazardous set of conditions;
- --Delineation of the hazard zones on a map;
- --Screening of proposed development; and
- --Review and conditioning of projects.

Because this procedure outlines King County's implementation of its seismic hazard policy, and because the principles should be generally applicable to any municipality's approach to these risks, the steps are described below in greater detail.

HAZARD DEFINITION

Seismic hazards come in a variety of forms. They include the "direct hazards", such as ground shaking, rupture, and failure (including landsliding and liquifaction); and the "indirect hazards", such as floods, fires, and tsunamis. Not all of these categories will be relevant concerns in all regions; because planning efforts typically lag at least one earthquake (or more) behind the empirical data, past experience is usually available to guide the choice of relevant concerns in a particular region. In the Puget Sound area, effects from the 1949 and 1965 earthquakes suggest that ground failure and the effects of direct shaking on buildings are of primary concern. Landslides and evidence of liquifaction were reported in several localities as well.

CHARACTERIZATION OF HAZARDOUS CONDITIONS

The identification of hazardous conditions and the delineation of their areal extent is guided first by the scale of the desired product. On a continental scale, the determining factors include tectonic province and the distribution of known or inferred earthquakes, irrespective of the theoretical understanding of their occurrence. Within a region of "high" seismic risk, such as the Puget Sound area, the hazard zones will depend on the type of seismic hazards judged relevant. The direct effects of shaking are measured by the <u>intensity</u> of the earthquake, which in turn depends on both geographic and geologic factors. Indirect effects will also depend in part on the intensity, together with more specific requirements (e.g., tsunamis or floods obviously require low elevations and proximity to water).

For a given earthquake, energy will radiate outwards from the focus, ideally producing concentric shells of ever-decreasing seismic effects. Yet any plot of earthquake damage after a single event will show variability in this simple pattern: regions where the damage, and thus the intensity, is as high as areas much closer to the epicenter, and sites where those effects appear anomalously low relative to their neighbors. Land-use planning, when applied to seismic hazards, is primarily the attempt to recognize and prepare for those areas where the intensity of a quake will be anomalously high.

The conditions that will control the variability of earthquake-related damage include:

- --proximity to active faults,
- --soil type and soil conditions,
- --site inclination, and
- --subsurface focusing of earthquake energy.

Any of these factors could in theory be made a part of the basis for seismic zonation of an area (i.e. the discrimination of areas of differing seismic hazard or risk). In practice, some of these determinants are more applicable or usable than others. In King County, only soil conditions and site inclination are used. Earthquakes here are relatively deep-seated and no surface trace of active faults in this part of the Puget Lowland have been identified, so proximity to known faults is nowhere relevant. The modeling of earthquake focusing is neither complete nor universally accepted, especially prior to 1979 when the ordinance governing seismic hazard zones was created. In contrast, soil types have been long accepted as a primary determinant of earthquake damage, both from the amplification of earthquake energy passing through thick unconsolidated sediments and from the potential for liquifaction. Slope inclination reflects the potential for increased landsliding of incipiently unstable soil masses during and immediately following an earthquake, observed most recently during the 1965 event. The identification of landslide-prone areas is itself an exercise in multiple determinants, of which slope inclination is only one factor.

MAPPING OF HAZARD ZONES

Ideally, the representation of seismic hazard zones would combine the various factors that determine the potential level of the hazard. For a given region or sub-region, where the likelihood of an earthquake of a given magnitude was roughly constant across the entire area, that hazard level might be quantified by the maximum horizontal ground acceleration for a quake of a given energy release. The resulting product would be contour map delineating several such categories.

In practice, the data are rarely available to make such estimates, although such information is becoming rapidly more available. Instead, a simple "good-bad" discrimination is made, typically on the basis of whether any of the unfavorable factors is present at a site.

The source of data to identify those factors can be a major weakness of the final hazard map. Municipalities generally do not have the resources to create their own maps of seismically susceptible soils, and so they must rely on existing soils or geologic mapping. Typically these existing maps were not specifically intended to identify seismically hazardous soils; they may also lack adequate information on the depth of the deposit. So although an complete data source would show and identify the known types of seismic hazards, including artificial fills, recent alluvial soils, low-density organic soils, thick unconsolidated deposits, areas of potential focusing, and landslide susceptibility, more commonly the information available consists of surface soil types and slope information only.

In spite of these deficiencies, the actual determinants of seismic response correlate fairly well with available information. Deep, unconsolidated deposits are most common beneath surfaces of alluvial sediment, which typically include areas of loose, organic soil as well. Saturation of these sediments is also common. Steeper slopes correlate fairly well with landslide hazard. Yet use of existing mapping may also identify areas where no credible seismic hazard exists, such as shallow pockets of peat on an undulating till surface or moderate-gradient hillslopes underlain by competent bedrock.

SCREENING OF DEVELOPMENT PROPOSALS

Once a map is prepared, a mechanism must be established to screen and divert affected development proposals from the standard permitting process. In King County, that authority was created by the Sensitive Areas Ordinance, which required that virtually all proposals requiring a permit be checked against the final map showing "hazardous" and "non-hazardous" areas. The process is quite straightforward; the location of the project is checked on a 1:62,500 map of the hazard zone by the intake permit technician (in the case of building permits) or lead planner (in the case of subdivisions or other large projects). If the project lands within the hazard zone, it is referred to a geotechnical specialist for further review and conditions. About 10% of the land area of the developing portions of the County (i.e. outside of the eastern tree farms and National Forests) is so categorized.

REVIEW AND CONDITIONING OF PROPOSALS

Once a project has been identified as lying in a seismic hazard zone, the technical reviewer must choose among several options:

--Because of the project, no concern is warranted (e.g., a kitchen remodel or a pole-supported carport).
--Because of the location, no concern is warranted (e.g., not actually in the hazard zone because of mapping error or map-reading error).
--The project lies in a seismic hazard zone, but the seismicity is the least of the project's concerns (e.g., excessive depth to bearing soil or active landslide threat). This category is by far the most common in the seismic hazard zones in King County.
--The seismic hazard is in fact a significant concern for the project and will not be addressed by other, more pressing needs.

Assuming that authority has been established, a municipality will typically proceed in a similar fashion for either of the last two options, where conditions or requirements beyond the standard zoning and building codes are deemed necessary. The applicant will be directed to hire a professional consultant to design a solution, which will be reviewed (usually) and approved by the municipality. For seismic hazards in King County, typical proposed mitigation have included subgrade replacement or improved site drainage. In most cases they represent engineering solutions to other, non-seismic problems at the site, which have the additional consequence of reducing the seismic hazard to a level equivalent to "non-hazardous" sites.

In only a few cases is a seismic-specific structural solution deemed necessary. The need in these cases generally transcends the information on the seismic hazard mapping, because they depend on additional knowledge by either the municipality or the consulting engineer about the depth of unconsolidated deposits, the historical association of the site's vicinity with high earthquake damage, or the peculiar nature of the structure.

LIMITATIONS OF LAND-USE PLANNING IN SEISMIC HAZARD MITIGATION

Because the scope of a planning technique is ultimately a function of the supporting ordinances, its limits will depend on the specific municipality that applies it. In King County, recognition of seismic hazard zones is not an avenue to disallow development. The ordinance provided the means to create a map identifying areas associated with higher-than-typical seismic risk and the ongoing authority to require additional study and mitigation of that risk for specific projects. Yet no project has been denied exclusively for reasons of seismic risk in this area.

Seismic zonation also has not been used in this area to date as a factor in long-range land-use. Only in one area, for an as-yet unadopted communuity plan, has a density reduction been proposed that takes seismic hazard into account as one of several determining factors. Three reasons probably underlie this general inattention. First, the conditions that yield high seismic hazard also correlate well with other, more immediate land-use constraints, such as flooding in alluvial valleys or landsliding on steep slopes. Second, seismic hazards are widely believed to be adequately manageable using structural and engineering techniques. Under such conditions, denial of property use is considered an extreme and indefensible approach. Even reduction of the density of development has not been considered a warranted step in light of this hazard alone.

Finally, the area has experienced no major earthquakes in almost 25 years. Their absence has fostered little support for more extreme land-use controls in seismic hazard zones, because there is very little first-hand experience, either popular or professional, on the success of the less extreme development restrictions and techniques applied to date. It will be interesting to see, at some future date, if our relative complacency has been warranted.

NEW EDUCATION, AWARENESS, AND PREPAREDNESS PROGRAMS AN OVERVIEW

By

Carole Martens
School Earthquake Safety and Education Project (SESEP)
Seattle, Washington

INTRODUCTION

Recently a reporter asked me if, in my opinion, any progress toward earthquake preparedness had been made in Washington. I asked him what time frame he was referring to: our time or geologic time? Luckily at this conference we are evaluating change in geologic time--where a few thousand years is a small frame of reference. So on those terms, I can begin to discuss earthquake education, awareness, and preparedness by saying progress has been made.

HISTORY

Nearly 50 years have passed since a series of four large quakes between 1939 and 1949 clearly established this area as a major earthquake zone. The largest and most damaging event occurred thirty-nine years ago yesterday, on April 13, 1949, when the Puget Sound/Portland area experienced a 7.1 Richter Magnitude quake that caused severe damage to structures, disrupted lifelines and resulted in 7 deaths. Two of those deaths were students in Washington State Public Schools. Recognizing that a large number of the structures damaged were school buildings and that, had it not been Spring vacation in many of the state's school districts, the death toll among school children could have been much higher, the Seattle School District developed and distributed a guideline for carrying out school earthquake drills. A cover letter stressed the importance of being prepared for the next earthquake.

The assumption one would like to make is that after nearly 50 years of earthquake awareness and thirty-nine years of practicing earthquake drills, our schools are prepared to deal with a school-day earthquake emergency. The School Earthquake Safety and Education Project (SESEP) learned during its four-year project that this is not the case.

SOME SESEP FINDINGS ON SCHOOL EARTHQUAKE PREPAREDNESS

SESEP was housed within the University of Washington Geophysics Program, supported by the Federal Emergency Management Agency (FEMA) with funding provided to the Washington State Department of Emergency Management--now a division of the Department of Community Development. One of SESEP's goals was to reduce the vulnerability of the school population to the life-threatening consequences of future earthquakes.

Some project findings were 1) schools generally were unprepared for earthquake emergencies: drills were not required in all school districts; when required, they were frequently not carried out (Though earthquake drills were required in one urban school district in 1983-84, only 49 of the 67 elementary schools held drills); and parents were not informed about school emergency plans, if a plan existed; and 2) motivation to develop earthquake safety plans existed because of the eruption of Mt. St. Helens in May of 1980, but no clear information on what to include and how to proceed was available.

Needs identified by the project clearly point out that past intermittent efforts to involve schools in earthquake preparedness activities had not achieved the level of preparedness desired. SESEP determined that schools were not prepared to handle earthquake emergencies, although some were motivated to begin earthquake emergency planning, and schools needed education and information to assist them in the process.

This lack of preparedness prevailed in spite of a statutory requirement, with mandatory language, that schools shall be prepared to meet sudden emergencies. RCW 28A.04.120 (10), Duties and Powers of the State Board of Education, written into the Washington Administrative Code (WACs), Chapter 180-41, Pupil Safety, since October, 1970, mandates that school district boards of directors shall be responsible for providing instruction of pupils and shall develop specific plans and procedures consistent with WAC 180-41...and in accordance with guidelines to be provided by the superintendent of public instruction.... Since its adoption, this statute has, in most cases, been narrowly interpreted to mean sudden "fire" emergency only. School earthquake emergency planning takes place in school districts were it is regarded as a priority, but not on an institutionalized scale as in the case of school fire preparedness.

PAST PUBLIC INFORMATION AND AWARENESS PROGRAMS

Over these past 50 years, many efforts have been made to increase public information and awareness of the earthquake risk and the need for preparedness in the Puget Sound, Washington area. This was affirmed in a research project, Earthquake Mitigation Policy: The Experience of Two States conducted in the 1980s by Drabek, Mushkatel, and Kilijanek. The two states were Washington and Missouri. Their summary said, "The earthquake hazard clearly has not been a neglected topic in Washington State....all [efforts] raised the consciousness of the general public and policy makers, but they all were stopped short of their ultimate goals.

Some of these efforts have resulted in significant gains. Some examples are the study committee formed by the American Society of Civil Engineers in 1950 to review damage caused by the 1949 event, and headed by Professor Al Miller, University of Washington Civil Engineering Department; the articles that resulted entitled, "Lessons in Structural Safety Learned from the 1949 Northwest Earthquake"; the 1970s legislative review committee, the Ad Hoc Committee on Geologic Hazards; and the statutory adoption of the Uniform Building Code as a statewide design standard.

Certainly public and governmental awareness has increased, but none of these efforts has resulted in a state level commitment to fund and embark on a permanent and on-going program of earthquake hazard reduction for the welfare of the citizens of the state of Washington. The need is intensified as we look forward to two decades of population growth--the U.S. Census Bureau projects a 15.7% increase in population for Washington State by the year 2010--much of which will be within the Puget Sound region, an area designated Seismic Risk Zone 3 in the Uniform Building Code, and can expect major earthquake damage.

NEW EARTHQUAKE EDUCATION, AWARENESS AND PREPAREDNESS PROGRAMS

There is some reason for optimism when reviewing what is being done today. No one group or individual can know every effort that is being made. My attempt here will be to review some new programs. Most focus on one of several categories: schools, the design profession, the community or the legislature. New programs, in this discussion, will be defined as programs initiated since the USGS "Workshop on 'Earthquake Hazards in the Puget Sound, Washington area'" held in Seattle in October, 1985. That workshop included presentations on earthquake awareness, earthquake education and earthquake preparedness.

SCHOOLS

Target Group: Grades K-3, 4-6

Goal: Education and training leading to students and teachers understanding the causes and effects of earthquakes and being able to take appropriate self-protective actions in an earthquake

Program: Development of Earthquake Education teaching modules for K-3 called "When the Unusual Happens," and 4-6 called "Rumble Ready." Packages include a letter to the parents, 3 lessons plus related activities and a choice of slides/audio or a videotape of an original story illustrated with art work by high school art students.

Impetus: Linda Noson, Carole Martens with writer Connie Coleman; Seattle's Franklin High School art teacher, Ms. Lynn Knell-Jones; artists Tim Baxter and Brian Chin; storyteller Spencer Shaw; and the Seattle School District. Production and distribution is by the University of Washington Health Sciences Center for Educational Resources.

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Target Group: Grades K-6

Goal: Education and training leading to students and teachers understanding the causes and effects of earthquakes and knowing what to do in an earthquake

Program: Development of a draft Earthquake Safety and Education Curriculum for grades K-6. The goals of the program are that students will gain awareness of the impact of earthquakes on the human and natural environment; understanding of what we know about earthquakes and how we know it; and earthquake preparedness as individuals and as communities.

The draft curriculum is now being assessed by the curriculum division of the Office of the State Superintendent of Public Instruction (SPI) to determine their interest in further development of it and the possible inclusion of the concept in their environmental education curriculum.

Previous developers of environmental education curricula (such as Project Learning Tree and Project Wild) have limited the concepts included to man's effect on the environment and various ways to change behavior harmful to the natural environment. This curriculum, when developed, will include the environment's effects on man and man's ability to alter the harmful impact by selective actions.

<u>Impetus</u>: School Earthquake Safety and Education Project with the assistance of a committee of teachers, district and SPI science education specialists and a science curriculum doctoral candidate at the University of Washington.
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<u>Target Group</u>: School District Facilities Staff

<u>Goal</u>: Education and guidance leading to hazard mitigation

<u>Program</u>: Non-structural Earthquake Hazards Identification and Mitigation Guidebook for school facilities divisions. The information can easily be transferred to other facilities as well. The final copy is near completion and preliminary drafts have been approved for publication as a supplement to the "Safer Schools" manual by the School Support Services Director of the Office of the State Superintendent of Public Instruction (SPI).

<u>Impetus</u>: School Earthquake Safety and Education Project with the assistance of a committee from the Seattle School District Facilities Division, the School Support Services Division of SPI, and private consultants in structural engineering and design.
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<u>Target Group</u>: All schools, school districts, or other groups wanting earthquake education information

<u>Goal</u>: Make available earthquake awareness and education information

<u>Program</u>: Videotape of SESEP director giving typical school earthquake safety and education presentation. Presentation includes causes and effects of earthquakes; explanation of materials available; demonstration of the earthquake education models developed by the Environmental Volunteers of California. Needs refilming due to excess noise on audio track.

<u>Impetus</u>: Dr. George Willett, Superintendent , Mary M. Knight School District; filmed and distributed by Educational Service District 113, Olympia.

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<u>Target Group</u>: School Bus Drivers, School District Administrators

<u>Goal</u>: Provide earthquake preparedness training program

<u>Program</u>: Videotape of SESEP assistant giving presentation aimed at school bus drivers. Provides information on earthquake zones, typical earthquake damage and goes through a scenario of a morning school-bus route earthquake disaster. Ends with recommendations for appropriate actions. Includes model procedures and a driver instruction sheet.

<u>Impetus</u>: Ms. Sheryl Everson, Seattle School District school bus driver. with Laidlaw Transportation, Seattle School District School Support Services, EBI O'Ryan (a private enterprise) and the School Earthquake Safety and Education Project.

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<u>Target Group</u>: The Pierce County School Community

<u>Goal</u>: Provide public education and information which will result in awareness and preparedness

<u>Program</u>: Earthquake awareness and preparedness program for the Pierce County school districts. A program was developed after reviewing available materials including the Hanna-Barbera earthquake preparedness program featuring Yogi Bear comic books and videotapes. A fund raising campaign resulted in adequate funding to purchase the Yogi Bear materials for use in all elementary schools in the County. Additional materials focusing on Pierce County were developed.

<u>Impetus</u>: Bill Lokey, Pierce County Department of Emergency Management, working with the City of Tacoma, the Lakewood Chamber of Commerce, and businesses, organizations, and school districts.

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<u>Target Group</u>: The central administration and each school site in the Highline School District

<u>Goal</u>: Development of specific earthquake preparedness plans

<u>Program</u>: Adoption of a district goal to be prepared in the event of a school-day earthquake. All levels within the district worked together toward this goal.

<u>Impetus</u>: The School Board and Superintendent adopted the goal, gathered information, invited the School Earthquake Safety and Education Project (SESEP) in as consultants, held a four-hour workshop/planning session and developed the outline of their preparedness plan. Later the district included earthquake education in a summer in-service training seminar for area elementary science teachers

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Target Group: Washington State School Districts

Goal: Provide a model policy for school earthquake preparedness

Program: Policy office began development of a model policy in order to distribute it to school district boards of directors statewide as a model for school earthquake emergency preparedness.

Impetus: Washington State School Directors Association (WSSDA) Director of Policy Services; Dr. George Willett, Mary M. Knight School District Superintendent

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Target Group: School District

Goal: Increase awareness and provide guidance in a school day earthquake or other emergency

Program: Adoption of emergency procedures and/or policies on the subject of managing school-day emergencies of a broad description--most including or limited to earthquake emergency. School Districts having programs known to me include: Olympia, Mary M. Knight, Seattle, Sultan, Lake Washington, Highline.

Impetus: Varies between districts

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COMMUNITY

Target Group: General Public

Goal: Demonstrate the causes and effects of earthquake ground shaking

Program: The Pacific Science Center has begun a program of scheduled demonstrations of the causes and effects of earthquake ground shaking. They use a set of educational models developed by the Environmental Volunteers of California.

Impetus: The School Earthquake Safety and Education Project and its supporting agencies: the Federal Emergency Management Agency (FEMA) and the Washington State Department of Community Development, Division of Emergency Management (DEM)

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Target Group: The Community

Goal: Education and information leading to a united community effort to prepare to be self-sufficient in the immediate aftermath of a large, damaging earthquake

Program: The Eastside Mothers for H.E.L.P. is a neighborhood group formed to raise public awareness of the potential impact of a major earthquake on the area, to develop and distribute information, and to help Eastside communities with earthquake emergency preparedness.

Impetus: Ms. Beverly Carter, after seeing the KOMO TV documentary, "On Shaky Ground"

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LEGISLATURE

Target Group: The policy makers of the state of Washington

Goal: Recommend state level policies and actions which, if acted upon, would help reduce the damage and loss of life from a major earthquake in Washington State

Program: The Washington State Seismic Safety Council was convened by the Director of the Department of Emergency Management (DEM) at the direction of the governor following his veto of legislation establishing an independent commission. The Council of 14 members began meeting in November, 1985, and submitted its report, Washington State Seismic Safety Council Policy Recommendations to DEM in September, 1986. The report concluded with a section entitled "Priorities for State Action" which included four legislative recommendations and eight State agency recommendations.

Impetus: Legislation initiated and supported by individual citizens and groups concerned about the need for on-going and aggressive state leadership and action in the area of earthquake education and earthquake hazard reduction

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Target Group: Washington State House of Representatives

Goal: Raise legislators awareness of the need to recognize the earthquake threat to the citizens of the State

Program: For Earthquake Awareness Week, 1987, a House member obtained permission from Hanna Barbera and duplicated the Yogi Bear comic book on earthquake preparedness. She also developed a House Floor Resolution stating that the House of Representatives recognized the serious threat to the citizens of the State due to the potential for major earthquakes and recognized the need for State action. She distributed copies of the comic book and the resolution to each member of the House, then urged the adoption of the resolution. It passed.

Impetus: Representative Georgette Valle, Democrat from the 34th District in Seattle, and member of the Washington State Seismic Safety Council, working with Harry Halverson, Olympia, and Carole Martens of SESEP.

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Target Group: The policy makers of the state of Washington

Goal: Passage of legislation leading to state level actions which would result in the reduction of potential loss of life and property from a major earthquake in Washington State

Program: During the 1987 and 1988 legislative sessions, bills were introduced based on the Washington State Seismic Safety Council Policy Recommendations for State action. The 1987 bill, SB 5885, calling for an inventory of public facilities and for earthquake education, passed the Senate. Progress for the session was ended in the House Ways and Means Appropriations Subcommittee and it was not scheduled a hearing in 1988 in its house of origin, the Senate.

In the 1988 session, HB 1405, Earthquake Education, was introduced. It called for a $30,000 appropriation to provide State matching funds to capture the National Earthquake Hazard Reduction Program (NEHRP) funds available to Washington for FY 1989, and which falls before adoption of the next Washington State biennial budget. The bill passed House State Government but failed to move out of House Ways and Means. However, the Chair expressed willingness to provide the state matching funds by including the item in the budget. The Senate agreed in conference committee. The governor signed the budget with the item remaining.

Impetus: Prime sponsor of HB 1405 and HB 483 (same wording as SB 5885), in the House was Representative Georgette Valle, Democrat from the 34th District, Seattle; and of SB 5885 in the Senate, Senator Stuart Halsan, Democrat from the 20th District, Lewis County.
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DESIGN PROFESSIONS

The Structural Engineers Association of Washington (SEAW) in cooperation with the Continuing Education Committee of the Earthquake Engineering Research Institute (EERI) and the Applied Technology Council (ATC) has sponsored earthquake education programs on Observations of earthquake impacts in the Whittier event and "State of the Art in Earthquake Evaluation of Structures--an Overview."
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MEDIA

All of the major television channels and Channel 9 aired shows relating to earthquake awareness and preparedness during the period being discussed.

Channel 4, KOMO TV, researched the issue locally and filmed an hour-long documentary entitled, "On Shaky Ground." The show aired on December 12, 1986, at 8:00 P.M.--prime time on a Friday evening. Since they have received more than 400 requests for copies of the tape and numerous requests to re-air the film. SESEP used the film in earthquake awareness presentations, as does Eastside Mothers for H.E.L.P.

"On Shaky Ground" may have accomplished more for earthquake awareness in Washington State than any other single element of which I am aware.
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EXECUTIVE BRANCH

The Governor's annual proclamation of Earthquake Awareness Week is a program which gives each of us an opportunity to discuss earthquake preparedness with our families and co-workers.
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THE FUTURE?

At present there is little understanding of the full significance of the earthquake risk by decision makers. Often a school district response will be: We do earthquake drills; a state-level response might be: We retrofitted the state capital building.

School earthquake preparedness funding is always in competition with highly visible and important causes: drug abuse prevention; AIDS curriculum development. This is consistently used as an excuse not to fund school earthquake preparedness. In districts where it is a priority, ways have been found to accomplish both.

Some members of the school community have specific ideas about what we need to do to change our future course from foreseeable losses in an earthquake to one of preparedness. During the last year SESEP was funded, a survey was developed and sent to 250 persons who had had contact with SESEP. They either:

- o Participated at a SESEP pilot school
- o Responded to publicity about earthquakes
- o Attended a SESEP workshop
- o Requested information
- o Held a school district administrative or board position

Our objective was to learn several things: what policies are needed to get earthquake education and preparedness programs in place in Washington's school districts and assure their implementation and continuation; and what programs already exist that could add an earthquake component with little effort and cost. Attached is a copy of a summary of the results.

CONCLUSIONS

Limited, narrow-focused, typically short-lived programs can accomplish a good deal. But so much more is needed. Schools and other groups need committment to earthquake preparedness at the top levels, policies and funding, and clear guidelines on what to include and how to proceed--with specific details worked out at the local level. A successful earthquake awareness and preparedness program can only occur when the State of Washington recognizes the need for permanent and on-going state level programs and makes a commitment to provide leadership and the required funding. Until then, Washington State will remain at risk.

SCHOOL EARTHQUAKE SAFETY AND EDUCATION PROJECT (SESEP)
GEOPHYSICS PROGRAM, UNIVERSITY OF WASHINGTON
FUNDED BY FEMA/WSDEM 9/83 - 9/87

SUMMARY OF QUESTIONNAIRE RESPONSES

July 31, 1987

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250 Questionnaires sent
9 Could not be delivered
39 Completed and returned = 16%* response

Breakdown by category of respondent

2	Parents
10	Building Staff
8	Building Administrators
11	District Administrators
2	School Board Members
1	ESD Administrator
5	Misc: City Council, County/City DEM, Fire District, Red Cross

Breakdown by geographic location of respondent

WASHINGTON
- Adna
- Cape Flattery
- Darrington
- Elma
- Everett
- Lacey
- Longview
- Mount Vernon
- Puyallup
- Randle
- Rochester
- Seattle
- Shelton
- Snohomish
- Sultan

OREGON
- Portland

CALIFORNIA
- Tiburon

CANADA
- Vancouver, B.C.
- Victoria, B.C.

* Though it is acknowledged that a 16% response to a survey is not academically acceptable, the survey is included for informational purposes. It is helpful to see the areas where the seven categories of respondents are in greatest agreement, notable questions C and D.

9B2 80036

A. What policies are necessary for a school district to have in place to assure that each school building and the district as a whole can respond quickly and effectively in a school-day earthquake emergency?

SUMMARY OF RESPONSES TO A:

Districts need to adopt strong Board policies [or a state law is needed] which clearly state the committtment to fund, develop, implement, and monitor earthquake emergency preparedness programs.

District earthquake emergency preparedness programs should mandate that each school develop a plan. Using state-provided guidelines, site-specific building plans should be developed by building-level Safety Committees.

Ideally, plans should include earthquake drills with periodic evacuation drills, staff first-aid training, alternate districtwide communication system, student retention vs. dismissal decision, assignment of staff responsibilities, hazard identification and mitigation, emergency supplies and equipment, staff and student education, coordination with city-county and other emergency responders, communication of school plan to parents and community, annual building safety checks, accountability, and funding to buildings.

Legislation may be necessary to initiate program.

B. What school district administrative or director-level support might assist those at the school building level in developing and implementing earthquake safety and education programs?

SUMMARY OF RESPONSES TO B:

Support needed from the district administrative or director-level sited most often is: An administrator responsible for program development and implementation.

Also sited as necessary: Awareness and committment at administrative and director levels; support services available, eg. staff training, building maintenance, clearly-defined responsibilities, accountability via annual report, and guidelines from the Superintendent of Public Instruction (SPI).

C. Ideally, where should school earthquake safety and education programs and plans be initiated: the state level? the district level? or the school building level? Why? How would the system work?

SUMMARY OF RESPONSES TO C:

At what level should school earthquake safety and education programs and plans be initiated?

Total of 37 responses:

3	Legislature	Mandate, Funding
16	State (SPI)	Guidelines, Funding, Resources
10	District	Obtain State Help, Guidelines
3	Building	With State/District Funding
5	All levels	All levels Work Together
1	Community	

D. Identify existing programs (both safety and curriculum) that could be expanded to include an earthquake section with minimal time and financial impact.

SUMMARY OF RESPONSES TO D:

The area of greatest agreement was that 1.) earthquake safety programs should be part of each school's safety committee responsibilities, and that 2.) earthquake safety and education curriculum components should be incorporated into subjects which could most easily accommodate them, such as:

Science
Social Studies
Health, Safety

Building safety checks could be incorporated with routine maintenance checks.

SESEP program could be used as model.

OVERVIEW OF EMERGENCY MANAGEMENT PLANNING AND RESPONSE PLANNING

By

Chuck Steele
Federal Emergency Management Agency - Region X
Bothell, Washington

My comments this morning are mainly related to those who are the two percenters in the audience, viz., those who represent the State and local government implementation component in the overall National Earthquake Hazards Reduction Program (NEHRP) scheme of things. But first, I would like to step back and review the NEHRP from an overall perspective. NEHRP was created in 1977 with the Goals of reducing future losses of life and property, and preventing severe disruption that could be caused by a catastrophic earthquake. The Act directed the Federal Government to lead, coordinate and conduct earthquake research , hazard mitigation, and disaster preparedness activities.

Of the $65 million annual NEHRP Budget, only $1.3 million is directed Nationwide to State and local preparedness planning projects; that is the two per cent. When California's roughly 57% is subtracted from this total, an average of around $35,000 is left for the 16 other States that participate in NEHRP funding (California's figure is around $700-800,000).

The six basic program elements these funds must be distributed to are now well established through our agency, and are described in a document entitled "State and Local Earthquake Hazards Reduction: Implementation of FEMA Funding and Support." They are:

a. State Seismic Advisory Boards
b. Hazard Identification
c. Vulnerability Assessments
d. Preparedness and Response Planning
e. Mitigation Planning
f. Public Awareness/Education

Though the funding is meager, there have been some very creative products that have resulted. They range from the State of Washington's excellent School Earthquake Safety and Education Project, to production of an award winning earthquake awareness videotape in Utah. They include a medical response plan in Kentucky, seismic design standards in the Virgin Islands, vulnerability studies in several States and an examination of the earthquake safety of State-owned and leased buildings in Alaska. The State and local government accomplishments funded in part through NEHRP in California are dramatic and have been very effective.

Indeed, the two percenters have been very busy and have gotten great mileage out of very limited resources. If the "Commentary and Recommendations of the Expert Review Committee," chaired by George K. Bernstein, is listened to, it is possible that the two percenters will get more than double, to around $2.8 million per year (however, they will still be two percenters, since the total NEHRP Budget also more than doubles). Mr. Bernstein, a former Federal

Insurance Administrator (FIA being a component of FEMA) chaired the Expert Review Committee that examined NEHRP and recently produced its Commentary and Recommendations. The report is very cognizant of the important role implementation plays in the entire process. It says: "There is concensus that greater emphasis needs to be placed on implementation if the goals of the Act are to be realized during the next decade." This is acknowledged by the fact that a significant body of research presently exists that could solve specific implementation problems if it could be incorporated into practice.

The basic purpose of the Expert Review Committee was to review current NEHRP activities and make recommendations to be considered by the involved agencies for the upcoming five year planning period of 1989 to 1993. In the context of the revised five year plan, the committee recognized "that an increase in resources for implementation is necessary to address the gap that exists between research itself and translation of research into earthquake hazard reduction practices." While the report recognizes the need for cost sharing in State and local assistance projects, it also suggests that NEHRP be a catalyst in areas where there is a lower level of interest or awareness, and that it play a leadership role in bringing together all facets of the implementation community.

The literature is full of references to the importance of good scientific data, and how that, in turn, can translate into sound implementation. The USGS's Bill Kockelman, who is no stranger to the world of implementation, reduces the components for any successful earthquake hazard reduction program to 5:

1. Conducting scientific and engineering studies
2. Translating the results of these studies into reports and maps that are understandable
3. Transferring this information to users and assisting them
4. Selecting and using appropriate hazard reduction techniques (such as design criteria)
5. Reviewing the effectiveness of hazard reduction techniques

At the FEMA/USGS Workshop in Denver in September 1987, this concept was discussed long and hard. All agreed with the basic process and needs spelled out by that process. When it came to implementation, people from Utah saw great value in the scientific products and, in turn, used these products to convince State and local officials to take several actions (like upgrading hospitals, retrofitting a VA hospital, developing a strong State/county Earthquake Response plan, establishing numerous mutual aid agreements, cooperative agreements and MOU's, conducting State/county earthquake exercises based on products of the research and a host of others). The report was well prepared, well communicated and well received by those who would be most affected from the perspective of preparing for earthquakes (local officials, the media, private utilities, etc.).

The Puget Sound is not a newcomer to earthquake hazard identification and assessment studies. The first "Blue Book" for this area was sponsored by FDAA (a predecessor component of FEMA) and was prepared in 1975 by the USGS. This report had all the right essentials. It started by positing a maximum credible earthquake of magnitude 7.5 with epicenters near Seattle and Olympia, and gave anticipated damage patterns on a county-by-county basis that included estimated loss of life, injuries, number homeless, and degree of impairment of all vital needs (such as lifelines, medical, food, communications, and schools).

Was this report successfully applied? I will not attempt to answer that question. Dick Buck of our Disaster Assistance Programs Division delivered a paper on that subject at the 1987 FEMA/USGS Workshop in Denver. He detailed the actions that followed release of the report, including extensive media coverage, and missionary work by the then-FDAA in the form of workshops, seminars, development of a Federal Response Plan and a major exercise of that plan.

Similar actions by the State emergency management agency did not occur at that time, and no specific local programs resulted during that time, probably because of the lack of any funding incentives. However, Mr. Buck describes the Study Report as one that probably has had much more subtle and long-term effects than what appeared on the surface. He described it as the standard reference or baseline for all who have an interest in the Puget Sound earthquake problem, and cites subsequent local earthquake planning efforts spurred by its content (e.g., Whatcom County) as well as notable State activities that came later (such as the 1986 bill in the Legislature to establish a seismic safety commission and the School earthquake Safety and Education Project). It is obvious, as you can tell by listening to others on this program, that many effective local efforts are underway, whether or not they are related to the "Blue Book."

What does this all mean in terms of where we are now? The work underway in the Puget Sound-Portland project is probably the best thing that could happen in this area in terms of rekindling the need for earthquake preparedness planning, especially since real events (thankfully) have not been prominent in this area in recent years. The data base that results should be invaluable. I would hope that the final products would be as utilizable as they were described by users of the most recent such study, that for the Wasatch Front. If all of the science leads us to damage and loss profiles related to the larger subduction zone event described earlier, Federal, State and local officials will have to become much more active players on the implementation stage.

I believe this area is ready to assume a greater role in emergency preparedness activities, especially in State and local implementation. It is ironic that we could be entertaining throughts about something "new" in view of the fact that National Earthquake Hazards Reduction Program is already 10 years old, and we have been funding earthquake activities for a longer time than that. But at least in our office, there has been a commitment, for the first time, to hire a person to work full-time on earthquake in an effort to fulfill many of the NEHRP goals, including that described in the Work Plan as a leadership role for implementation in the Puget Sound-Portland project.

There are many things FEMA can offer in the implementation area both indirectly through the State/local grant program, and directly. For example, FEMA has been responsible for development of a rather well-done series of guidebooks aimed mainly at local officials, known as the Earthquake Hazard Reduction Series. This series covers all aspects of earthquake preparedness programs and seismic design, as can be seen in the titles. Further work will soon be published in the following areas:

- Seismic Design Standards for High Occupancy Buildings
- Costs of Seismic Rehabilitation
- Rehabilitation Priorities Handbook
- Seismic Strengthening Handbook
- Rapid Visual Survey Handbook
- Identifying Existing Hazardous Buildings
- Multihazard Mitigation Handbook

Most of these documents are prepared through the Building Seismic Safety Council or the Applied Technology Council. They are aimed at the implementer and can be understood by the non-engineer. The BSSC also has a Speakers Bureau available as a service, and a toll-free number for assistance (1-800-66-NEHRP). Our Regional Offices, for the most part, have not actively communicated these publications and services to implementers in the past. This is just one thing that will be more actively pursued with addition of a dedicated earthquake person.

FEMA has also developed some excellent courses through its National Emergency Training Center which can be deployed to the field or taken at Emmitsburg (EMI). We will encourage both. We specifically intend to field-deploy the following two courses in the Puget Sound region within the next several months:

- Earthquake Mitigation for Utility Lifeline Systems
- Nonstructural Earthquake Hazard Mitigation for Hospitals

I am also encouraged by statements that have been made by Kate Heimbach regarding the State of Washington's desire to get into a very comprehensive and long-range earthquake reduction program, one that would become institutionalized within State government. Her statements have been backed up with a very ambitious, all-encompassing scope of work that has been proposed for funding starting this fiscal year. I would hope the State would proceed quickly to hire a professional earthquake planning staff that would be capable of carrying out the many and complex tasks that are in this program. Certainly there could be no better opportunity or time than now, especially in view of the excellent data that will be produced through the Puget Sound-Portland project. The project is begging for this kind of leadership in the Implementation component.

Finally, I would hope there would be more formalized involvement between the States and local governments, or groups of local governments. One need only look south of the Oregon border to see the model for this, viz., the very successful Regional organizations in the Los Angeles and San Francisco areas referred to as SCEPP and BAREPP. These highly successful regional organizations have, in turn, established very significant planning partnerships with the ultimate implementers, the local governments in their areas. In fact, some would say that the success of the Regional efforts is because of the successful dealings with local governments. Some of the Planning Partnerships involve grants to major counties to prepare five year plans, coordinated emergency preparedness plans, common seismic mitigation measures, mutual aid agreements, and the like. FEMA is presently exploring the possibility of funding local governments through NEHRP. A recent workshop with all NEHRP-funded States in Denver raised the question of how to increase local participation, especially in view of FEMA's emphasis on mitigation, local governments being the prime mitigators. Increased local involvement has been suggested by many groups, including Congress and the Western States Seismic Policy Council, among others.

One of the more exciting initiatives underway in FEMA is planning for Federal Response. Although there has been Federal earthquake response planning in the past, this is a rather major effort that is being undertaken in all 10 FEMA Regions. I will not attempt to describe it but, rather, will defer at this time to the person from our Disaster Assistance Programs Division who is the Project Manager for this effort, Mr. Bob Freitag.

EVALUATION OF EARTHQUAKE HAZARD AND RISK IN THE PUGET SOUND AND PORTLAND AREAS

By

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SESSION II

Group I: Building Practises

The purpose of this discussion group is to explore current practises for the reduction of seismic hazards in buildings; emerging methods of hazard reduction; future needs; and barriers to the implementation of hazard reduction.

A. Current practise

Methods of seismic rehabilitation in the Puget Sound area are undergoing constant evolution. Many jurisdictions regularly deal with the concept of seismic rehabilitation while others rarely, if ever, insist on seismic improvement of older buildings. There are no code formats currently in general use which adequately address the issues of seismic rehabilitation; consequently, the practising engineer is left largely alone to assimilate the increasing volume of technical and empirical data produced by ICBO, ATC, NSF, USGS, FEMA and others. While doing so, the engineer must develop a design philosophy consistent with competing bureaucratic and economic demands of the owner, architect, and regulator. This design philosophy is most often unstated, and even if presented, does not meet contemporary standards of new building design even for life safety.

In large part then, the development of seismic retrofit is anecdotal and relies on practises which have developed validity simply by their repeated use. Puget Sound has, for the last fifteen years, renovated primarily masonry and wood-frame structures; therefore, the practises developed in these buildings hold credence for other, more complex building types as well. Following are the methods most often employed:

1. Anchorage, both of walls and parapets.

2. Development of global lateral systems, usually of a very stiff type, regardless of a building's site/structure response.

3. Anchorage of building elements, such as masonry infill walls, equipment and fixtures.

4. Development of horizontal diaphragms.

5. Maintenance and enhancement of vertical continuity.

6. Development of detailing procedures to mitigate hazards inherent in irregular building configurations and pounding.

There have, in addition, been movements in the past to add elements of ductility to otherwise very stiff structures; this movement is now largely discredited.

B. Emerging practises

Emergent practises are currently focused on two basic elements: the development of code formats consistent with the high variability of older buildings and the development of practises which are more responsive to the economic demands of rehabilitation as well as the structure's likely existing performance characteristics. Each of these requires a great deal more development, particularly the development of even the most general rehabilitation codes for seismic strengthening and the laboratory testing of more satisfactory rehabilitation methods. Several of these emergent issues include:

1. Code developments such as ATC-14 which particularize the problems inherent in the many older building types. These codes are general; however, they have systemetized issues by building type rather than the making of presumption, as contemporary building codes do, of a particular standard for building construction by material.

2. The development of the analytic and technical tools to assess site/structure response and to provide systems which improve a building's existing qualities rather than simply provide an entirely different way of behaving during an earthquake.

3. Continued development of inelastic analysis tools which better reflect an older structure's characteristics.

4. The development of a progressive response philosophy by techniques aimed at providing structures with initial strength and ductility using as much as possible their current resources. The issue is to develop a least-to-most important level of deterioration within a building system tied to a philosophy for life safety and the economic life of the building.

In this regard, methods for improving building ductility need to be addressed. Older buildings are decidedly lacking in this area and such methods as column jacketing and the addition of frames where appropriate need to be discussed.

Also, techniques and design philosophies for the improvement of damping characteristics within structures are being explored.

5. Experiential data bases are being refined to assess the responses of retrofit methods. Whittier, in particular, allows comparison of retrofit methods with unrenovated construction.

6. Base isolation may become practical in a limited number of cases where the historic character of a structure is compromised by conventional methods.

THE NEED TO MITIGATE EARTHQUAKE HAZARDS TO LIFELINES

By

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ABSTRACT

Most attention and concern regarding earthquakes and the impacts on people have centered on the effects of earthquakes on buildings and structures. The effects on lifeline facilities, those which people rely on for the most basic of human needs, has not received adequate attention. Following the 1971 San Fernando earthquake, it became apparent that the impact of earthquakes on lifeline facilities such as water and sewage delivery systems needed more attention. The American Society of Civil Engineers created the Technical Council on Lifeline Earthquake Engineering and several subcommittees to deal with these critical facilities such as water and sewage, power, communications, gas and liquid fuels, and the related topic of seismic risk.

This paper describes the efforts of the City of Portland, Oregon to deal with seismic risk matters that affect our system and our ability to continue to function under all conditions.

INTRODUCTION

The 1971 earthquake in San Fernando, California caused extensive damage to a wide range of lifeline facilities in addition to the building and structure damage which gained national attention such as the collapse of the Veterans Administration Hospital. Equally important was the near collapse of the lower San Fernando dam which could have affected tens of thousands of people directly and affected the water supply to the millions that depend on the critical water facilities that pass through this area. Had there been an additional aftershock, the flood would have been devastating. The 1906 San Francisco earthquake disrupted water facilities and allowed a fire to ravage the entire city. More closer to Portland, windstorms, floods, and other hazards have impacted the city and have resulted in a recognition of the fragility of components of the water supply system. The Portland Water Bureau has taken steps to address certain of these needs and is looking further for other needs that need to be addressed.

The lack of earthquake activity in the Northwest, particularly in the Portland region in recent years, may have created an aura of apathy regarding earthquake motion and the devastating effect it can have. Further, the emerging research on subduction type earthquakes such as the article by Heaton and Hartzell in the April 10, 1987 issue of Science magazine are beginning to raise some doubts. The possibility of great earthquakes and the similarity of subduction situations to other parts of the world needs to be discussed among lifeline purveyors and utilities more fully so that steps can be taken, programmed, or budgeted to harden facilities as a normal course of operations.

LIFELINES

Lifelines are the critical facilities and utilities that bring a modern, urban population those commodities that are urgently needed for life, health, and safety. The American Society of Civil Engineers through their Technical Council on Lifeline Earthquake Engineering recognize the following key lifeline functions:

- Water and sewage lifelines
- Electrical power and communications lifelines
- Gas and liquid fuel lifelines
- Transportation lifelines

All of these lifeline systems are critical to meet the human needs of food, shelter, and clothing, but are by no means the only critical needs during a catastrophic emergency. Other needs are functional buildings such as hospitals and food distribution centers; bridges for transportation; electrical power plants; port structures; and airports are further examples of critical point facilities.

Several of these lifelines are aerially distributed in the form of buried pipes or pipes on bridges. For example, in the City of Portland, 40 percent of our installed asset cost is in the form of buried pipes and long, large diameter pipeline delivery systems. Also, transportation lifelines such as roadways and railway systems extend over long distances and are impacted by ground shaking, subsidence, and other effects of earthquakes. Gas and liquid fuel pipelines are generally buried and under extremely high pressures and are also susceptible to disruption. Electrical power systems and communication systems extend over vast expanses and are networked to provide reliability but are also subject to gross disruption.

AFFECTS ON THE PORTLAND WATER BUREAU

The earthquakes of the past in the Portland area have not created great public observable disruptions to service. Occasional rockfalls and disruptions of power to pumping stations and the consequent outage of water have been minor to moderate. However in 1964, a combination of severe weather that created deep snow packs followed by a change in the weather which melted the snow packs quickly resulted in flooding in the region of Oregon and Washington. This manifested itself in a flood or record at the recently completed Bull Run Dam No. 2 that caused two of Portland's three water conduits to be taken out of service by flood action, undermining, and the breaking of the largest supply pipeline. This event was quickly addressed since men, materials, and equipment were available to address the problem immediately.

Subsequently, another emergency affecting the water supply in 1972 resulted when ice bridging at a remote site gave way on the North Fork, one tributary of Bull Run River that undercut a landslide mass, and exposed decomposed volcanic ash materials of colloidal size. This resulted in the entire water system being impacted by material that would not settle out in the reservoirs and lead to a long period of turbid water. The resulting emergency declaration by the governor and subsequent repair work using FDAA (now FEMA) grant funds to repair the damage to the natural channel ended up costing in excess of $1 million dollars and lead our thinking to the future development of an emergency groundwater backup system.

Following the emergency repairs in 1972, another grant-funded effort was undertaken to look at the watershed for further disaster causing influences. This work, the DIMP Project (Disaster Identification and Mitigation Project), had several elements, including the review of the entire watershed for geologic hazards. The resulting work by Beaulieu in 1974 has helped to focus the

Bureau concern to hazardous areas of the watershed. In addition, a hydrologic model of the entire watershed using sophisticated computer simulation techniques was undertaken and the computer simulation was calibrated to earlier flood events. The computer model was then used to simulate probable maximum flood as a result of probable maximum precipitation. These flows were then simulated over the dams and spillways to check their safety. This work has been reviewed in subsequent years following the installation of hydropower facilities and has been found to still be state-of-the-art in its character.

Additional studies of the condition of facilities and equipment has resulted in capital projects to add emergency power generators and a wide range of other related activities.

The Bureau is undertaking a full hazard assessment review of water facilities this year that may result in further needs being identified for a wide range of hazards, including earthquake. The Bureau added hydropower facilities to the dams in the watershed, and at one location where older distribution reservoirs exist. The subsequent FERC requirements for review have resulted in several dam safety investigations as well as the Corps of Engineers' dam safety investigations in 1978.

More recently, the Bureau undertook the review of a large 3-million gallon elevated water storage tank in 1985. This review of the Denver Tank resulted in a seismic evaluation of several steel water storage reservoirs in 1987. We reviewed the geologic and soils situation, conducted seismic studies and structural evaluations, and recommended lowering several reservoirs until strengthening and repairs could be made. This work included the review of eleven surface tanks, nine standpipes, and ten elevated tanks, 30 facilities in total.

EARTHQUAKE INTENSITY

The work of our geotechnical consultants (Cornforth Consultants) and seismic evaluation of the steel water storage tanks noted above resulted in the awareness in the 1 in 500-year event of a maximum credible earthquake (MCE) for these tanks to be a near field event of magnitude 6.0 within ten miles. The far field events of magnitude 7.0 at 55 miles (St. Helens zone) and magnitude 8.0 at 120 miles (Puget Sound) were not as significant as the near field event. Another project in January 1986 reviewed the liquefaction potential at a large reservoir built in 1911 that holds 75 million gallons of water. Reservoir No. 6 is centrally located in the city at a location called the Mt. Tabor complex and since a small hydrogenerator between two reservoirs of different elevations exist, FERC regulations required a liquefaction study. The 28-foot high soil embankment was analyzed and our consultant, Derek Cornforth, engaged Dr. Ignatio Arango and Professor H. Bolton Seed on the analyses. They recommended using a 1 in 5,000 year occurrence interval for high hazard dam structures such as the Mt. Tabor soil embankment. Since the embankment serves as a dam for this reservoir, an earthquake of magnitude 6.5 with peak ground acceleration of 0.32 g was selected. Professor Raymond B. Seed at Stanford performed a finite element study of the horizontal shear stresses on the embankment and the foundation materials as a part of the liquefaction study. As a result, it was found that the facility is safe under the stated earthquakes.

PIPELINES

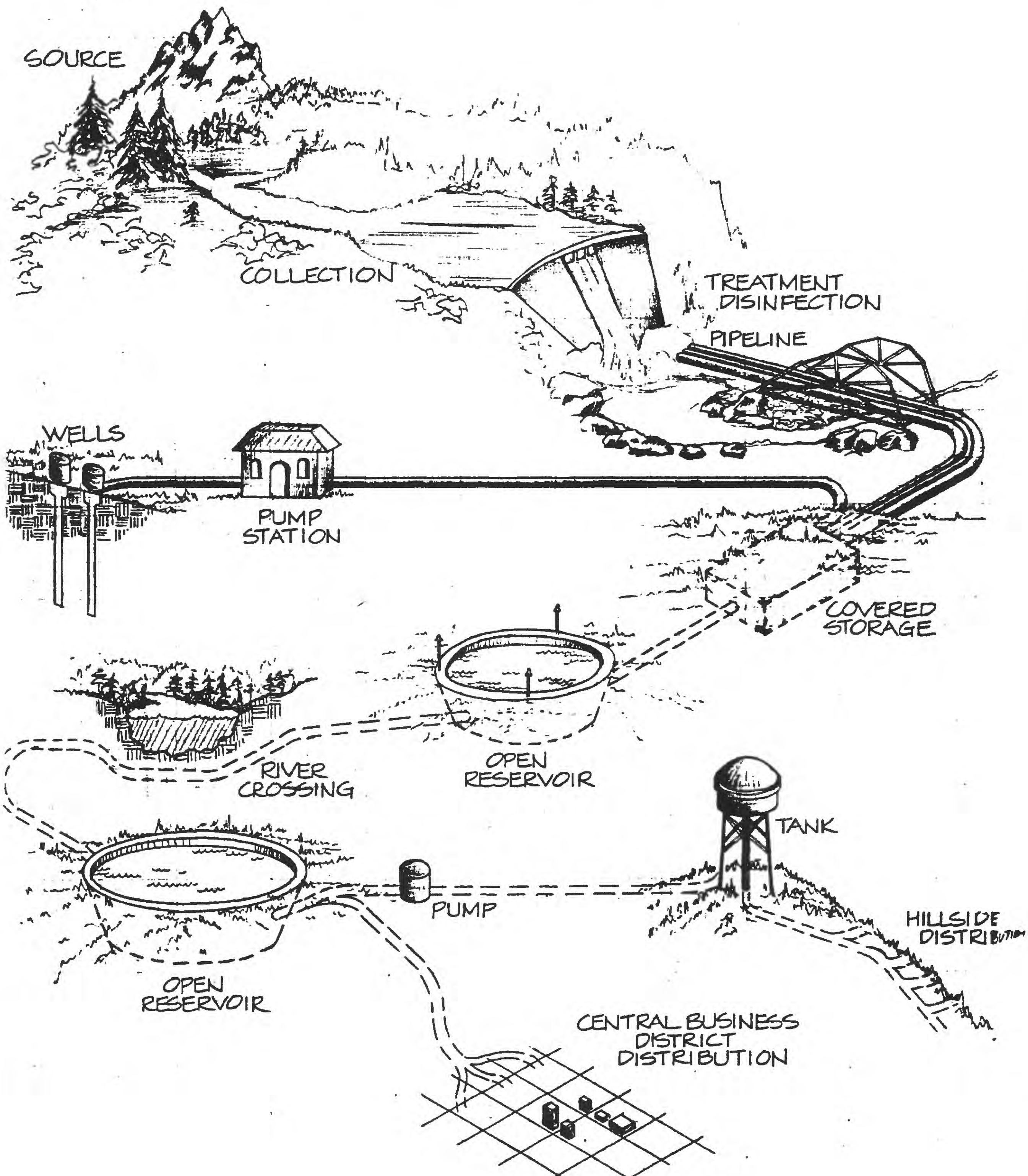
The Portland Water Bureau has a continuing interest in how earthquakes would affect the facilities of the Bureau and our critical mission of supplying water to the people of Portland and those who rely on us for water. The Bureau is in the midst of conducting a hazard assessment study, and as part of that effort, has submitted a grant application under the National Earthquake Hazards Reduction Program to describe the seismicity and earthquake hazards confronting the service area and to understand more fully the earthquake effects on various pipelines. Loss algorithms will be developed to describe earthquake intensity versus expected loss for the pipeline networks and for concentrated facilities such as pump stations and tanks. Dr. Leon Wang of Old Dominion University will be involved with this work as well as Don Ballantyne of Kennedy/Jenks/Chilton Engineers in the review of concentrated facilities and the expected effects of earthquakes. The unique feature of this grant proposal is that we intend to look not just at water facilities but at the sewage facilities operated by the City of Portland.

LIFELINE PURVEYORS MUST BE INVOLVED

It is evident from my work in emergency planning and discussions with other utilities that there is a general lack of emergency planning and very little plan exercising, and a general lack of recognition for the potential impacts of earthquakes in our area. In order to foster an awareness and interest in changing this situation, it will be necessary to catch the attention of high officials in all of these key lifeline areas. Toward that end it would be helpful to have ways and means of communicating and keeping interest at a reasonable level such as video tape presentations and investigations of earthquakes and their impacts. A great deal of literature is available as noted in the ASCE Annotated Bibliography. Other presentations such as walk-throughs of facilities with experts to discuss damage would be helpful. In addition, workshops and working groups to heighten awareness of all that should be concerned over the next several years will be crucial to the success of any earthquake mitigation efforts.

When the USGS began talking about the possibility of Mt. St. Helens erupting, there was little concern because no volcano had erupted in recent memory. However, following the May 18 event at Mt. St. Helens, a greater credibility has been placed on USGS concerns. Now that the Survey is raising our concerns about the possibility of large and great earthquakes in the Northwest, it is an appropriate time to explore and implement those communications devices that would lead to fresh looks at all of the lifeline utilities that are so critical to us in our modern urban existence.

SYSTEM SKETCH



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WATER LIFELINES DISRUPTED IN 1964 FLOOD EVENTS

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COASTAL EFFECTS OF A GREAT SUBDUCTION EARTHQUAKE: REGIONAL LAND USE IMPLICATION

by

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Land use planning which responds to highly specific characteristics of vulnerability is an important method to reduce earthquake hazards. In order to develop these planning methodologies, however, a more refined understanding of susceptibility is required. The first step in hazard based land use planning is, therefore, a scientifically based method for hazard delineation. Subsequently, land use decisions can be based on specific vulnerabilities to distinct and definable risks.

In coastal areas, a primary vulnerability to disruption from earthquakes is from inundation. This flooding can be caused by distant tsunamis generated in the earthquake's source region from local tsunamis generated by ground failures such as underwater landslides, and from water fluctuations from seiche.

This paper reports on the process used to assess the implications of the tsunami hazard on the outer Washington coast. First, exposure is defined. Subsequently, exposure is translated into population and land use risks.

COASTAL HAZARD ASSESSMENT

Evidence presented in recent investigations (Bourgeois, Reinhardt 1987; Atwater 1987) indicates that the outer coasts of the Cascadia subduction zone are vulnerable to tsunami activity. Atwater (1987) reported evidence for at least six subsidence episodes in the last 7,000 years. In all cases, vegetated coastal lowlands were buried by intertidal mud. In three of the episodes, patterns of sand sheets lying atop the buried lowlands could be explained by inundation due to tsunamis and the resulting shoreward transport of sand. Other research (Reinhardt & Bourgeois 1987; Atwater, Hull, & Bevis 1987) cites additional evidence for subsidence and possible tsunami related flooding in the past thousand years.

Year One of the study reported in this paper defines the general regions most likely to be threatened by a tsunami generated in the Cascadia subduction zone. The study used a wave propagation model and a source model. It indicates that, as a result of source motions, highest tsunami energies would be directed toward the outer Washington coast and possibly the San Juan straits (Hebenstreit 1988).

The Juan de Fuca plate is roughly 800-900 kilometers long. It is subducting at a rate of 4-4.5 centimeters/year. Of the three subareas along the Cascadia subduction zone (Gorda Plate, South Cascadia, and North Cascadia zones), the South Cascadia zone is probably the most likely to experience a large subduction zone earthquake.

Contours of the calculated seafloor uplift were first superimposed on contours of bottom topography for each of three source areas. In all cases, the model indicates that uplift takes place offshore with some subsidence on land. These uplift/subsidence assumptions are comparable to observations in the 1960 Chilean and 1964 Alaskan earthquakes.

In the Cascadia south zone, as with other areas examined, the extreme wave height values are found along the coast within the source region. Dominant wave energy distributions are confined to the immediate source area; i.e. the most extreme wave heights are found along the coastal zones within the source uplift zone. It was also found that the elevations tend to taper off (although not uniformly) to the north and south of the immediate area of the uplift (Hebenstreit 1988). The projected vulnerability also corresponds to the location of sand lenses discovered on the outer Washington coast, i.e. at Willapa Bay and Grays Harbor by Atwater, Bourgeois, and Reinhardt.

The mean value for the simulated wave heights in the South Cascadia zone indicates height just below six meters above MLLW. As Figure 1 indicates, areas with projected mean wave heights in the range of eight or nine meters are, however, found in the area between Newport, Oregon and Grays Harbor, Washington.

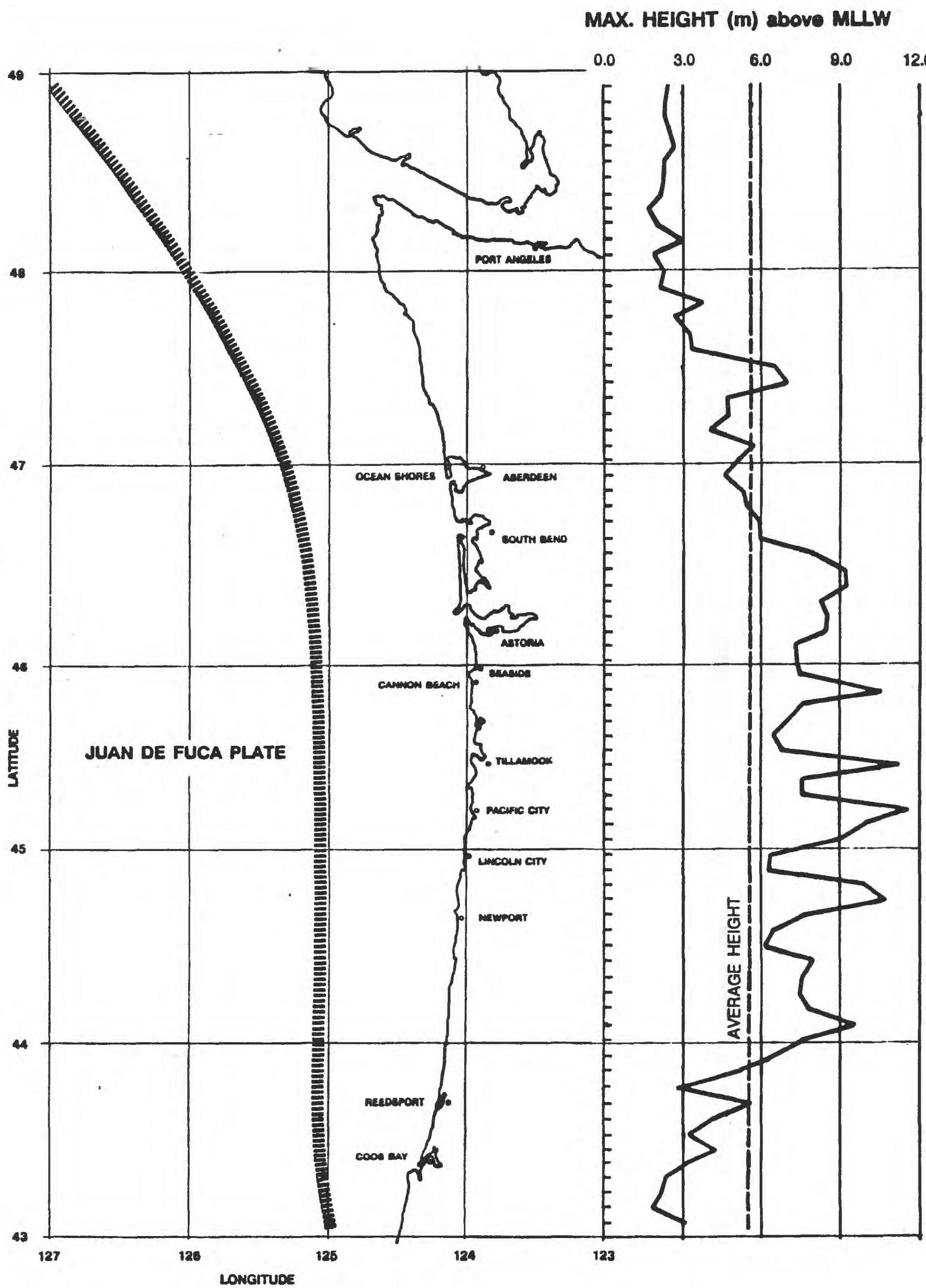

Figure 1 Projected Wave Heights South Cascadia Zone
(Source: Hebenstreit 1988)

REGIONAL PLANNING IMPLICATIONS

Once exposure is projected, vulnerability must be converted into risk. A wide range of land uses are represented in the coastal urban areas projected to experience mean wave heights above seven meters. They include:

- Residential: South Aberdeen
- Second Home and Tourism: Ocean Shores; Seaside-Cannon Beach; Newport
- Industry: Grays Harbor (Hoquiam, Aberdeen, Cosmopolis, Montesa no), Coos Bay

Analysis of the land use patterning results in organization of coastal risks into three categories:

- Populations directly at risk
- Land use based/economic disruption
- System disruption to bridges and roadways and other lifelines

POPULATIONS AT RISK

Year round population levels as defined by the U.S. Census are low in the coastal segments in which energy is focused. These patterns, however, are not true indicators of population densities. At any given time, the wide sandy beaches of the Oregon coast are popular destinations for both Seattle-Tacoma and Portland urban areas. The 1986 population estimate for the Seattle-Tacoma PMSA was 2,285,000, while the estimated population for Portland-Vancouver, Washington) was 1,350,000 (U.S. Census, 1988). Virtually the entire coast is heavily populated during the summer months by campers and by tourists staying in the many beachfront hotels and the potential for life loss can be high. For example, Cannon Beach, Oregon reports that its annual sandcastle building contest attracts 15,000 to 35,000 spectators (see Appendix). Many more people attend the July 4th festivities in Seaside, Oregon.

The predominantly second home community of Ocean Shores, Washington is entirely below ten foot in grade. Needless to say, none of this area was inhabited during previous tsunami events. It should also be noted that a decision has recently been made to locate the new high school that will service a large segment of the coastal county within the inundation zone.

Second Homes in Ocean Shores: Population levels in the hazard zones are often seasonal.

Another type of concentrated risk is the port of Grays Harbor (Aberdeen and Hoquiam). It is the principle port used by the northwest forest products industry which extensively uses chemicals in treating lumber products. Fires generated in the port would quickly spread to the neighboring residential and commercial areas. In the industrialized ports of Hoquiam-Aberdeen-Grays Harbor, Washington and Coos Bay, Oregon, populations are at risk from both direct water impact forces and from indirect forces such as fires and contamination generated in the port. The zones include: 1) the immediate impact or inundation area and 2) the area vulnerable to fire spread and contamination which is airborne (chlorine gas, etc.) and/or is carried inland on surface waters, i.e. the many rivers feeding into the bays and harbors.

LAND USE DISRUPTION

As mentioned above, year one of the research has projected the focus of tsunami energy and the estimated wave heights at the coast. The next step will be to project inundation patterns including runup, depth of flooding and flood velocities as modified (either increased or retarded) by land-based variables. These variables include major buildings, soil conditions, and other factors to be identified during the course of the research. Data on regional land use patterning was obtained from U.S.G.S. quad maps for generalized settlement patterns, then verified through field observations.

Flooding is to a significant degree dependent upon elevation. Thus, a critical variable is projecting inundation and risk is a determination of the areas prone to subsidence. These areas can reasonably be expected to be soft and highly saturated such as the alluvium in virtually the entire urbanized Hoquiam/Aberdeen areas (DNR 1987). Figure 2 indicates soil types.

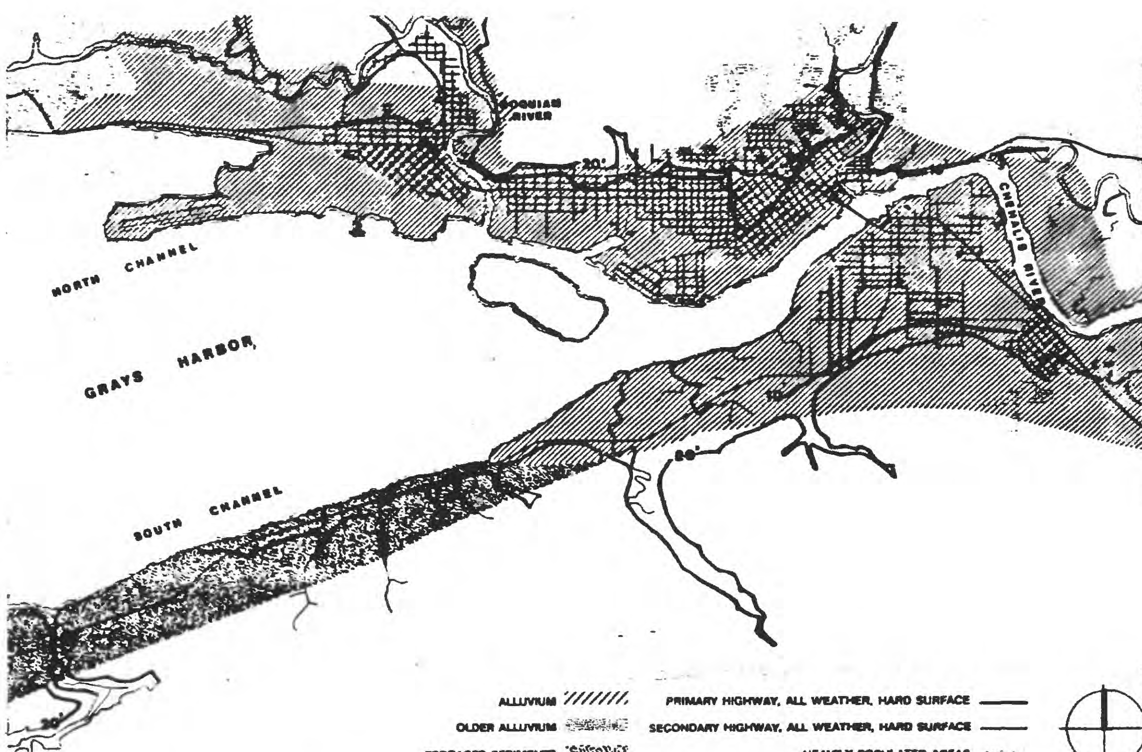

Figure 2 Soil Types in the Hazard Zone

Calculation of land use impacts necessitates estimate of inundation areas which to a large extent is a function of ground elevation. For land use planning purposes, it is assumed that since subsidence appears to have been experienced in the past, it seems likely, based on the prevalence of soft soils that it will occur again. If it is assumed that these soft soils will fail, then all of the industrial areas, the majority of the commercial centers, and a significant component of the residential areas are at risk.

Soils in the flood plain are primarily alluvial silt and fine sand, locally with organic material. Some areas are mantled by artificial fill. The dominant soil types of the flood plain area are approximately five to six feet deep and range from moderately well drained, somewhat excessively well drained to excessively well drained on the diked tidelands. This soil type formed in sandy and loamy river dredgings. The other type of soil found primarily in the flood plain of South Aberdeen is a silty clay loam. It is a deep artificially drained soil found on flood plains and deltas protected from tidal overflow. This soil type formed in clayey alluvium deposited in quiet water of coastal bays. Close to the fairly abrupt boundary between the flood plain and the adjacent uplands there are zones of coarse sand and gravel. It appears that these zones are probably interbeaded with finer grained materials (U.S.D.A., Soil Conservation Service, 1984).

Assuming that subsidence occurs, the elevations shown in Figure 2 must be adjusted downward by two to three meters to reflect soil strength/failure susceptibility from ground motion effects and/or erosive effects of the flood waters. The vulnerable area has therefore been extended inland. The area of land use analysis encompasses all lands below the twenty foot contour. Slope in the area is 0 to 2 percent. As Figure 3 indicates, this area of potential inundation encompasses all the industrial areas, the downtown Central Business District of both Aberdeen and Hoquiam, and residential areas in both communities.

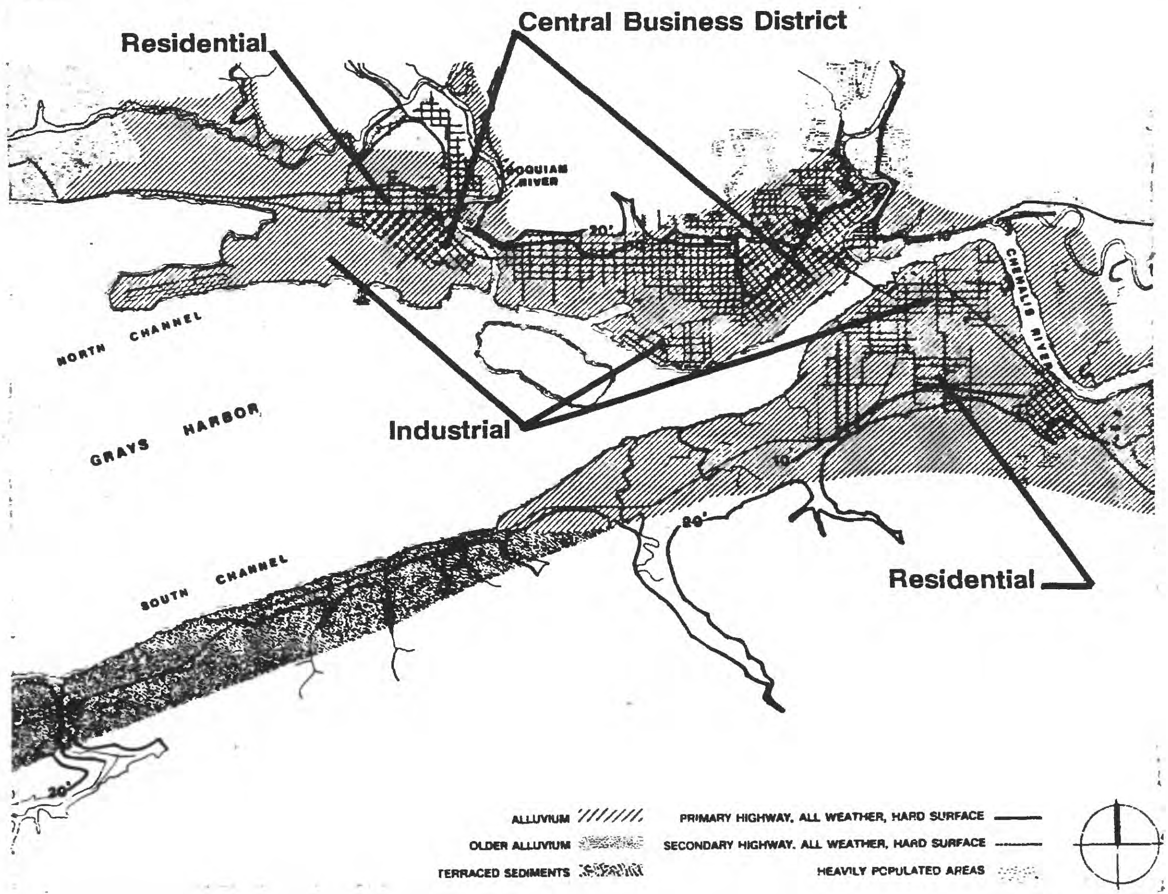

Figure 3 Land Use Correlated with Soil Types

Just as settlement patterns are inaccurate indications of population levels, they are also not reliable indicators of potential economic disruption. For example, the greater Aberdeen-Hoquiam Cosmopolis area has an estimated population of 30,695 (Washington State 1988), yet the port of Grays Harbor is the busiest port in the Northwest with respect to distribution of Northwest lumber. The lumber/forest products industry headquartered in the Seattle-Tacoma corridor is a main employment generator in the Northwest. Since primary implications of the impacts to all land uses are property loss and monetary damage, the magnitude of these impacts can only be calculated in terms of the multiplier effects for the industry as a whole rather than the more limited perspective of the industrial port in Grays Harbor. The industrial areas are also the potential source of secondary implications which should be calculated. These impacts include fire, long term economic disruption, and environmental dangers, e.g. pollution of ground and surface water.

Fires generated in the port areas can easily be spread to adjoining residential areas.

LIFELINE DISRUPTION: ROADS AND BRIDGES

A complete network of State highways, county roads and city streets serve the coastal communities. Two principle State highways, State Route (SR) 12 and 101, serve the area from the east, north, and south. A four lane highway, SR 12, connects Aberdeen and Hoquiam with the north-south Interstate 5 system corridor. Highway SR 101, which is basically a two lane highway, serves the Olympic Peninsula and southwest Washington. Two lane routes connect Ocean Shores and Westport and points north and south along the Pacific Ocean. Note that the routes of the highways are characterized by soft soils. As such, there is a high probability that transportation will be interrupted, making response and rescue difficult, e.g. fire fighters to the port.

Geologic evidence indicates that large stands of trees retarded the tsunami (Reinhardt 1987). The lowland forests have been replaced by

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urbanization. Thus, trees will no longer function as protective buffers retarding advancement of the waves. The location of woods along the highway are illustrated in Figure 4 to indicate the location of protective forests. In most areas, the coastal roads are not protected.

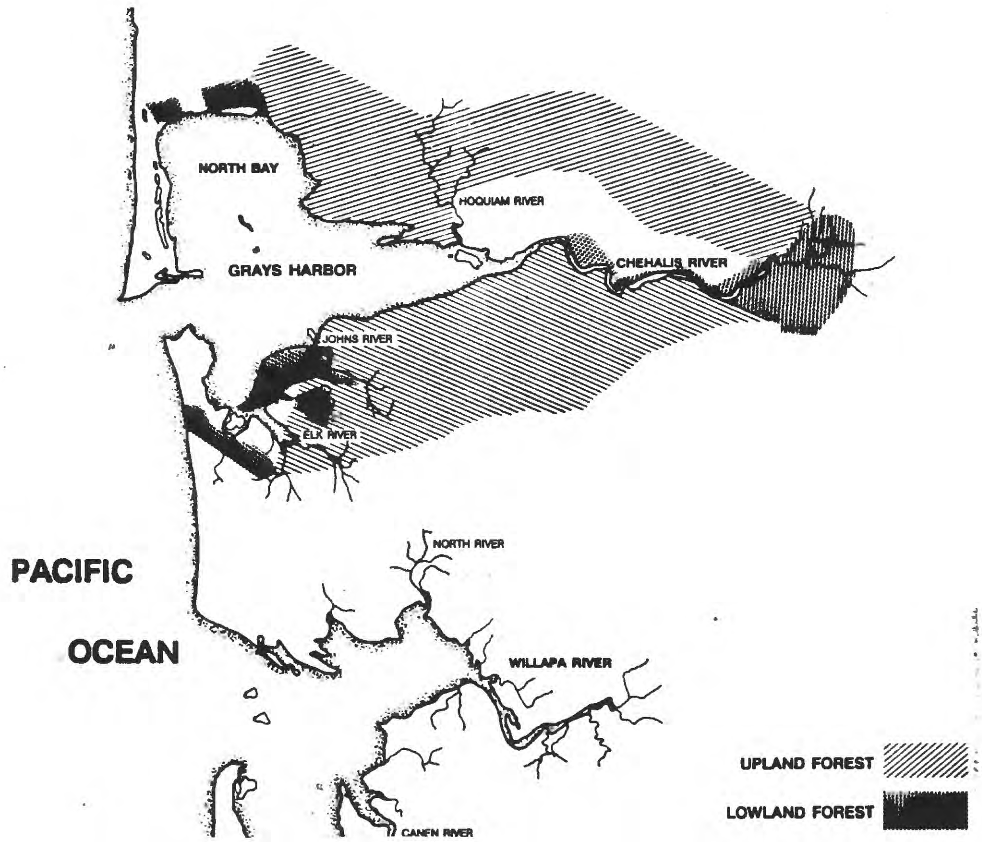

Figure 4 Protective forests no longer screen major highways. Bridges span the many rivers feeding into the urbanized area.

Review of data collected in conjunction with analysis of damage in the 1964 Alaskan tsunami specifically mentions damage to four bridges in the southern Washington-northern Oregon region. Disruption from a large magnitude event in the proximity could be even more disruptive to the industrialized area. For example, because of the many rivers feeding into Grays Harbor there are many bridges, e.g. three draw bridges over the Chehalis and Wishkah Rivers and one draw bridge crossing the Chehalis River between Aberdeen and South Aberdeen/Cosmopolis.

CONCLUSIONS

The next step in the research project is to quantify the risk mentioned in this paper. First, the inundation area, flood level, and velocity will be calculated numerically. Subsequently, the year round and seasonal populations at risk will be identified. An inventory of flammable and hazardous materials below the twenty foot contour is also being conducted. Numbers and types of industries as well as secondary hazards (fire and contamination potential) are being identified and the population at risk in the airborne and fire spread hazard area will be delineated.

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Sandcastle Day

The 24th Annual Sandcastle Contest

Saturday, May 21, 1988

Sandcastle Day, Cannon Beach's single biggest event, came about because of an earthquake. In 1964, the Alaska earthquake sent a wave of water toward the Oregon coast--that tidal wave washed up Ecola Creek, taking out the bridge, causing Cannon Beach to be a dead-end town. There was no longer a north entrance and exit to the downtown area. Once the new highway was completed, visitors to the North Coast began bypassing Cannon Beach, a move that caused much handwringing by local merchants and residents alike.

It took three energetic women, Margaret Artherton, her daughter Billy Grant, and Marian Crowell, to do something about it. Tired of hearing the groaning, these three said, "let's do something about the situation." They did. They came up with the idea for Sandcastle Day.

Originally designed for children, it soon became an event for families--mostly local people and their friends. But, like a lot of good ideas, it grew and grew, primarily by word-of-mouth. What was once an event for children has grown into one that has close to 1000 contestants each year and annually attracts 15,000 to 35,000 spectators. The unusual and original sandsculptures cover an area 2500 feet long by 50 feet wide.

Photo: Hal J. Denison

Sculptures from previous Sandcastle Day celebrations.

As it became more popular, The Cannon Beach Chamber of Commerce became more involved and began promoting the event until, today, it has become known nationally and internationally. It has become so successful that The Chamber has been asked to help set up similar contests in other areas, including California, North Carolina, and Australia.

This year's Sandcastle Contest is Saturday, May 21. Visitors may join regular participants (some have been participating for 18 years!) and build their own castles. If they don't want to participate, they can join the thousands who come to admire the finished sculptures.

And by the way, the bridge is back in place. ▼

– Sandi Pantz

APPLICATION OF GEOGRAPHIC INFORMATION SYSTEM TECHNOLOGY TO URBAN SEISMIC HAZARDS STUDIES IN THE PACIFIC NORTHWEST

By
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INTRODUCTION

Geographic Information System (GIS) technology is a powerful and useful tool that has proved beneficial for achieving the goals of hazards assessment of urban areas which are at risk from earthquakes. A GIS enables large sets of data to be synthesized into informational products which will be used by land use planners and public officials for mitigation of seismic hazards.

A GIS is a configuration of computer hardware and software that allows users to organize, manipulate, analyze, and display large sets of geographical data. Many of the end-products of urban hazards assessment are graphical, such as maps of probabilistic acceleration, seismic ground response, landslide susceptibility, and liquifaction potential. Although the graphical end products are the most familiar application of GIS technology, other applications, such as modeling of surfaces, slope determination, earthquake loss estimation, characterization of land use, density of population, and other statistical attributes, are also possible. Thus, a GIS is a powerful, multi-purpose tool.

Inherent in the traditional seismic hazards assessment process is the merging and integration of geological, geophysical, and engineering data sets and the use of theoretical models (Figure 1). Data acquisition and data analysis are done quite independently and the data sets are dispersed, often without regard to the inevitable need later for an integrated data base. Comparison of some critical data sets may not be possible until late stages of the hazards assessment. A different perspective places the GIS at the hub, integrating data acquisition, data base management, and hazards analysis activities (Figure 2). Because each of these activities influences the structure of the others, innovative data comparisons and manipulations are possible early on. In this view, hazards analysis draws upon data sets from the data base in a simplified, integrated system; the hazards analysis should in fact influence what data acquisition activities are undertaken. Similarly, the design of the data base and structure of the constituent data sets is controlled by requirements of the analysis and the character of the data acquisition activities.

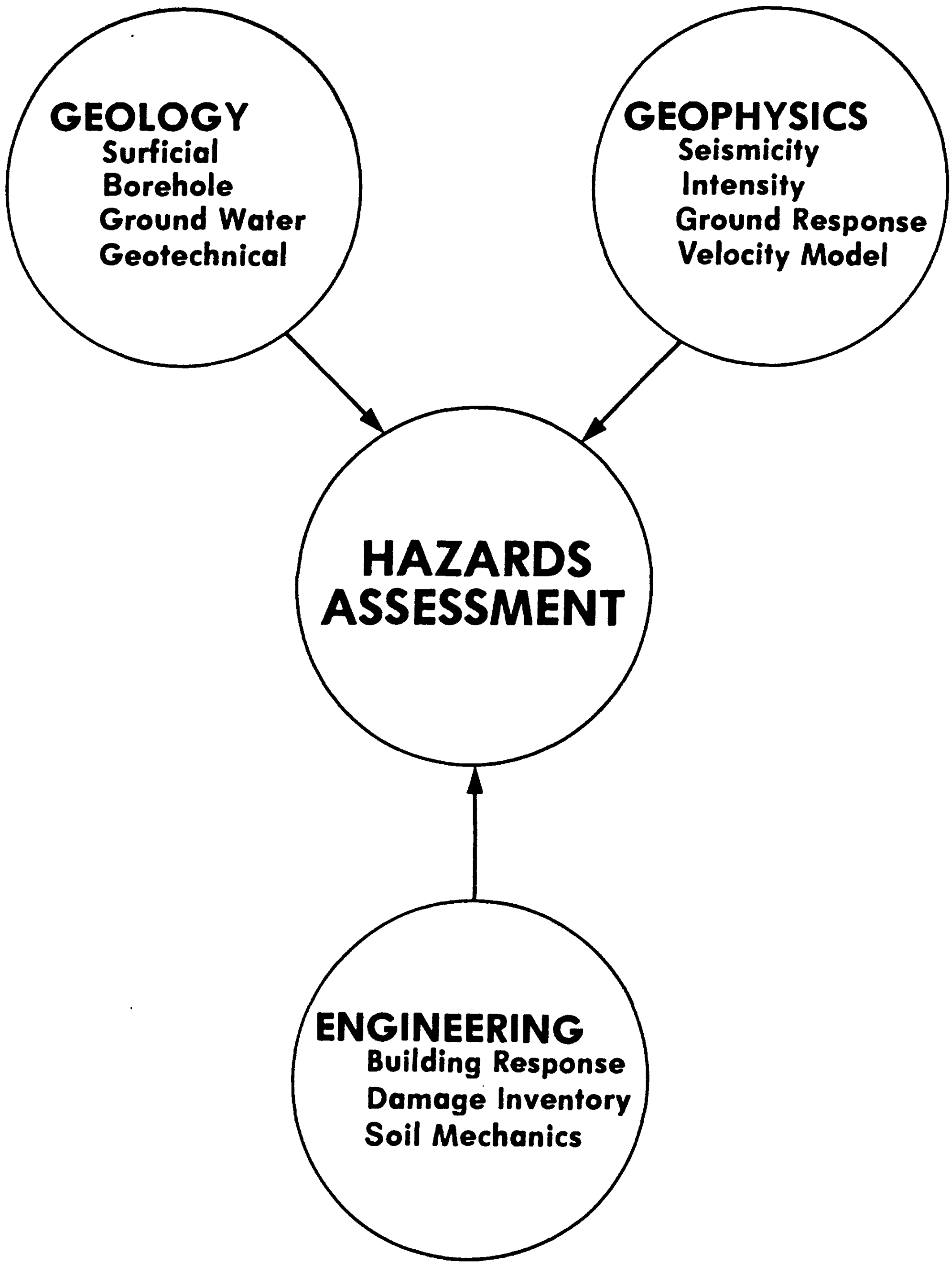

Figure 1. -- Schematic diagram showing a traditional seismic hazards assessment in which data sets and models from three disciplines are integrated.

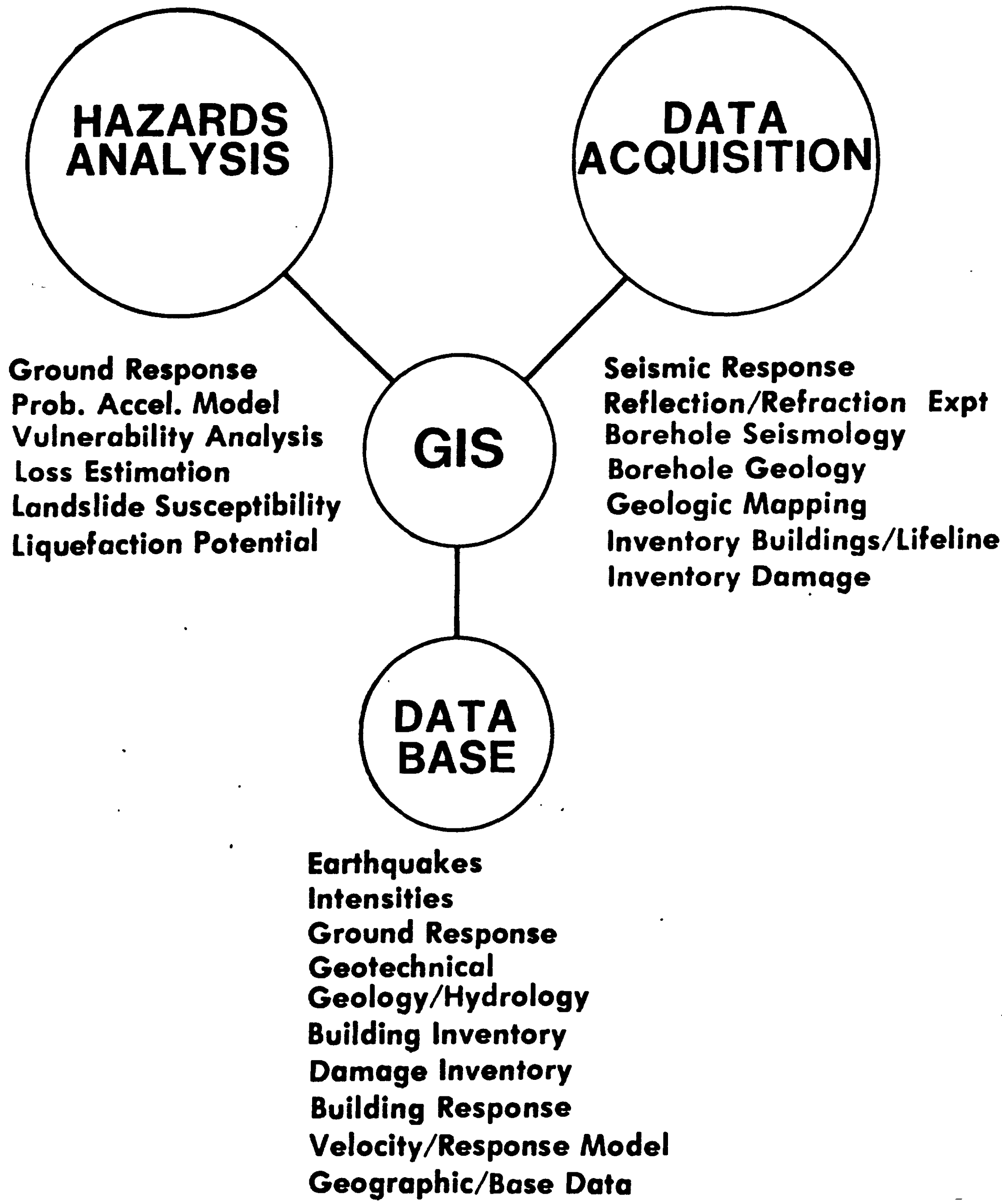

Figure 2. -- Schematic diagram showing a different approach to seismic hazards assessment employing a GIS linking three classes of activities.

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The USGS has begun a project of application of GIS technology to urban hazards assessment of Puget Sound and Portland urban areas. In FY 1988, one major objective of this project is to link the interests and personnel from the Geologic Division and National Mapping Division of the USGS, Washington State Department of Natural Resources, and a variety of local governmental entities from several cities in Washington. As the project develops, additional groups and organizations will be encouraged to participate.

OBJECTIVES

The overall goal of this project is to apply GIS technology to urban hazards assessment usage. The general objectives are:

- DATA BASE -- Build, manipulate, and maintain a digital urban hazards data base (UHDB) comprised of fundamental geographical, geological, geophysical, hydrological, engineering, and socioeconomic data for urban areas in the Pacific Northwest. Building the data base will require extensive effort to capture data sets that may or may not be in digital (or computerized) or graphical form. Examples of available digital data include catalogs of earthquake epicenters and historic intensity observations, some well locations, surface water and ground water data, USGS Digital Line Graph (DLG), and Census (DIME file) data. Examples of data which will require digitization are boundaries of bedrock and surficial geological units, isopachs of surficial units, and isolines of depth to bedrock. Examples of data capture which will require special processing are land use and land cover (rasterized) data, hypsography (topographic and bathymetric contours), and air photos.

- ANALYSIS -- Perform spatial analyses on data contained in the UHDB and to produce derivative data sets for inclusion in the UHDB. It will be possible to analyze spatial data using GIS applications software. For example, any attribute having spatial variation can be modeled and generalized as a two-dimensional matrix of regular polygons or a set of irregular polygons; similarly, any numerical attribute having spatial coordinates can be modeled as a surface. Use of the GIS to analyze fundamental data will, in some cases, result in derivative data sets which themselves may be organized, manipulated, and displayed. Examples of derivative data are isolines of seismic intensities, ground response, and depth to specific geologic units; slopes derived from hysometric data; thickness of water-saturated units; and exceedance probabilities for acceleration.

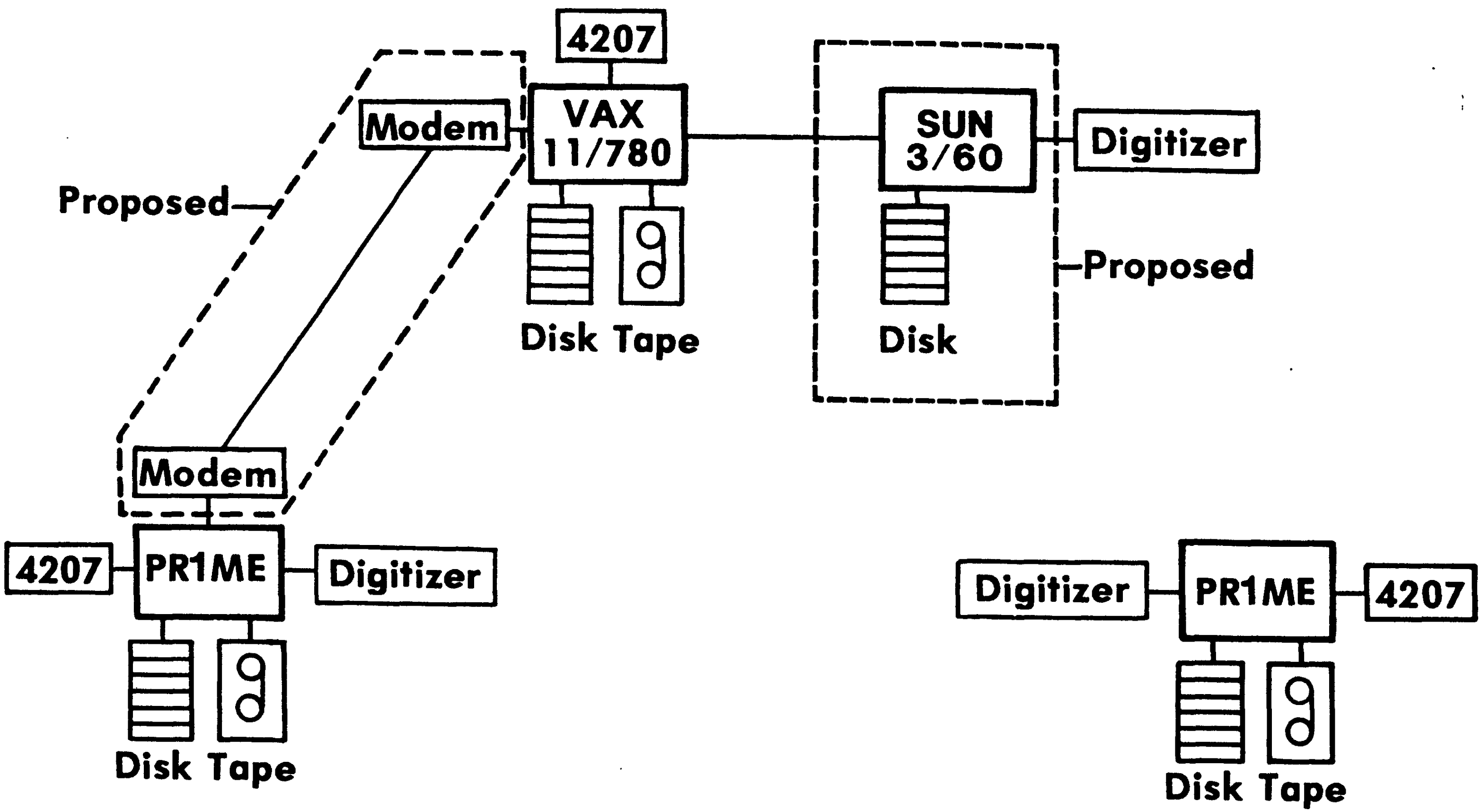

Figure 3. -- Schematic diagram showing proposed USGS GIS hardware to be used for urban seismic hazards assessment. High-speed modems link USGS Central Region GIS Laboratory (lower left) with Branch of Geologic Risk Assessment computer facility (top) and new GIS workstation (upper right). Detached configuration (lower right) represents compatible computer systems at collaborating institutions.

• PRODUCTS -- Design and generate high-quality map and graphical products and tabular reports of data attributes. The GIS will permit generation of numerous maps having various data layers overlaying a standard base of (say) hydrography, hypsography, transportation net, and boundaries. One example is a ground response map containing surficial geology, ground response contours, and basement depth contours. Another example is a landslide susceptibility map containing surficial geology, slope contours, and thickness of water-saturated units.

• RESEARCH -- Perform experiments which seek to discover more effective techniques for generating derivative data sets. Some existing methodologies and techniques that are inefficient or cumbersome might benefit from use of GIS technology. Considerable attention will be given to streamlining the process of integrating and using multiple data sets in the GIS. Improvement in data capture techniques are of great importance. Utilization of query languages and an expert systems approach to access and analyze GIS data seem promising.

More specifically, in the Pacific Northwest, these four objectives will include numerous tasks, such as:

• DATA BASE -- Construct base map products using data sets (hydrography, transportation, boundaries) from existing USGS DLG tapes on a quadrangle-by-quadrangle basis for major urban areas (such as Seattle, Tacoma, Bellevue, Olympia, Portland); scan hypsographic plates of the same quadrangles to construct topographic and bathymetric contour line graph and digital elevation model (DEM) data sets; digitize numerous geologic, hydrogeologic, tectonic, and isoline maps to capture geologic, hydrologic, and structural units; convert earthquake epicenter and intensity data into GIS data files; capture geotechnical data (borehole geology and velocity, soils analysis) from existing computer files; capture Census tract data from existing data tapes.

• ANALYSIS -- Modeling of topographic surface from DEM; slope determination from surface model; contouring of intensity, seismic response, and geotechnical data; microzonation of urban areas on basis of surficial geology, seismic response, and geotechnical data; revision of urban land use areas.

• PRODUCTS -- Preliminary seismic response and landslide susceptibility maps of Olympia and Seattle; preliminary seismotectonic map of western Washington and Oregon.

• RESEARCH -- Improved interfaces between graphics software and external data bases; synthesis of a DEM from several elevation data sets of varying resolutions.

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IMPLEMENTATION

The UHDB will be implemented using the existing USGS Central Region GIS Laboratory PR1ME computer (located in Lakewood, CO) and a remote workstation and peripherals (located at the Branch of Geologic Risk Analysis in Golden, CO). The new workstation will be a SUN Microsystems 3/60C running ARC/SUN software; peripherals will include a high-accuracy digitizing table and terminal, large format pen plotter, and communications equipment. The workstation will be linked by an EtherNet connection to on-site VAXs and by high-speed data link to the Regional GIS Laboratory PR1ME computer. The workstation thus will be able to process data in stand-alone mode or as a high-quality graphics display terminal when connected to the PR1ME computer of the Central Region GIS Laboratory.

The Geologic, National Mapping, and Water Resources Divisions of USGS and many State and local governments use ESRI's ARC/INFO (Version 4.0) software package to perform GIS operations (data base management, data manipulation, data display). Usage of the same software package maximizes interchangability of data sets and applications programs, to the benefit of the network of GIS participants.

The overall approach in this project is long-range in scope, attempting to create a GIS environment in which investigators from many disciplines will find common ground (in the GIS facilities and through the UHDB) for performing experiments and complex spatial analyses which only a powerful GIS will permit. This ultimately means coordinating the GIS interests of several USGS operating divisions, other Federal agencies and bureaus, the State Geological Surveys of Washington and Oregon, municipal agencies in the major cities, and several university groups.

In the short term, there are many obstacles to overcome in establishing a network of GIS users, not the least of which are disparate requirements for digital geographic data, incompatible computer systems, incomplete or non-existent data standards, and incompatible data formats. Data capture continues to be a costly and time-consuming task, demanding imagination and innovation.

EARTHQUAKE SAFETY PROGRAMS IN THE SCHOOLS
ONE JURISDICTION'S EXPERIENCE

By

William Lokey
Pierce County Department of Emergency Management
Tacoma, Washington

Background

State Law (RCW 38.52) gives authority for Emergency Management Agencies to provide public education and information about natural hazards which may affect citizens. The schools have requirements for earthquake drills, building safety and emergency planning. Citizens, service clubs and other community groups are, or become, aware of earthquake hazards and want to help the community with earthquake safety projects. These three ingredients led to the development of Earthquake Safety and Preparedness programs in Pierce County.

The Pierce County Department of Emergency Management was receiving numerous requests for planning assistance from school principals and classroom teachers. PTA groups contacted the Department for information about safety programs and classroom demonstrations. Service clubs wanted programs, and a local Chamber of Commerce wanted to provide earthquake safety information for their local school district. Trying to handle these individual requests became very labor intensive, so after receiving some assurances of support, a community wide effort was begun to provide the most up-to-date and interesting information to every school district in the County and to any other organization or group with an interest in earthquake safety.

The Program

We patterned our program after several earthquake safety programs which had been done in the Puget Sound area by other local governments. We were also aware of the materials available through the University of Washington, State Department of Community Development, and the Federal Emergency Management Agency. Finally, we learned of a program developed by Hanna-Barbera in Californina using Yogi Bear to promote earthquake safety targeted at elementary school kids.

We approached the school districts and got a commitment from many of them to contribute 2 cents per student toward material costs. We received support from the Lakewood Chamber of Commerce and Pacific N.W. Bell. We approached the Exchange Club of Tacoma and some private foundations in the Pierce County area and received donations from them. We cooperated with the City of Tacoma and combined funds from both the City and the County. We raised enough to purchase 100,000 Yogi Bear Comic Books, which would provide one for every elementary school child in Pierce County twice. (We intend for the program to be ongoing.)

A video tape produced by Hanna-Barbera was also made available for each school district to be used in the classroom. This tape complemented the information in the comic book.

We put together a workbook containing the planning workbooks and guidance which was available from the University of Washington and from the Federal Emergency Management Agency. These materials would help districts develop emergency plans and programs for buildings and classrooms. These were distributed to each school district. Any calls that are now received for planning assistance are referred to the appropriate school district person.

Disaster research has shown that the closer a hazard comes to home, the more attention people pay to it. We took the Earthquake Safety brochures developed by the State, FEMA, the Red Cross and others and compiled a brochure that targeted the earthquake hazards in Tacoma and Pierces County. The Morning News Tribune gave us permission to use their photographs of historic damage in Tacoma. This has been very well received in the Community.

Finally, we prepared a slide tape program which also specifically targets the Tacoma-Pierce County earthquake hazard. This is now available for presentations for service clubs and businesses.

Lessons Learned

We learned several lessons as we developed this program that we hope will help it be more successful in the future.

1. People do pay more attention when the hazard is presented as relevant to their home town.

2. There needs to be one central coordinating agency which takes the lead in fundraising.

3. In dealing with school districts you must consider the separate roles of the Superintendents and Administrators, the safety coordinators, and the people responsible for curriculum.

4. If everyone is offered the opportunity to share in the costs, and government provides some "seed" money, fundraising seems to be more successful.

5. People were more supportive of an on going program with a 10 year goal of better educated citizens.

6. Support from the State is essential. If the public perceives the State does not think something is important, they will not give it priority either.

7. A central clearninghouse of information available from all sources, particularly at the State level would have been helpful.

EMERGENCY OPERTIONS CENTER COMPUTERIZATION
AND
PUBLIC AWARENESS PROGRAMS

By

B. Lance Olmstead
Emergency Program Coordinator
The Corporation of the District of Sanich
Victoria, British Columbia
Canada

Introduction

The Vancouver/Vancouver Island area of British Columbia lies in the same subduction zone as the Puget Sound/Portland area and poses the same risks to our citizens as it does to theirs. Our hazard analysis and historical incidence of earthquake activity in this area leaves no doubt as to the RISK we face. My comments are primarily aimed at hazard mitigation through Emergency Program Coordination and Public Education.

Emergency Operations

Every city, town and municipality must have basic plans duly approved by the elected officials. Failure to do so can result in confusion, increased loss of life, increased property damage, considerable economic losses and probably a lot of litigation for negligence caused by not taking basic measures to protect the public against a known hazard. Some legal authorities feel that litigation for negligence, (similar to that faced by employers who do not provide adequate information or equipment to protect the public from fire or dangerous goods and hazards) would be successful should government and business fail to help their citizens and employees protect themselves against the effects of an earthquake. In addition, the reduction of economic losses to the community, state and country that can be obtained by efficient preplanning and education are significant.

Once a community has obtained basic planning, legal authority and manpower and developed it into a framework that can manage urban rescue, casualty assessment, casualty treatment and the problem of evacuation and temporary shelter, (with all that entails) they must then be concerned with protection of property, clean-up and repair of the community infrastructure to reduce the economic losses. Finally, there comes the damage assessment and claims procedures for insurance companies and government. One can readily see that the phrase "Emergency Coordinator" implies onerous responsibilities over a long period of time.

There has been much written on methods of response to such widespread disasters and how to return to normal with the minimum of economic loss, and I will not comment further on these aspect. However, even though there are many computer programs which assist Police and Fire and provide access to lists of assets and personnel, there are very few programs which cater to Urban Heavy Rescue. One such program is being developed here in Victoria which we hope will greatly assist Search and Rescue organizations in locating personnel in collasped buildings. The general idea is to use computerized street plans, digitized building floor plans and site plans to assist searchers in ensuring all areas in a partially collapsed structure have been searched and to indicate where a rescue group should start their search in a collapsed structure. The big problem with these graphic programs in the past has been their lack of speed. I feel we have now solved that technical problem as we can now find a floor plan, have it on the screen in color and print it on a dot matrix printer in less than one minute. The system is totally "stand alone" and is configured for field operations in conjunction with batteries or portable generators. We expect this system to be a very useful tool in urban heavy rescue situations (see attached sample). I feel that there is a considerable body of work that yet remains undone in the emergency operations field and I urge our elected representatives and emergency services to place more emphasis and assets in this important area.

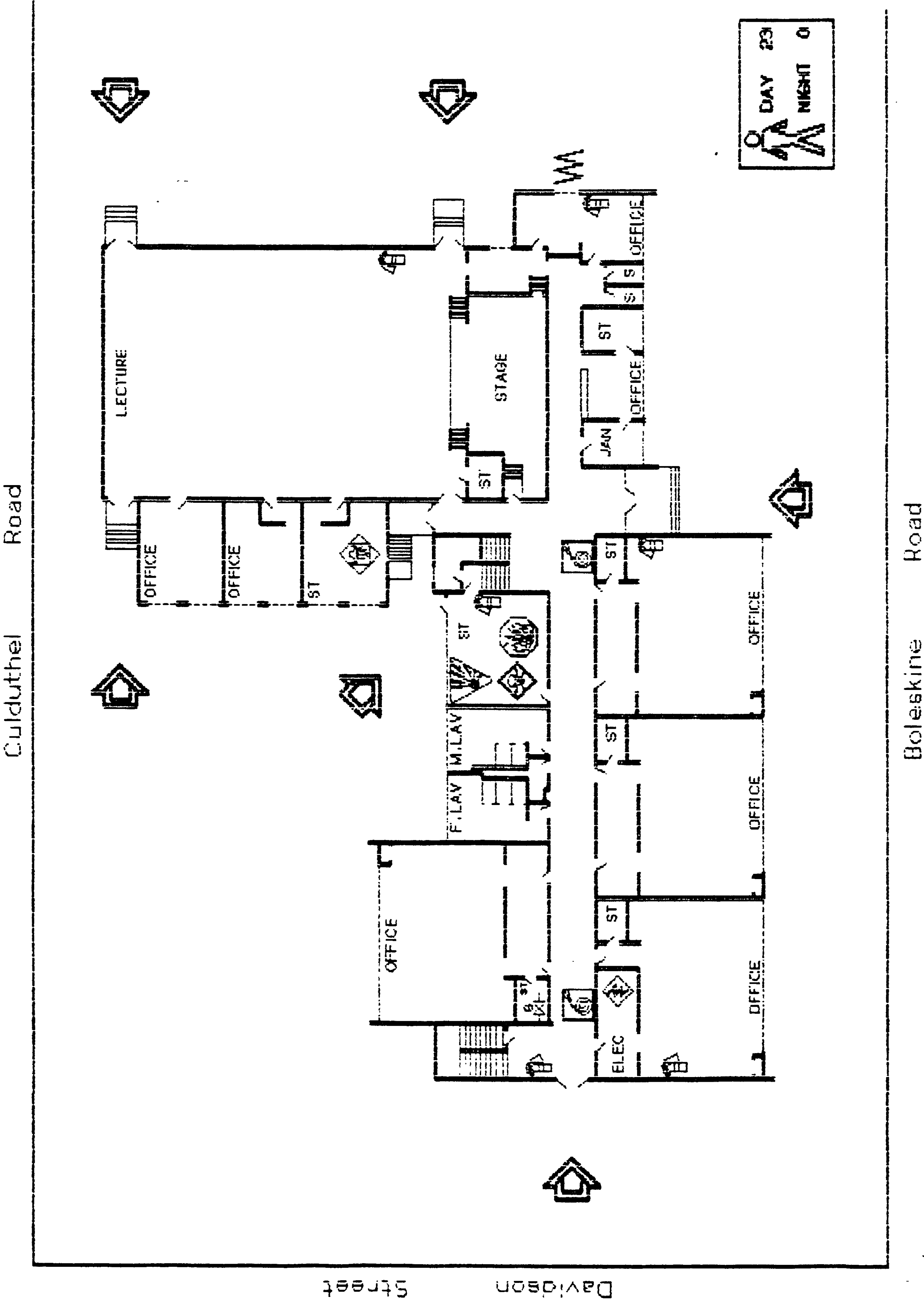
Public Awareness

Public awareness is a major problem everywhere, and strategies to deal with it have been generally unsuccessful. Saanich has decided that the problem can be more effectively dealt with through the schools (they will become adults) although it is a slow process. All schools need to ensure the safety of the children entrusted to them. This basic fact can be used to ensure appropriate participation. The litigation risk is also a key phrase which is very effective in convincing recalcitant administrations to get on with their earthquake awareness and planning responsibilities. Each school must ensure that staff are aware they must be able to deal with an earthquake situation on their own for at least the first six hours and probably twenty-four hours or more, depending on the severity of the quake. They must have instilled the "Duck and Cover" drill in their students, be able to evacuate the uninjured and walking wounded through the rubble to a predesignated meeting area. Know who is missing, conduct search and rescue operations for the missing, provide first aid for the injured, control, register and comfort their students and protect their school against ancillary damage from fire, flood, etc. Trying to move a group of traumatized children to another area through downed electrical wires and other earthquake damage is probably more dangerous than staying and reoccupying a section of the school. Preplanning is obviously essential if all of this is to be accomplished. The provision of evacuation kits in each classroom complete with minimal first aid equipment for cuts is essential. Distribution of first aid equipment is necessary as a collapse situation may bury a centralized supply. All exits should also have a stretcher, hard hats, gloves, etc., available for search and rescue operations. Training in search and rescue, first aid and fire protection using installed appliances is very important. All staff should also know how to shut off water, power and gas in order to protect the school against further damage.

When it comes to business, the next target for your awareness campaign, the same two key phrases can be used: Safety of Employees and Customers. Businesses will be responsible for dealing with similar problems as the schools with regard to their staff and to a more limited degree with regard to their customers. Employers should have detailed plans and personnel policies negotiated with staff regarding search and rescue, pay and allowances, first aid, evacuation, protection of assets and clean-up. Most employers have not yet considered these aspect.

In Victoria, our municipality has commenced a major attack on public awareness by the introduction of Project "Shakey Ground" (see enclosure). We feel this three pronged effort, although costly, stands the best chance of changing public opinion.

Awareness of what is required by way of preplanning before the quake, actions during the quake and method of limiting the risk to personnel and property after the quake is essential if we wish to limit casualties, decrease our physical asset losses, reduce the period necessary to return to normalcy and thereby reduce the total economic loss. Public awareness and preplanning can go a long way towards mitigating losses due to earthquake hazards. We all need to get on with it now.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PROJECT "SHAKEY GROUND"

The Vancouver/Vancouver Island area, as well as most of the west coast of British Columbia, is in an active earthquake zone. It is the opinion of most Emergency Program Coordinators such as myself, that not enough public information has gone out to our citizens to educate them in methods of limiting the risk to themselves and their property when the inevitable major earthquake hits our area. It is my opinion that most schools and businesses have not considered the consequences of such a disaster on their personnel or operations, nor have they educated their employees in methods of protecting themselves or their employer's assets. Some schools and most businesses do not even have basic emergency plans in place to permit them to cope during an earthquake, let alone subsequent to one.

In order to rectify this deficiency in public education, the Corporation of the District of Saanich has embarked upon a public awareness campaign in the Victoria area. Our program has three primary objectives.

Firstly, the production of five videos of six minutes duration each. These videos will identify the earthquake risk, indicate the preparations needed prior to an earthquake to limit risk to personnel and property, demonstrate the proper immediate and subsequent response to limit injuries to personnel, illustrate damage limitation and survival techniques after the earthquake and demonstrate methods of mitigating the psychological effects, especially among children, which earthquakes will cause.

These videos will be supplemented by four handouts. One handout will be a compendium of the videos for adults. The other three will be in "comic book" form, produced under the auspicies of the Hanna-Barbera Productions Corporation in Los Angeles, California. The first four page comic book utilizing the "YOGI BEAR" motif, is designed for very young children up to age ten. The second comic book is used to teach basic first-aid using items around the house and the third comic book is an eight page version of the first comic book and is used for older children.

Supplementing the video information and handouts will be an "Earthquake Simulator" which will be used to teach children and adults the correct initial response to an earthquake and the evacuation procedure required after the shaking stops.

The Municipality will acquire a tractor-trailer unit and outfit the trailer portion as the simulator. The trailer will be paneled, carpeted, illuminated and set up with sixteen school desks and a teacher's desk inside it. The audio-visual system will air the selected videos, the Educator will answer questions and then "press the button". An actuator will shake the trailer, giving the students an opportunity to feel what an earthquake might be like and then they will practise their "duck and cover" drill and evacuation procedures. By changing the interior of the trailer, a home or office setting can be simulated and employees or families can experience the simulation. The simulator will be towed from location to location to improve public awareness.

Phase One is the production of the five video clips. The cost of the video production is estimated at Forty Thousand Dollars ($40,000.). I am convinced the information on the videos would be of importance to management and staff for employee awareness programs in addition to students and parent-teacher groups.

Phase Two is the publication of four pamphlets. All pamphlets have been designed and forty thousand copies of the first pamphlet "A Blueprint for Earthquake Survival" has already been paid for and has been distributed to residents of Saanich. The three comic books are estimated to cost approximately Six Thousand Dollars ($6,000.) each, with a run of forty thousand copies for a total cost of Eighteen Thousand Dollars ($18,000.). If subscribed by government and business, their logo and credits would be published on the back cover.

The largest project item is the "Earthquake Simulator". Funding for the tractor-trailer and power generator is in place. There will be audio-visual equipment costs, interior design and furniture costs estimated at Fourteen Thousand Dollars ($14,000.). Annual operating costs for the project are estimated at Thirty Thousand Dollars ($30,000.) for a part-time Educator, Student Assistant and Driver, plus accommodation, fuel and repair costs.

Students would be the main benefactor of simulator use, but families and business would also benefit. The operating costs of the simulator on a "cost only" basis will be assessed as mutually agreed for those groups requesting access.

Preparation done in advance of an earthquake will limit the risk to the public, business employees and physical assets and help reduce lost production time subsequent to the earthquake.

I am, therefore, convinced this project is a worthy one and will result in greater awareness, fewer casualties, decreased economic loss and a quicker return to normalcy after the earthquake.

OBJECTIVES OF THE WORKSHOP ON "EVALUATION OF EARTHQUAKE HAZARDS AND RISK IN THE PUGET SOUND AND PORTLAND AREAS"

By

Linda Lawrance Noson
Federal Emergency Management Agency, Region X
Bothell, Washington

This workshop is part of an integrated 5-year Federal and State effort focused on earthquake hazards and risks in the Puget Sound and Portland areas. Study results in the region will be reviewed and discussed at workshops annually. A similar 5-year program has recently been completed in Utah. These programs are part of the National Earthquake Hazard Reduction Program (NEHRP). NEHRP was initiated in 1977 in recognition of the threat of catastrophic losses of life and property posed by earthquakes in the United States. The goal of NEHRP is to reduce personal and economic earthquake losses. Four Federal agencies provide National leadership for the NEHRP: the United States Geological Survey (USGS), the Federal Emergency Management Agency (FEMA), the National Science Foundation, and, the National Bureau of Standards.

USGS and FEMA were the Federal sponsors of the Puget Sound/Portland workshop. Their State partners in cosponsoring the workshop were the Washington State Department of Natural Resources, the Washington Division of Emergency Management, the Oregon Department of Geology and Mineral Industries, and, the Oregon State Department of Emergency Management. These State and Federal agencies along with numerous private organizations, universities and colleges, and other State and local agencies are involved in the effort to determine the nature and extent of the earthquake hazard in the Puget Sound and Portland areas and to implement efforts to reduce earthquake losses. The objectives of the workshop include:

- describe the present level of understanding of the nature and extent of earthquake hazards and risk in Puget Sound and Portland areas.
- identify additional information needed to improve that level of understanding.
- communicate scientific results in a clear fashion to individuals who must make decisions about how to respond to the hazards identified.
- facilitate dialogue between those carrying out research to device the hazards and those using research results to reduce risk.
  - What loss reduction studies can be initiated given what is presently known about earthquake hazards in Puget Sound and Portland?
  - What further information must be collected before further reduction efforts can be carried out?
  - Encourage networking among the diverse groups involved in this process.

Earthquakes are egalitarian in that they do not distinguish between political jurisdictions, type of occupation, income, etc. This diversity is reflected in the range of individuals, agencies, and organizations that must be involved to successfully reduce future earthquake losses. Nearly 200 people participated in the workshop including scientists, insurance industry experts, design engineers, land use planners, educators, emergency management groups and more.

The focus of the workshop's final day will be on the role the State could play to provide direction and guidelines to facilitate the implementation of earthquake hazard mitigation and preparedness actions. The foundation upon which these actions are developed are past experience of damaging earthquakes in Washington and Oregon and research that has been carried out to determine the causes and effects these earthquakes will have on residents of these States.

ESTIMATION OF EARTHQUAKE LOSSES IN THE PUGET SOUND AREA

S. T. Algermissen and E. V. Leyendecker
U.S. Geological Survey
Denver, Colorado

LOSS STUDIES

The USGS is currently conducting studies of earthquakes and losses due to earthquakes in several geographic areas throughout the United States. Work in the Salt Lake Valley in Utah (Gori and Hays, 1987) is nearing completion and new studies are underway in the Puget Sound area. Work on earthquake losses in this area is not new; however, much has been learned since 1975 when the last study (Hopper and others, 1975) was published. These new loss studies are being done both to develop improved estimates of the consequences of earthquakes and to develop improved techniques for conducting such studies.

Earthquake loss studies may be of the "deterministic" or "probabilistic" type. A deterministic study might consider the consequences of one or more earthquakes; frequently this might be the largest likely earthquake. Such a study is very useful for purposes such as emergency planning. The probabilistic study considers both magnitude and frequency of occurrence and may be "more realistic" than the above "worst case" scenario. Both deterministic and probabilistic studies are being considered for the Puget Sound area. The work of Hopper and others (1975) is representative of the scenario or deterministic type of loss study. Emphasis is being placed on developing the tools for use in loss studies rather than a complete assessment for the region. Accordingly a limited area of Seattle has been selected for conducting a detailed study of losses.

The study area is shown in Figure 1. It includes West Seattle, an area with considerable damage in 1965, and downtown Seattle. It extends north to about Salmon Bay and Lake Union and south to about the Boeing Plant. This area will be used as a demonstration of some techniques which can be used to conduct a loss study. Most of the work is being done by USGS personnel. Some work in losses that is being done under the USGS grants program is closely related and will be included in the study. These efforts will be coordinated when it is within the scope of the grant proposals.

DATA COLLECTION

The inventory of structures, except for housing, has been the weakest link in developing realistic estimates of total dollar loss by building type. The data collection procedures are centered around (1) a simple system for classifying buildings, (2) the census tract as the basic area for data collection, and (3) machine read "mark-sense" sheets for compiling a computer data base. Each of these factors is described below. It should be noted that the procedure can be used for either inventory or damage surveys.

The 1983 Insurance Services Office (ISO) classification system described by Steinbrugge (1982) will be used in the inventory survey of buildings in the census tracts. This classification uses a system of 5 major classes as shown below:

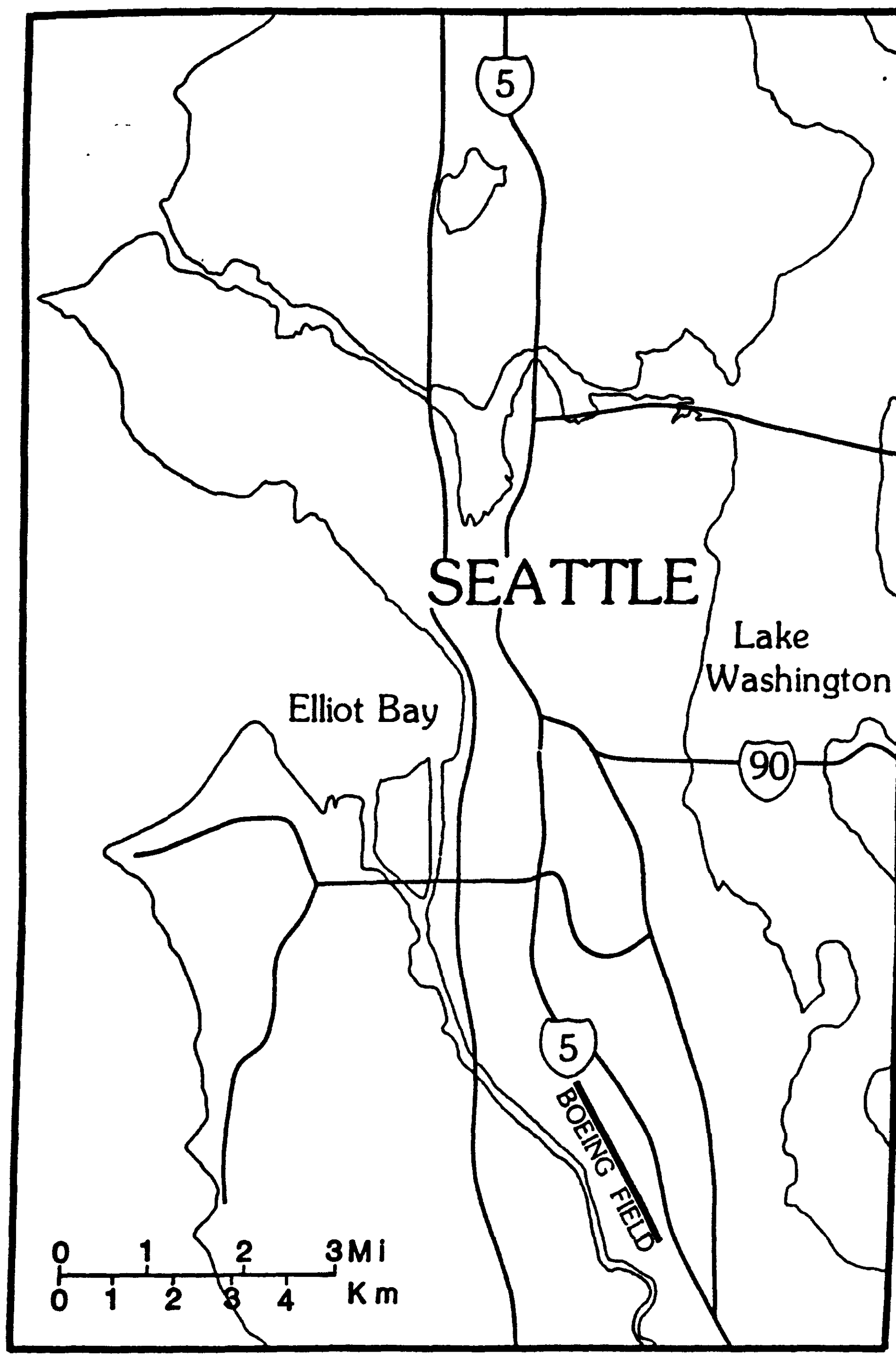

Figure 1. Planned earthquake loss study demonstration area.

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Class 1: Wood frame structures
Class 2: All-metal buildings
Class 3: Steel frame buildings
Class 4: Reinforced concrete buildings, combined reinforced concrete and structural steel buildings
Class 5: Concrete, brick, or block buildings

This system was selected for its relative simplicity and ease of use by a lay person with a limited amount of training.

The census tract will be used as a data collection unit in order to simplify the inventory of buildings. Since census data provide a relatively accurate count of residential construction, this is one component of an inventory that does not have to be compiled in detail. The type of residential construction (type of frame, siding, etc.) can be determined by relatively simple statistical sampling. Other types of structures require additional inventory work. Extensive sampling will be required in order to develop suitable inventories for structures other than dwellings.

Data will be collected on "mark-sense" sheets which describe building class and various types of damage if it is a damage survey. The mark-sense sheets are preprinted forms with multiple choice responses that are filled out with a soft lead pencil. The "marks" by the soft lead pencil can be "sensed" by an optical scanning device. Space is also provided for general comments and/or observations. The presence of this latter type of data can be "sensed" although it must be entered by hand. These forms are then read into a computer data base using an optical scanner. This procedure is shown schematically in Figure 2.

STRONG GROUND MOTION

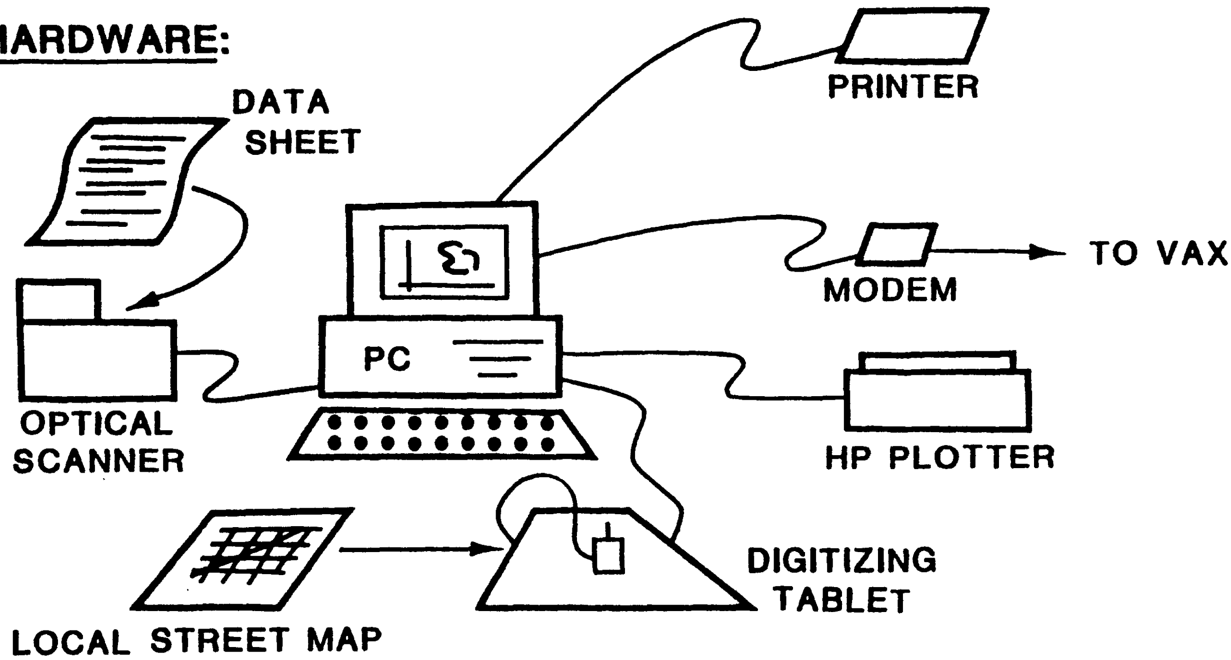
Most loss studies have used MMI as the measure of ground motion. Although the limitations of intensity for this use are well recognized, it is also well recognized that there is little information on building damage as a function of some other measure of ground motion. Thus the use of MMI is expected to continue for some time. It is, however, possible to estimate losses to structures by the use of damage attenuation curves such as those proposed by Steinbrugge, Algermissen, and Lagorio (1984). This technique requires the development of curves that represent the loss of a particular type of structure as a function of earthquake magnitude (or maximum intensity) and distance from the rupture surface of the fault.

The current work on ground motion, intensity, and local effects by King (King and others, 1988) will be included.

DAMAGE DATA

As would be expected, the largest data base for earthquake damage exists for California. These loss data have been categorized by building class and strong ground motion amplitude. The relatively simple classification of building stock described earlier has been used to compile existing damage statistics (Steinbrugge, 1982). Of necessity, the MMI scale has been used as

HARDWARE:



SOFTWARE:

PROGRAMS TO -

1. DIGITIZE LOCAL MAPS
2. GRID, SURFACE, CONTOUR
3. DRAW MAP
4. COMMUNICATE WITH VAX
5. DRAW GRAPHS
6. SCAN OPTICAL FORMS

Figure 2. Acquisition system for inventory development and earthquake loss data.

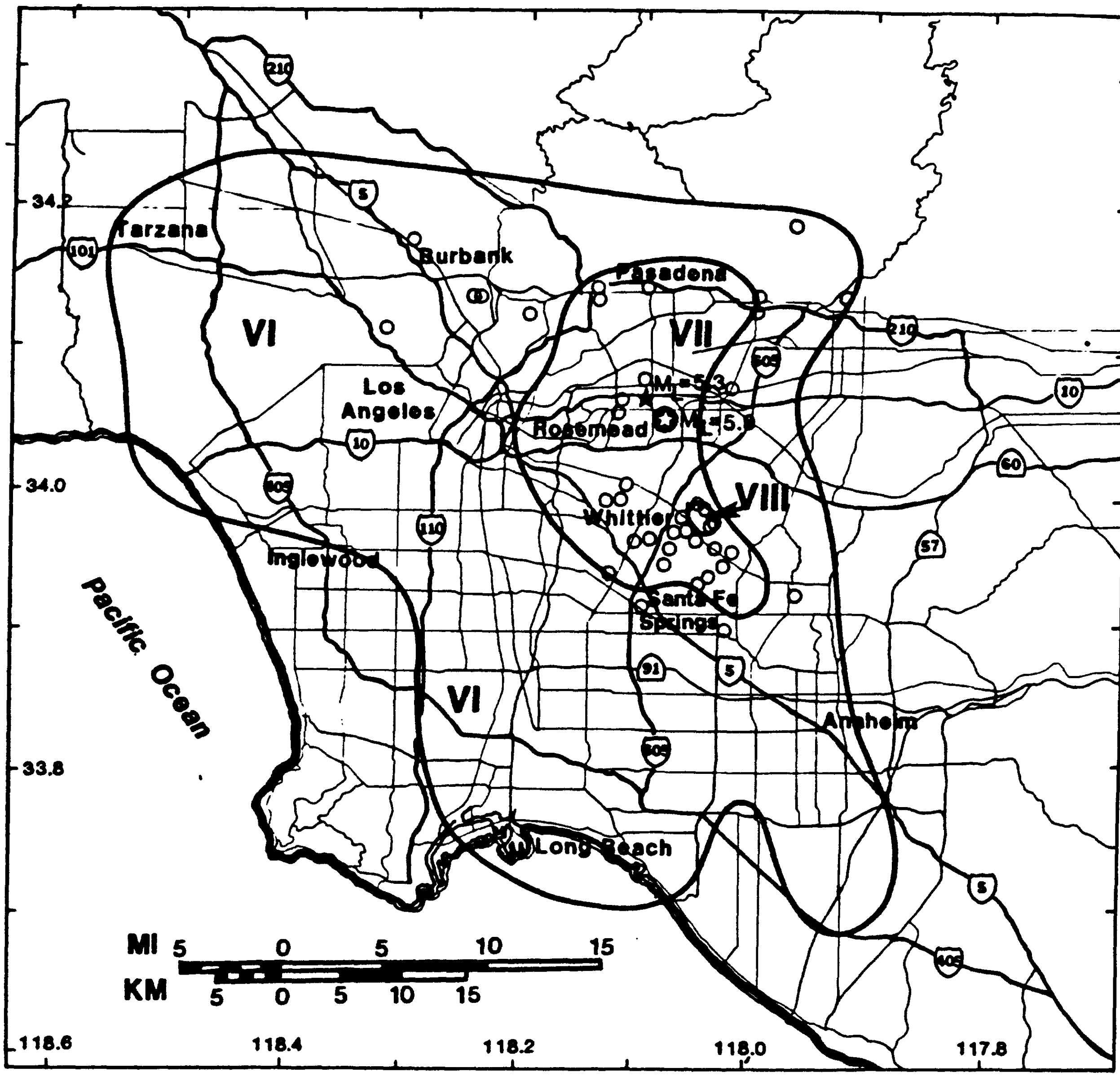


Figure 3. Preliminary regional Modified Mercalli intensity isoseismals in the Los Angeles area for the earthquake of October 1, 1987. Open circles represent the centers of census tracts surveyed. The circled star is the main shock epicenter. The star to the northwest of it is the epicenter of the largest aftershock.

a measure of ground motion. Due in part to the lack of widespread instrumentation it is anticipated that the use of MMI will continue for some time. These data have been cautiously extrapolated for use in other areas of the United States.

Efforts have been made to expand these data for California using an expanded classification system and loss estimates based on expert opinion to create damage statistics (Applied Technology Council, 1985).

FIELD USE

The procedure for data collection was tested following the October 1, 1988 Whittier Narrows Earthquake. Census tracts surveyed in Whittier are shown in figure 3. The open circles represent the coordinates of the center of housing in each tract. Boundaries of the tracts are omitted for simplicity. The survey procedures worked relatively well. However, it was concluded that the specific data recorded on the mark-sense sheets, while adequate, should be simplified as much as possible for use in future studies. There were also indications that minor modifications were desirable in the building classification system but major changes are not anticipated in the near term.

SUMMARY

Procedures for loss studies in the Puget Sound area have been briefly described. The building classification and survey strategies described have been tested and found usable and adequate for describing damage. Further refinement in the direction of simplification was found desirable for future use by personnel with training in its use but with limited background in structures.

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EFFECTS OF PAST EARTHQUAKES IN THE PUGET SOUND AREA

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Abstract

Historic earthquakes in the Puget Sound area have caused intensities up to the level of structural damage (Modified Mercalli intensity (MMI) VIII). The two largest such earthquakes occurred in 1949 and 1965 and produced their highest levels of damage near Olympia and Seattle, respectively. An unusual concentration of damage occurred in West Seattle due to the 1965 shock.

In addition to shaking damage, damage due to ground failures is common during large Puget Sound earthquakes. Ground failures from historic Puget Sound shocks include landslides, liquefaction, and settling.

INTRODUCTION

The seismicity of the Puget Sound basin and surrounding region is shown in figure 1. Only earthquakes large enough to cause damage (that is, having maximum Modified Mercalli intensity $I_0 \geq VI$) are shown. (A copy of the Modified Mercalli intensity scale is appended to this report.) Notice that there are only two shocks within the Puget Sound basin large enough to cause structural damage (MMI≥VIII): the 1949 earthquake near Olympia and the 1965 earthquake at Seattle.

TABLE 1. 1949 and 1965 Earthquakes Data

DATE	MAG	I_0	AREA[1]	DEPTH[2]	LOCATION
1949 April 13	7.1	VIII	388,000	70	Olympia
1965 April 29	6.5	VIII	337,000	59	Seattle

[1] Felt area in km^2.
[2] Focal depth in km.

An earthquake with I_0=IX in 1872, probably a little over 100 km east of the Puget Sound basin, caused only MMI=VI level damage within the basin.

The rapidity of intensity attenuation away from the epicenter of an earthquake is one of the factors that determines the extent of various levels of damage for a given earthquake. The rate of intensity attenuation varies in different parts of the country; for example, earthquakes on the east coast of the United States have about ten times lower intensity attenuation (and therefore much larger felt areas) than earthquakes in California for the same magnitude. Figure 2 (a) shows how intensity diminished with distance from the epicenter for the 1965 Seattle earthquake. From this graph it is evident that the attenuation of intensity is dependent or more than just distance from the epicenter, since many intensities are possible at a given distance. In fact, many factors influence the actual intensity resulting at a specific site, such as the fault movement causing the earthquake, the path from the focus to the site, and the site itself. One of the most important of these factors is the local geology at the site where the intensity is reported. For example, the intensity at a site on water-soaked alluvium is likely to be much higher than the intensity at a site on rock, for both sites at the same epicentral distance. Figure 2 (b) shows a subset of the data in figure 2 (a) containing only those sites on normally consolidated materials. In this case it is much more apparent that for a given distance range there is a predominant intensity.

The two MMI=VIII shocks will be discussed individually, followed by a short discussion of the shocks large enough to cause architectural damage (MMI=VII).

1949 EARTHQUAKE

The epicenter of the 1949 earthquake was between Tacoma and Olympia and caused MMI=VIII damage from north of Seattle to Longview (figure 3). Intensities within the city of Seattle (figure 4) range from IV to VII. Additional data not shown on figure 4 suggest intensities as high as VII–VIII on Harbor Island and the harbor area.

In Tacoma (figure 5), closer to the epicenter, intensities range from IV to VIII. The higher intensities (VII and VIII) are mostly in the central part of the city. Additional data not shown on figure 5 suggest one or two scattered MMI VIII's within the city.

Olympia (figure 6), the closest large city to the epicenter, has structural damage intensities (VIII) in the area of the state capitol where eight of the capitol buildings were damaged to the extent of two million

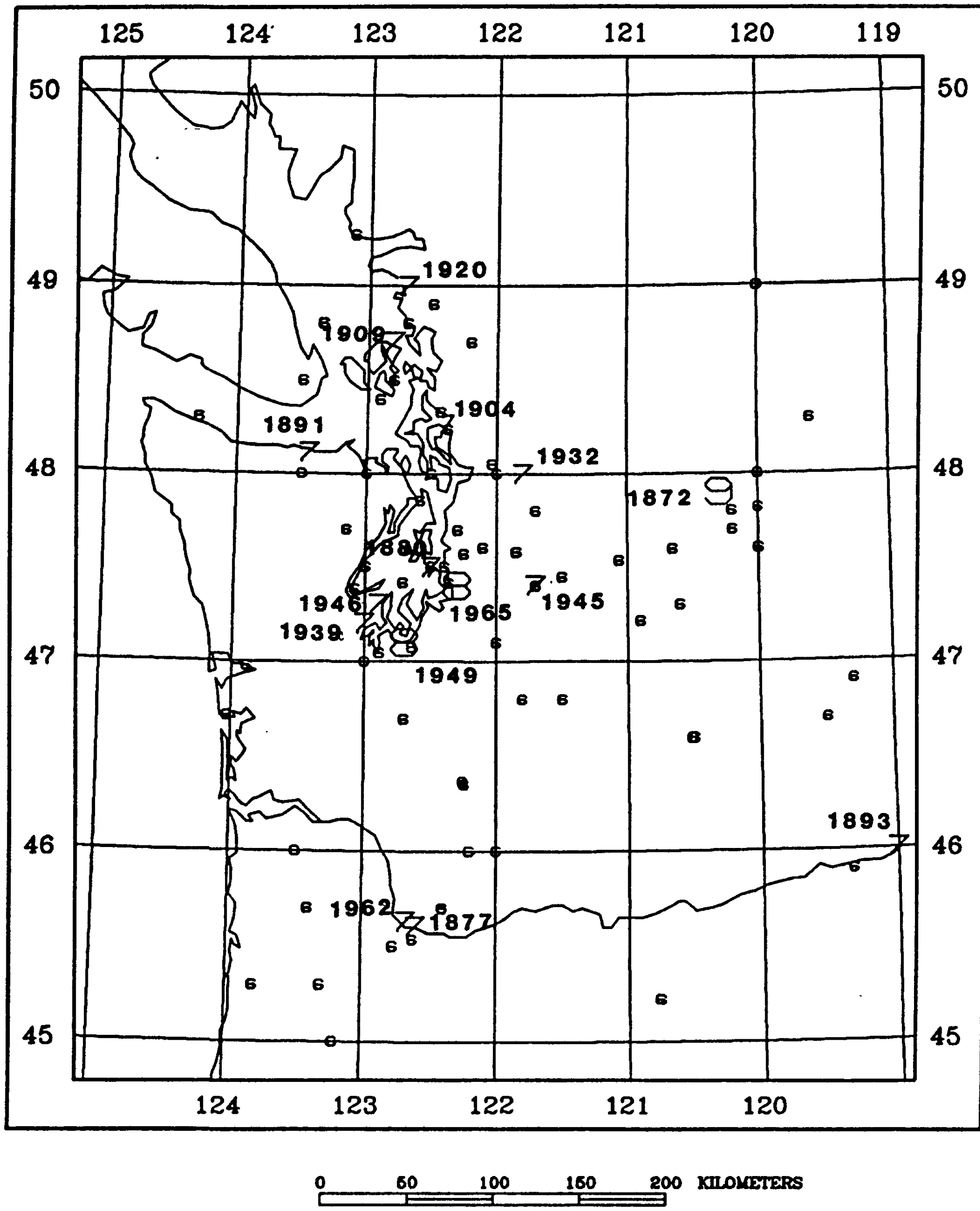

Figure 1. Puget Sound regional seismicity. The arabic numbers show maximum Modified Mercalli intensities (I_0) and epicentral locations. Years are noted for shocks with $I_0 \geq$VII M.M. Maximum intensities shown on this map are the highest given in any of the catalogs searched.

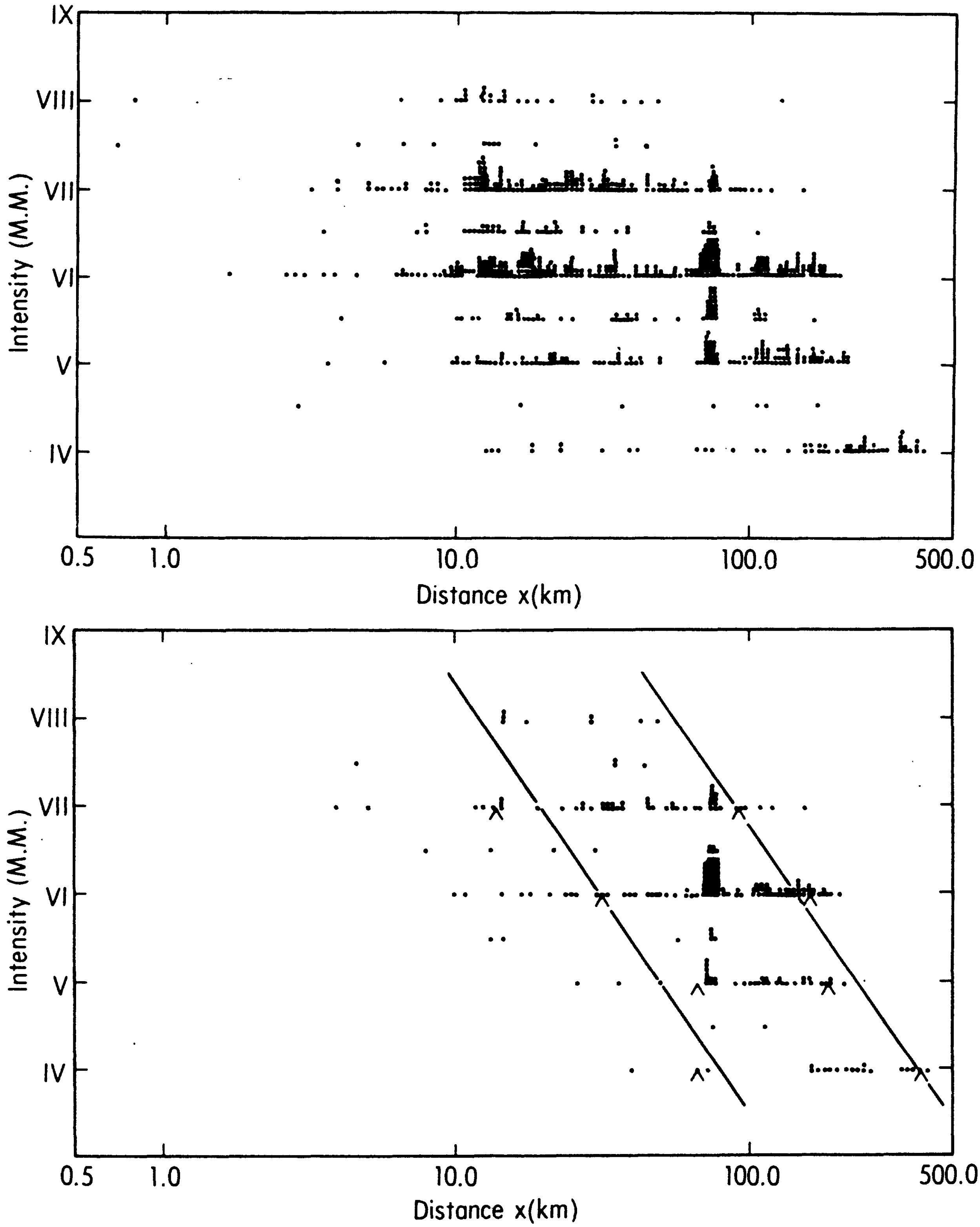

Figure 2. Plot of intensity attenuation with distance from the epicenter. Each dot represents a reported site intensity during the 1965 earthquake. (a) All the data for the 1965 earthquake. (b) Data for sites on normally consolidated materials only for the 1965 earthquake. The two pointers on each line show the range of distances within which 80% of the data lie. The two lines approximate the attenuation of the lower and upper sets of pointers, that is of the near-minimum and near-maximum distances at which a particular intensity was reported (Hopper and others, 1975).

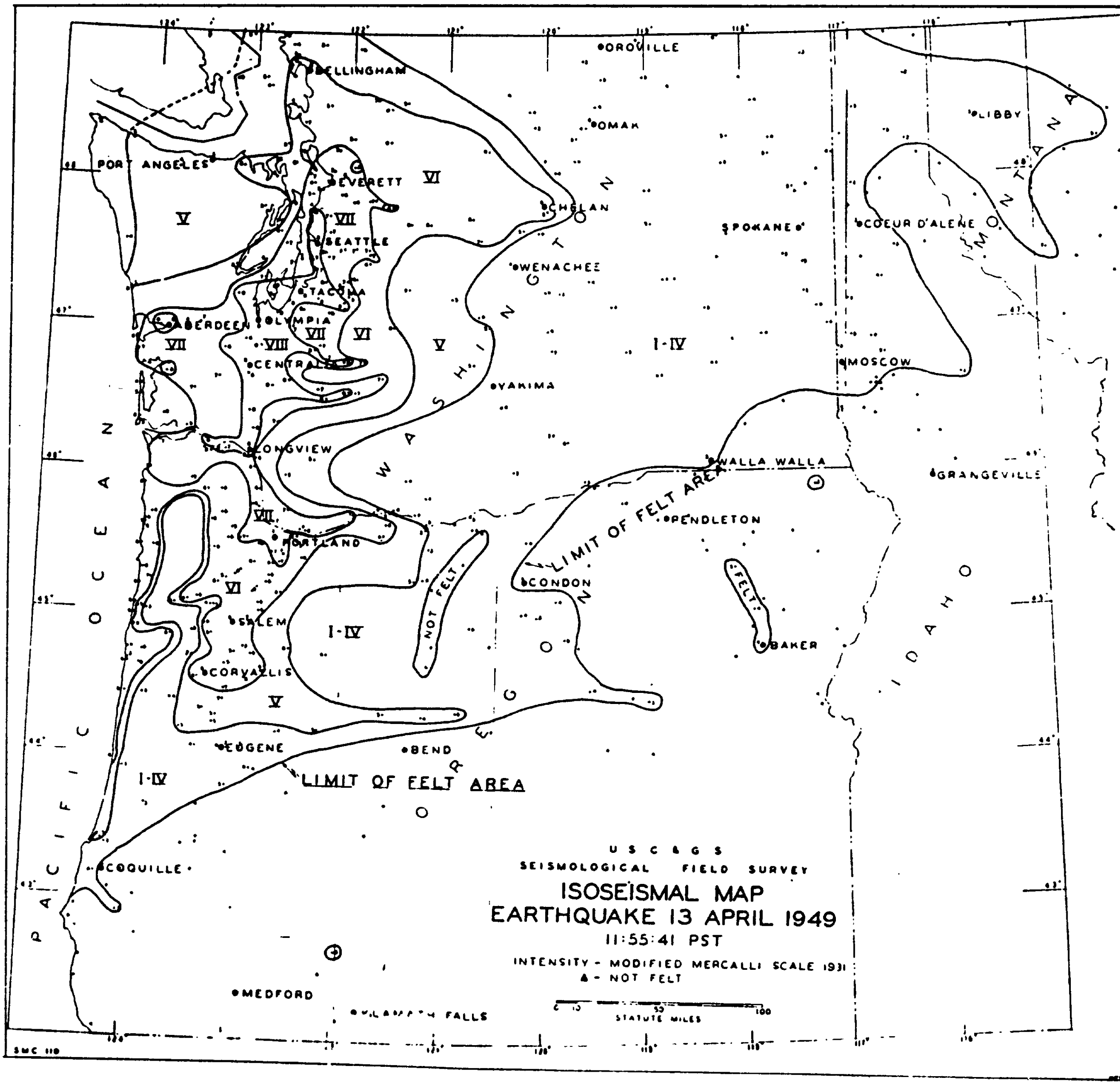

Figure 3. Isoseismal map for the 1949 earthquake near Olympia (Ulrich, 1949).

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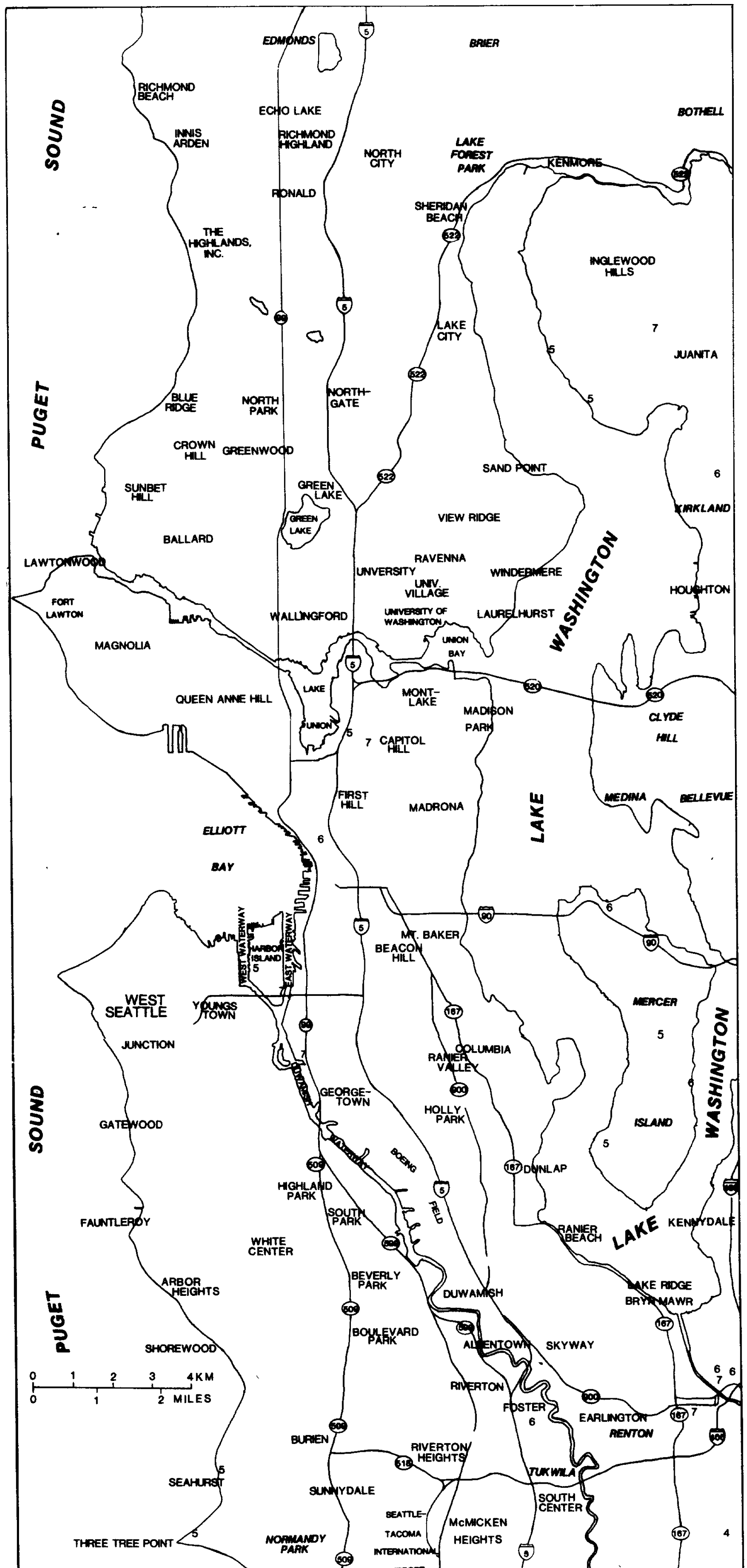

Figure 4. Intensities in the city of Seattle due to the 1949 earthquake. Data are from an unpublished intensity survey by the University of Washington.

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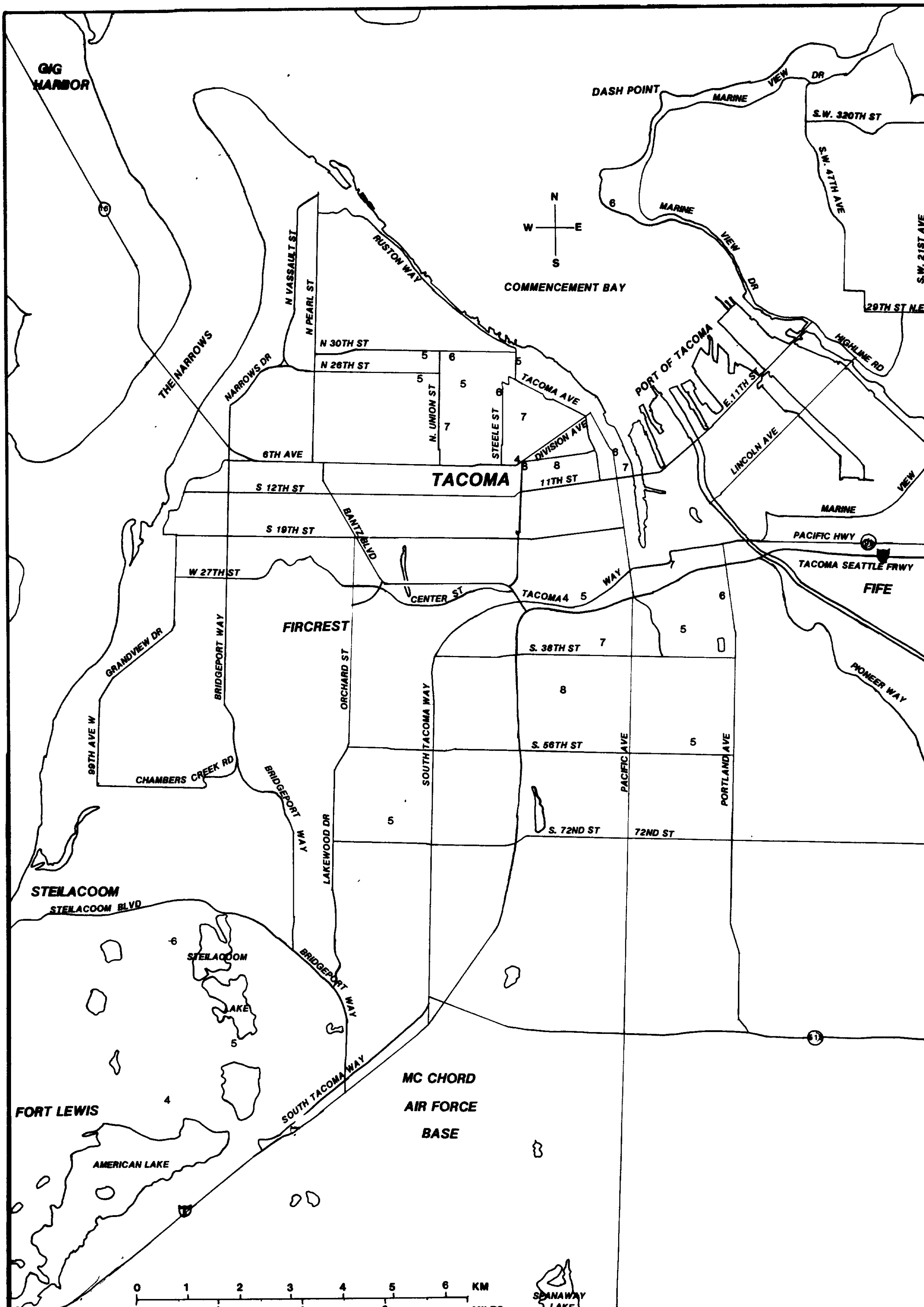

Figure 5. Intensities in the city of Tacoma due to the 1949 earthquake. Data are from an unpublished intensity survey by the University of Washington.

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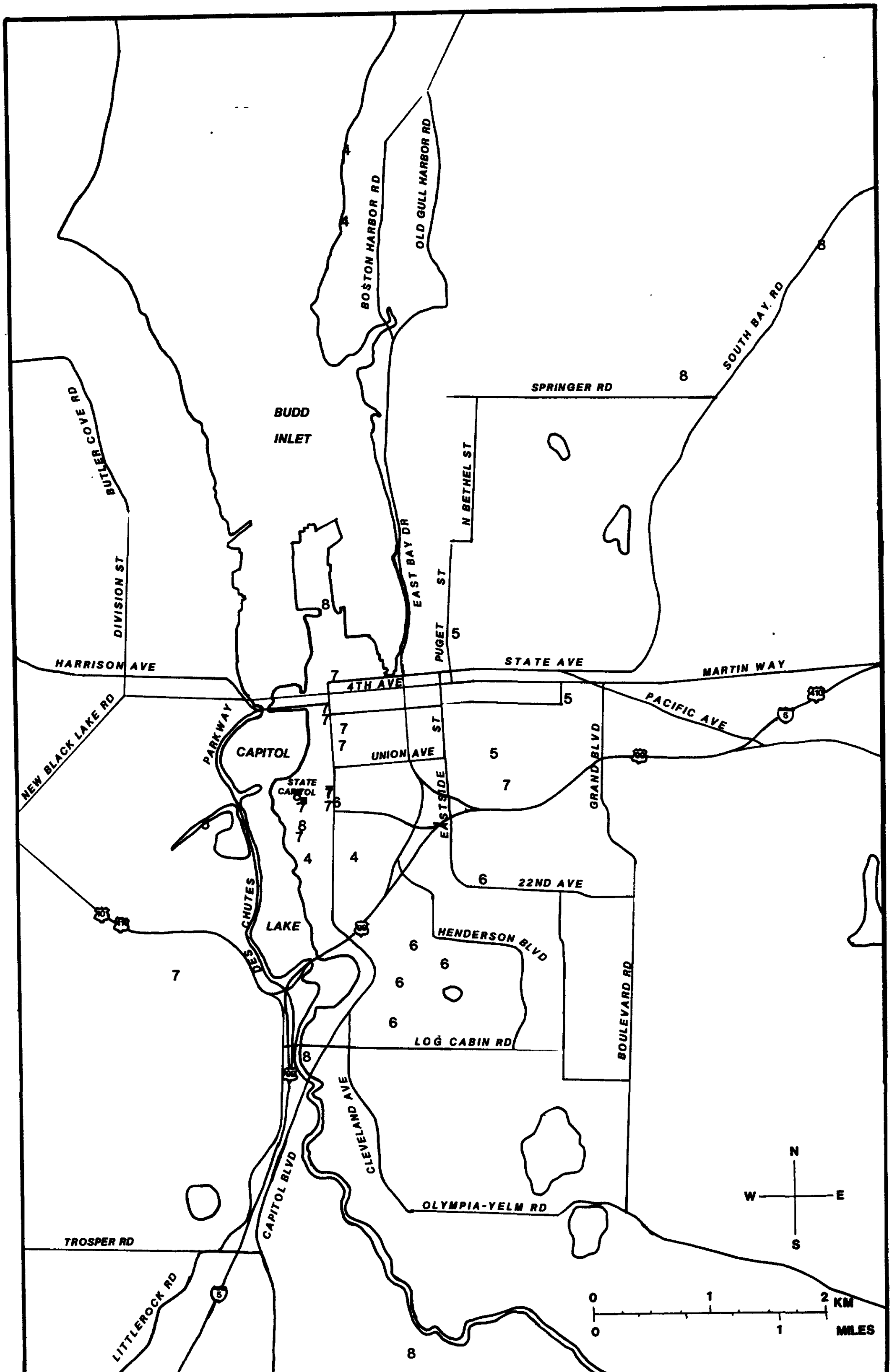

Figure 6. Intensities in the city of Olympia due to the 1949 earthquake. Data are from an unpublished intensity survey by the University of Washington.

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(1949) dollars (Murphy and Ulrich, 1951). Additional data for this map also show a few more MMI VIII's.

1965 EARTHQUAKE

The isoseismal map for the 1965 earthquake is shown in figure 7. The resemblance to the 1949 attenuation pattern is striking. Both shocks have elongated north–south interior isoseismals and have felt areas elongated toward the east across northern Idaho and northwestern Montana.

Although both the 1949 and 1965 earthquakes have maximum intensities of VIII, the 1965 earthquake is the smaller. Its magnitude and felt area are both slightly smaller than for the 1949 earthquake (see table 1). Also, whereas the 1949 earthquake caused enough damage at the MMI=VIII level for there to be an VIII isoseismal, in 1965 there were only a few scattered VIII's within a VII isoseismal.

Numerous data points within the city of Seattle (figure 8) make it possible to look at the distribution of intensities on a city-wide basis. Intensities within Seattle range from IV to VIII with the VIII's mostly clustered in West Seattle. Because the most serious damage seemed to be in West Seattle, a survey was done there utilizing damaged chimneys to determine relative damage on a block-by-block basis (figure 9). The percentage of downed chimneys in a block was often as high as 80%–100%, although most of the blocks surveyed had from 40% to 60% of their chimneys down. An important question to be addressed during the studies in progress is why West Seattle was so hard hit when other areas of Seattle with apparently similar geology and similar types and ages of construction (for example, Magnolia and Queen Anne Hill) were not.

Tacoma (figure 10) had isolated intensities as high as VII, but the predominant damage level was VI.

Olympia (figure 11), farther from the focus than Tacoma, nevertheless had far more damage at the MMI=VII level than did Tacoma. As in 1949, the highest damage was clustered primarily around the state capitol. However, Olympia had no structural damage in 1965 as it did in 1949.

OTHER LARGE EARTHQUAKES

A knowledge of the seismic history of the Puget Sound basin is essential to an understanding of the seismic hazard. A number of earthquakes, either smaller than the 1949 and 1965 shocks, or as large or larger, but farther away from the Puget Sound basin, are also important for any study of the area because they can cause locally high damage within their epicentral areas. Table 2 lists shocks of maximum intensity I_0=VII within the basin plus larger, more distant shocks. Isoseismals for six of these shocks are shown in figure 12. Better information is needed for most of these earthquakes in order to better see the intensity attenuation patterns. Some patterns do appear consistently in these maps. In particular, the felt areas of the 1945 and 1946 earthquakes (figure 12 (d) and (e)) show the same extension to the northeast that occurred in the 1949 and 1965 earthquakes. Some of the "isoseismal" maps shown in figure 12 are only maps of the overall felt area. These need to be much more detailed to understand the distribution of the intensities.

TABLE 2. Other Large Earthquakes in the Puget Sound Region

YEAR	I_0[1]	LOCATION
1872	IX	Cascade Mountains, central Washington
1877	VII	Portland
1880	VI–VII[2]	Bainbridge Island
1891	VI–VII[2]	Port Angeles
1904	VI–VII[2]	Victoria, Brit. Col.
1909	VII	Northwest Washington
1920	VII	Northwest Washington
1932	VI–VII[2]	Tolt River, Sultan
1939	VII	Olympia
1945	VII	Mount Si, North Bend
1946	VII	Near Tacoma
1946	VIII	Georgia Strait, Brit. Col.
1949	X	Queen Charlotte Islands, Brit. Col.
1962	VII	Vancouver, Washington

[1] Maximum intensity. Highest I_0 from catalogs searched.
[2] Maximum intensity not well established.

CONCLUSIONS

The seismic history of the Puget Sound basin extends back only a little over a century. During this period there have been two shocks large enough to cause structural damage (MMI=VIII) within the basin and one of MMI=IX in the adjacent Cascade Mountains. The two larger shocks within the basin have both been relatively deep (60–70 km) and have had correspondingly large damage areas and felt areas. It is reasonable to assume that such earthquakes can occur again and,

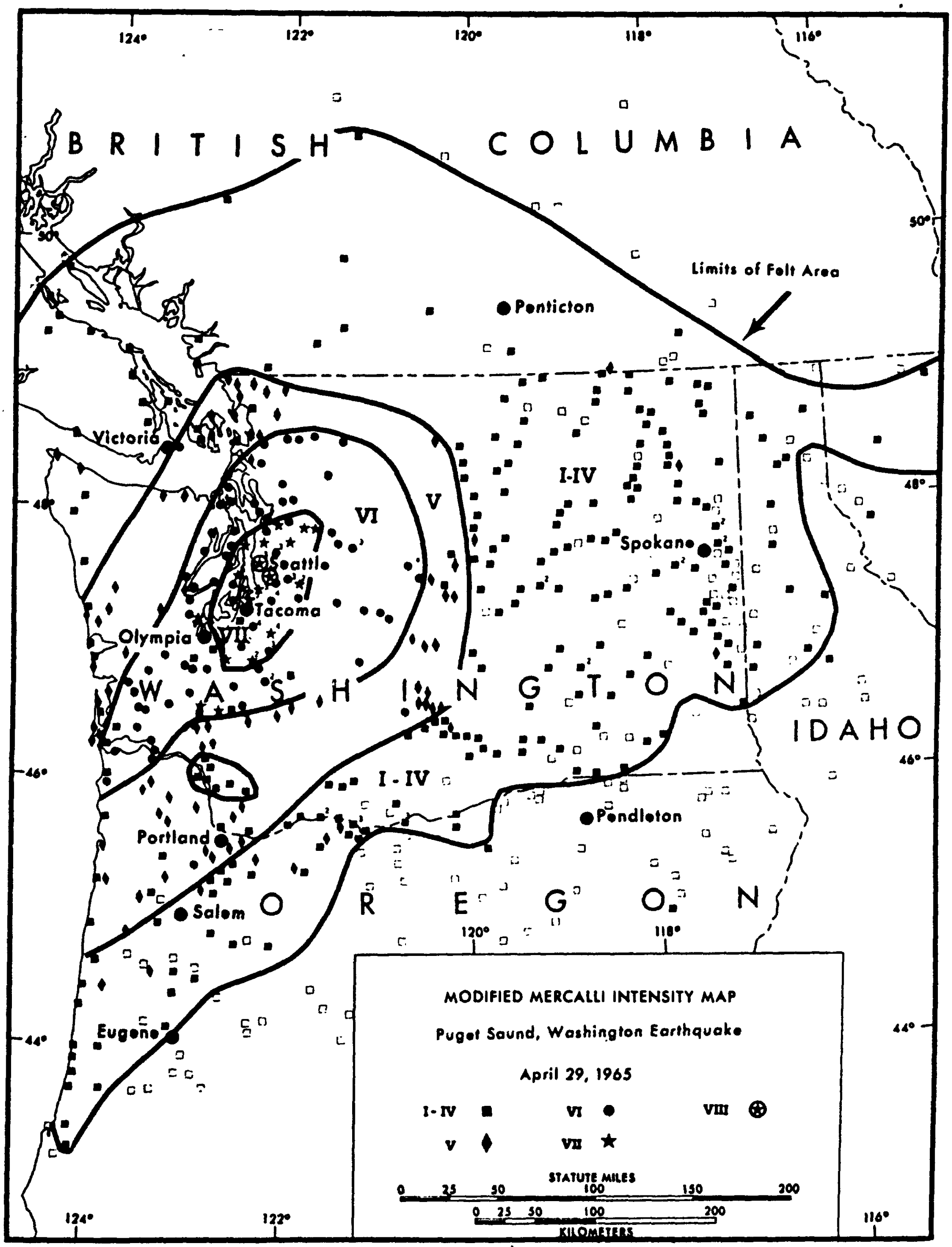

Figure 7. Isoseismal for the 1965 earthquake near Seattle (Algermissen and Harding, 1965). The open squares represent sites where the earthquake was reported not felt.

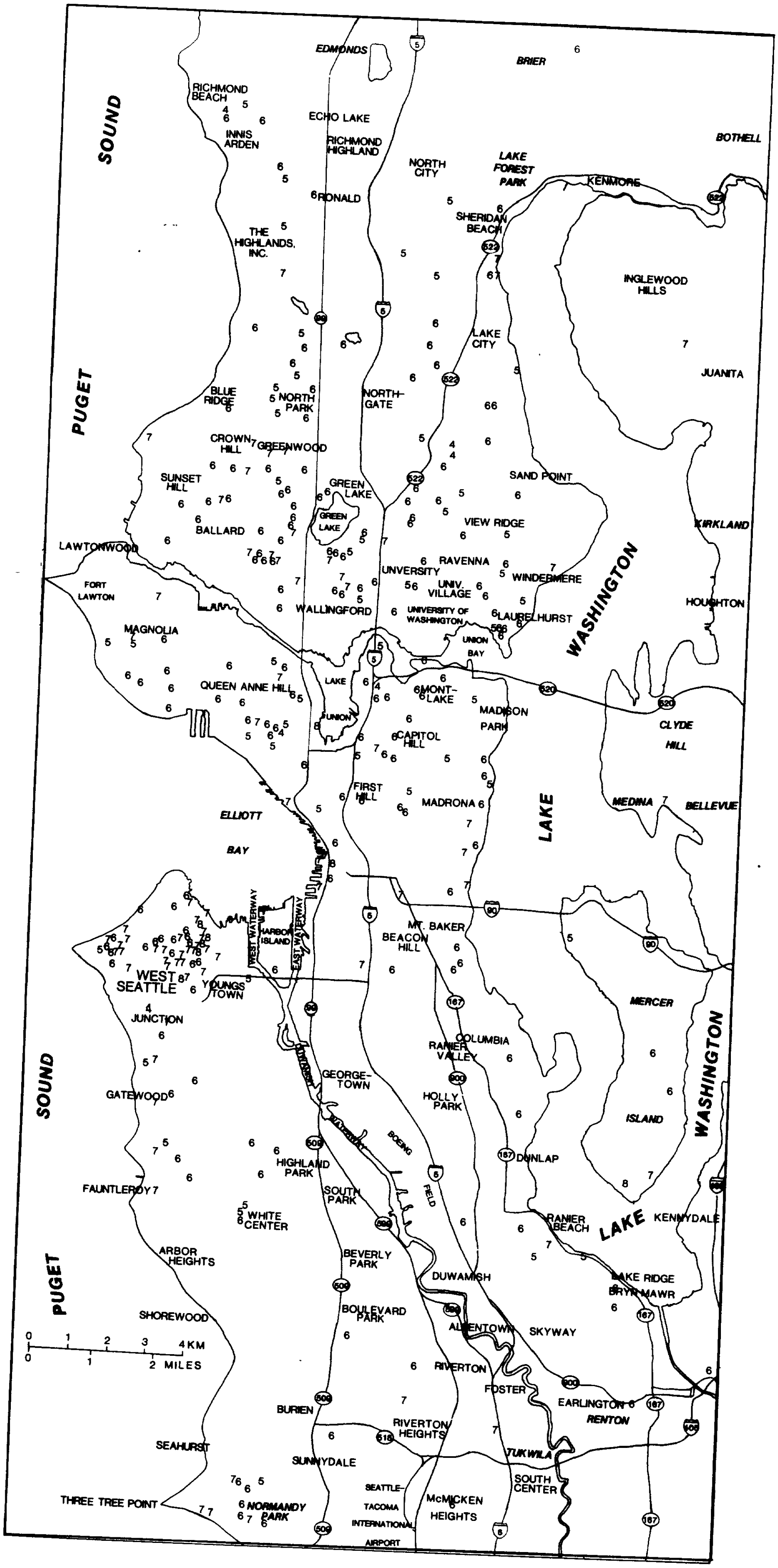

Figure 8. Intensities in the city of Seattle due to the 1965 earthquake. Data are from an unpublished intensity survey by the University of Washington.

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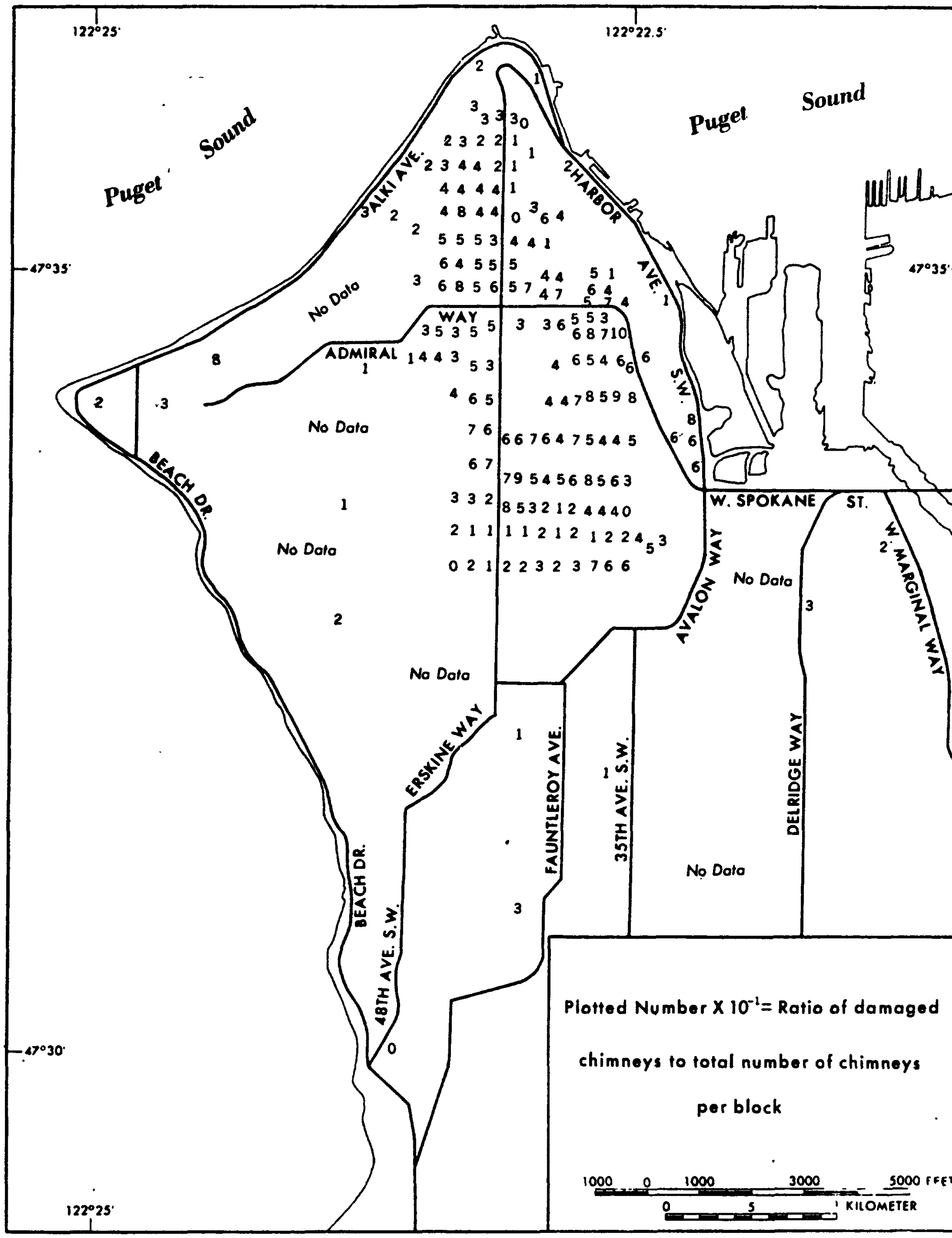

Figure 9. Percent chimneys damaged (times 10) in West Seattle due to the 1965 earthquake (Algermissen and Harding, 1965).

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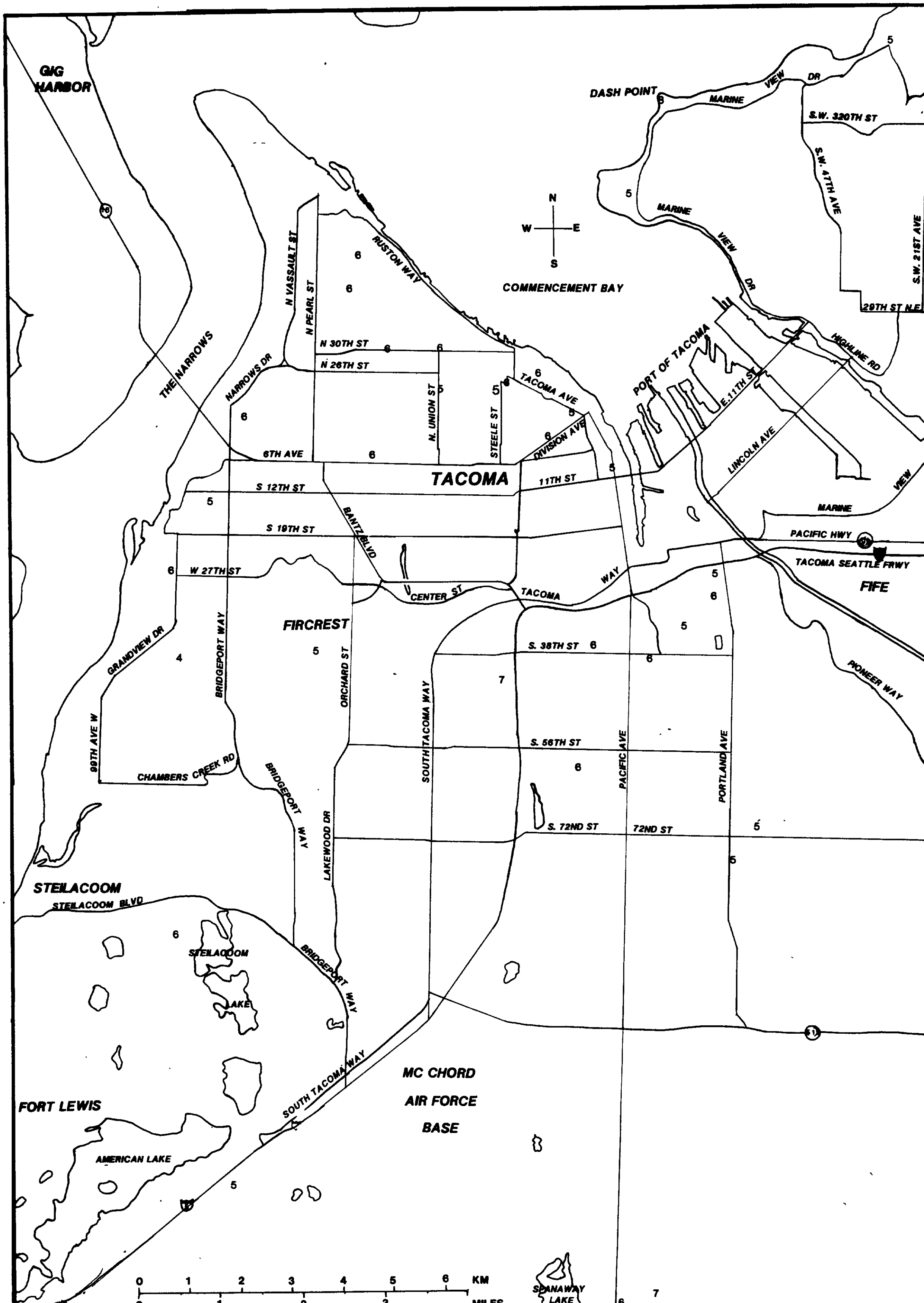

Figure 10. Intensities in the city of Tacoma due to the 1965 earthquake. Data are from an unpublished intensity survey by the University of Washington.

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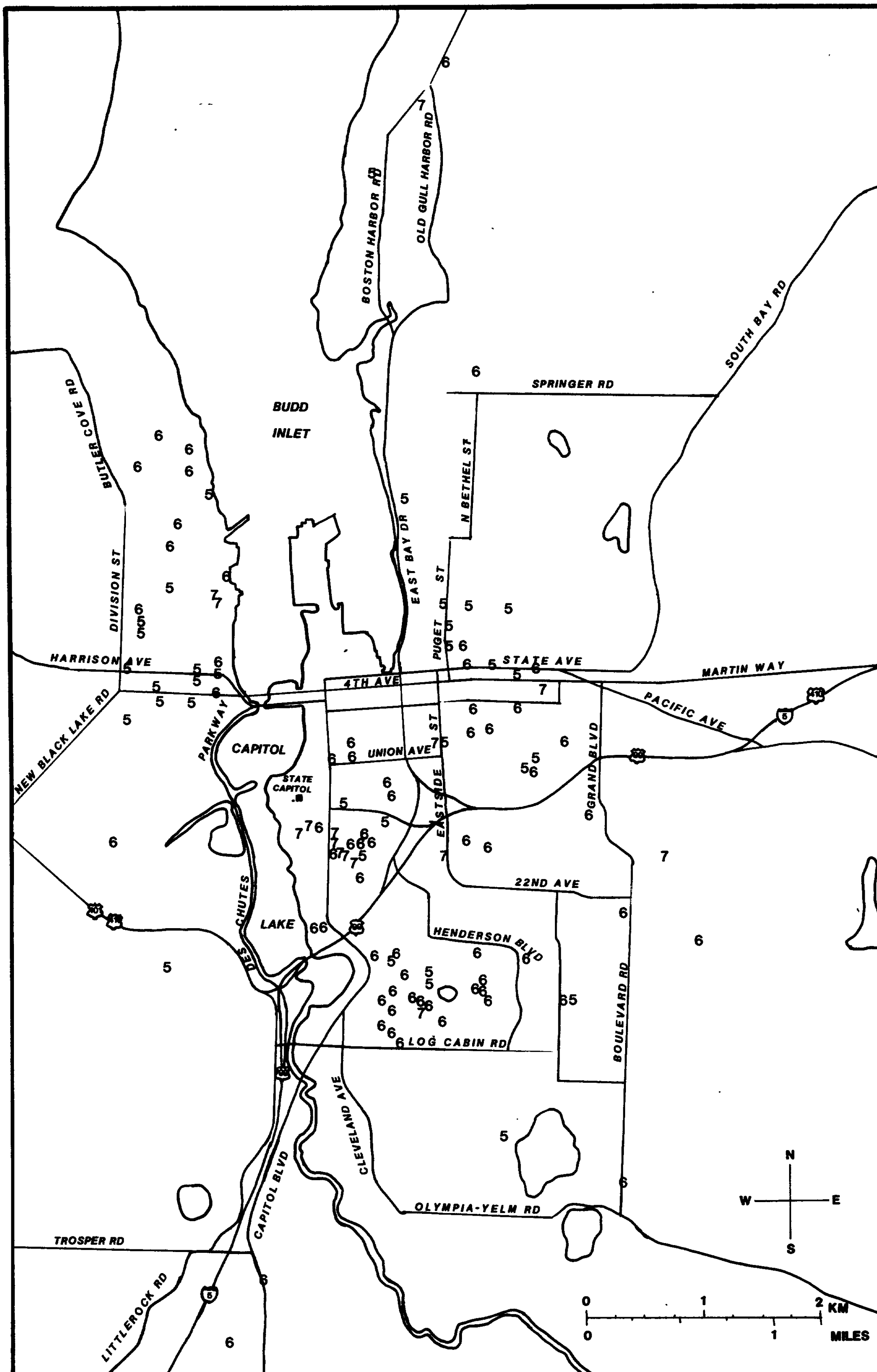

Figure 11. Intensities in the city of Olympia due to the 1965 earthquake. Data are from an unpublished intensity survey by the University of Washington.

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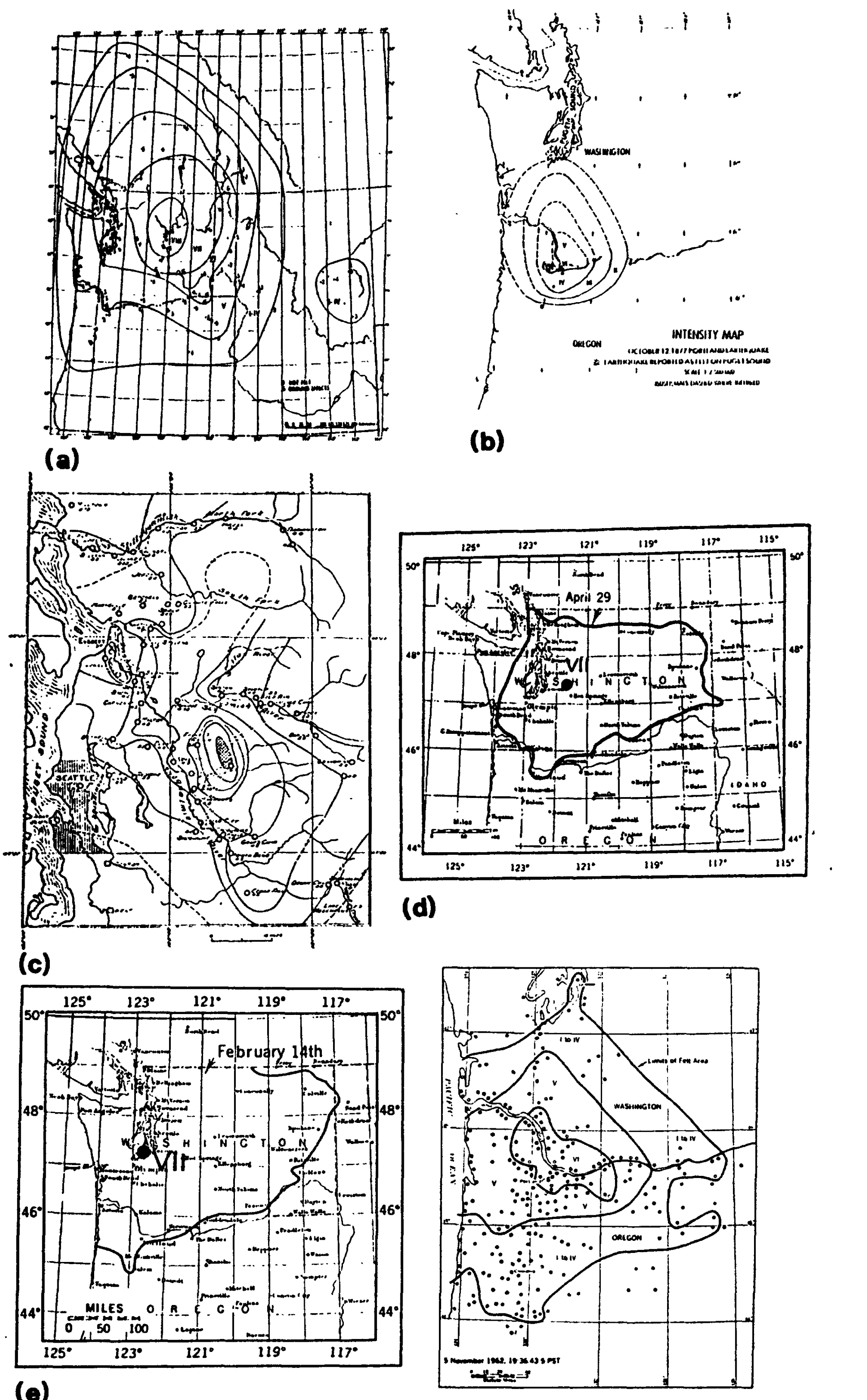

Figure 12. Isoseismals for six other shocks affecting the Puget Sound area. (a) 1872, (b) 1877 (Thenhaus, 1978), (c) 1932 (Bradford and Waters, 1934), (d) 1945 (Bodle and Murphy, 1947), (e) 1946 (Bodle and Murphy, 1948), and (f) 1962 (Lander, 1964).

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moreover, that a slightly larger earthquake is possible, even though it has not yet happened during the short historical record. An earthquake similar to the 1949 or 1965 shocks, but with magnitude 7.5 and maximum intensity of IX, could cause widespread structural damage over a densely populated area. Such an earthquake, if it occurred during rush hour, could leave over 2,000 people dead, over 8,000 injured, and perhaps 23,000 homeless (Hopper and others, 1975). Landslides and liquefaction in susceptible areas would block transportation systems and hinder relief and recovery efforts.

High intensities in historical Puget Sound earthquakes have been due to: (1) strong shaking in the meizoseismal regions of the earthquakes, (2) unusual amplifications of ground motion as in West Seattle in 1965, (3) widespread ground failures in susceptible soils, and (4) damage in an aging inventory of buildings, particularly buildings of unreinforced masonry. These conditions still exist and will continue to exist during the next earthquake in Puget Sound.

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Modified Mercalli Intensity Scale of 1931[1]

I Not felt—or, except rarely under especially favorable circumstances.
Under certain conditions, at and outside the boundary of the area in which a great shock is felt:
sometimes birds, animals, reported uneasy or disturbed;
sometimes dizziness or nausea experienced;
sometimes trees, structures, liquids, bodies of water, may sway—doors may swing, very slowly.

II Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons.
Also, as in grade I, but often more noticeably:
sometimes hanging objects may swing, especially when delicately suspended;
sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly;
sometimes birds, animals, reported uneasy or disturbed;
sometimes dizziness or nausea experienced.

III Felt indoors by several, motion usually rapid vibration.
Sometimes not recognized to be an earthquake at first.
Duration estimated in some cases.
Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away.
Hanging objects may swing slightly.
Rocked standing motor cars slightly.

IV Felt indoors by many, outdoors by few.
Awakened few, especially light sleepers.
Frightened no one, unless apprehensive from previous experience.
Vibration like that due to passing of heavy, or heavily loaded trucks.
Sensation like heavy body striking building, or falling of heavy objects inside.
Rattling of dishes, windows, doors; glassware and crockery clink and clash.
Creaking of walls, frame, especially in the upper range of this grade.
Hanging objects swung, in numerous instances.
Disturbed liquids in open vessels slightly.
Rocked standing motor cars noticeably.

V Felt indoors by practically all, outdoors by many or most: outdoors direction estimated.
Awakened many, or most.
Frightened few—slight excitement, a few ran outdoors.
Buildings trembled throughout.
Broke dishes, glassware, to some extent.
Cracked windows—in some cases, but not generally.
Overturned vases, small or unstable objects, in many instances, with occasional fall.
Hanging objects, doors, swing generally or considerably.
Knocked pictures against walls, or swung them out of place.
Opened, or closed, doors, shutters, abruptly.
Pendulum clocks stopped, started, or ran fast, or slow.
Moved small objects, furnishings, the latter to slight extent.
Spilled liquids in small amounts from well-filled open containers.
Trees, bushes, shaken slightly.

VI Felt by all, indoors and outdoors.
Frightened many, excitement general, some alarm, many ran outdoors.
Awakened all.
Persons made to move unsteadily.
Trees, bushes, shaken slightly to moderately.
Liquid set in strong motion.
Small bells rang—church, chapel, school, etc.
Damage slight in poorly built buildings.
Fall of plaster in small amount.
Cracked plaster somewhat, especially fine cracks chimneys in some instances.
Broke dishes, glassware, in considerable quantity, also some windows.
Fall of knick-knacks, books, pictures.
Overturned furniture in many instances.
Moved furnishings of moderately heavy kind.

VII Frightened all—general alarm, all ran outdoors.
Some, or many, found it difficult to stand.
Noticed by persons driving motor cars.
Trees and bushes shaken moderately to strongly.
Waves on ponds, lakes, and running water.
Water turbid from mud stirred up.
Incaving to some extent of sand or gravel stream banks.
Rang large church bells, etc.
Suspended objects made to quiver.
Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.
Cracked chimneys to considerable extent, walls to some extent.
Fall of plaster in considerable to large amount, also some stucco.
Broke numerous windows, furniture to some extent.
Shook down loosened brickwork and tiles.
Broke weak chimneys at the roof-line (sometimes damaging roofs).
Fall of cornices from towers and high buildings.
Dislodged bricks and stones.
Overturned heavy furniture, with damage from breaking.
Damage considerable to concrete irrigation ditches.

VIII Fright general—alarm approaches panic.
Disturbed persons driving motor cars.
Trees shaken strongly—branches, trunks, broken off, especially palm trees.
Ejected sand and mud in small amounts.
Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters
Damage slight in structures (brick) built especially to withstand earthquakes.
Considerable in ordinary substantial buildings, partial collapse: racked tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling.
Fall of walls.
Cracked, broke, solid stone walls seriously.
Wet ground to some extent, also ground on steep slopes.
Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
Moved conspicuously, overturned, very heavy furniture.

IX Panic general.
Cracked ground conspicuously.
Damage considerable in (masonry) structures built especially to withstand earthquakes:
threw out of plumb some wood-frame houses built especially to withstand earthquakes;
great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames;
serious to reservoirs; underground pipes sometimes broken.

X Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks.
Landslides considerable from river banks and steep coasts.
Shifted sand and mud horizontally on beaches and flat land.
Changed level of water in wells.
Threw water on banks of canals, lakes, rivers, etc.
Damage serious to dams, dikes, embankments.
Severe to well-built wooden structures and bridges, some destroyed.
Developed dangerous cracks in excellent brick walls.
Destroyed most masonry and frame structures, also their foundations.
Bent railroad rails slightly.
Tore apart, or crushed endwise, pipe lines buried in earth.
Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI Disturbances in ground many and widespread, varying with ground material.
Broad fissures, earth slumps, and land slips in soft, wet ground.
Ejected water in large amount charged with sand and mud.
Caused sea-waves ('tidal' waves) of significant magnitude.
Damage severe to wood-frame structures, especially near shock centers.
Great to dams, dikes, embankments, often for long distances.
Few, if any (masonry), structures remained standing.
Destroyed large well-built bridges by the wrecking of supporting piers, or pillars.
Affected yielding wooden bridges less.
Bent railroad rails greatly, and thrust them endwise.
Put pipe lines buried in earth completely out of service.

XII Damage total—practically all works of construction damaged greatly or destroyed.
Disturbances in ground great and varied, numerous shearing cracks.
Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive.
Wrenched loose, tore off, large rock masses.
Fault slips in firm rock, with notable horizontal and vertical offset displacements.
Water channels, surface and underground, disturbed and modified greatly.
Dammed lakes, produced waterfalls, deflected rivers, etc.
Waves seen on ground surfaces (actually seen, probably, in some cases).
Distorted lines of sight and level.
Threw objects upward into the air.

[1] Wood, H. O., and Neumann, Frank, 1931, Modified Mercalli intensity scale of 1931: Seismological Society of America Bulletin, v. 21, no. 4, p. 277–283.

CONSIDERING EARTHQUAKE RISK REDUCTION POLICIES AND PRACTICES

By

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This paper addresses relevant social science considerations to earthquake risk reduction within the context of the USGS Puget Sound/Portland earthquake hazards assessment. Unfortunately, social science considerations are often relegated a secondary role in discussions of earthquake risk reduction. As noted in what follows, social scientists have made useful contributions to our understanding of factors affecting natural hazards policy adoption and implementation. This knowledge base along with information about current policies and problems provide important lessons for the design of appropriate and feasible risk reduction strategies for the Puget Sound/Portland areas.

Policy Formation and Implementation

There is a burgeoning social science literature about policy formation and implementation that is relevant to discussions of policies for earthquake hazards. The focus of recent political science research on policy formation has been upon factors associated with opportunities for policy enactment. The recent focus of the closely related, but disciplinary more diverse, implementation research has been upon the relationships between policy design and the incentives or disincentives that particular policies create for desired behavioral changes.

Policy Entrepreneurs and Policy Formation

In studying policy formation, political scientists have in recent years moved away from rational policy-making models to more free-flowing models of policy-making. The new models emphasize the separate streams of policy ideas, problems, and political currents from which occasions for policy enactment arise as unpredictable windows of opportunity. What emerges from such descriptions is a policy-making world in which political entrepreneurs must champion causes and a store of proposals need be at the ready when fleeting windows of opportunity open.

In applying these newer theoretical perspectives, social scientists who have studied policy formation concerning earthquakes and other hazards had little success in identifying conditions other than earthquakes themselves which occasion opportunities for policy enactment. While several case studies (e.g., Alsch and Petak, 1986; Wyner and Mann, 1986) exist of policy enactment for earthquake risk reduction, they reflect the broader literature in depicting fleeting episodes when political currents are supportive of specific policy action. Typically, new policies are considered only after long periods of fledgling efforts to draw attention to the need for reforms.

The main lessons of this research for those advocating enactment of new policies for earthquake risk reduction are:

(1) *Expect a long "softening up" period.* Given the low placement of earthquake hazards on policy agendas, it takes a long time -- often a decade or more -- for officials and relevant professionals to grapple with the important technical, political, and economic considerations of introducing changes in existing practices.

Alesh and Petak (1986), in their study of retrofit policies for hazardous buildings, note that it took eight years from the time Los Angeles Councilmember (now Mayor) Bradley formally requested a feasibility study for addressing the problem of pre-1934 unreinforced masonry buildings until the Council enacted their 1983 ordinance. It will be another 3 to 10 years before owners will have been required to comply with the ordinance.

In Washington state, it has been some 15 years since sustained state-level efforts to build a constituency for earthquake risk reduction were initiated with the Washington State Engineering Advisory Council formed by the governor in 1971, and the Ad Hoc Committee on Geologic Hazards formed by the state Senate Committee on Commerce in 1973.

(2) *Anticipate unpredictable and fleeting "windows of opportunity"*. Windows of opportunity for enacting policy changes are not predictable and rarely last more than a few weeks or months. The norm is for situations to arise where earthquake provisions can be tacked onto related legislative measures. For example, seismic provisions might be added to new provisions for historic structure rehabilitation. Or, earthquake education provisions might be folded into new science curricula as part of education curriculum reforms. On rarer occasions when earthquakes occur in nearby areas, there will be more widespread, but still fleeting, interest in addressing earthquake risks.

(3) *Learn to be more entrepreneurial about advocating policy reforms.* Even when viewed from the inside, one of the central features that stands out in descriptions of policy-making in federal, state and local legislative arenas is the level chaos that dominates policy-making. Some types of individuals or organizations -- which have been labeled "policy entrepreneurs" in the policy literature -- tend to thrive in such situations. Their skills lay in first recognizing when windows of opportunity might open, and second in having ready concrete proposals to offer as solutions to the problem at hand.

Policy Instruments, Implementors, and Intermediaries

Perhaps the greatest contributions to date of social scientists to earthquake risk reduction have been both identifying the complex chain of implementing actions various risk reduction measures entail and sorting through the relevant decision-making considerations that affect implementation success. The state-of-art for this work has involved analyzing implementation considerations for risk reduction measures aimed at influencing people's behaviors with respect to land use, design, and construction or rehabilitation of new and existing structures.

Implementation-relevant research by hazards specialists, geographers, planners, and political scientists can be summarized as follows (see, May and Bolton, 1986 for further discussion):

(1) *The range of prospective risk reduction measures is fairly well prescribed.* While the appropriateness and feasibility of implementing particular measures varies considerably among different jurisdictions, the types of measures that might be employed have been detailed by planning professionals and hazard researchers (e.g., Blair and Spangle, 1979; Jaffe, Butler, and Thurow, 1981; Kockelman, 1983; Nichols, 1982). These include building code provision for new construction, hazardous abatement provisions for existing construction, various zoning provisions, special use or critical facility permits, lifeline location or design restrictions, seismic area impact review requirements, real estate disclosure requirements, and the purchase of property rights or property itself.

(2) *The relevant chain of actions, actors, and decision-making considerations affecting implementation success are important to consider.* In depicting the prospects for successful policy implementation, implementation theories have focused attention on two aspects of the policy process: (1) the chain of actions that must be undertaken in order to achieve desired behavioral changes among "target groups" affected by a given policy, and (2) the decisionmaking considerations that affect behaviors of "target groups" and intermediary implementors with respect to the policy under consideration. Social scientists have applied

these broad notions about policy implementation in identifying the relevant considerations to implementation success for risk reduction policies. The difficulty lay in specifying which of the generic considerations apply to any particular set of policies and locations.

(3) *We have learned to be much more cautious about assuming implementation success.* One of the salient lessons of the earthquake risk reduction implementation studies (e.g., Palm, 1983; Wyner and Mann, 1986), is the extent of implementation problems and resultant lack of implementation success for risk reduction policies. These findings call attention to the importance of careful analysis of relevant decision-making considerations so that policies can be designed that anticipate implementation problems. In addition, we should be cautious about accepting cost-benefit studies or other policy analyses that assume full implementation of policies under consideration.

Risk Reduction Policy for Washington and Oregon

Within this region there have been case studies of risk reduction efforts within selected communities but no comprehensive studies of risk reduction practices. As a consequence, there is limited knowledge of existing local-level policy and less understanding of actual development, land use, or building practices. In brief, previous research and other documents (more generally, see the review of state policy actions by the Washington Seismic Safety Council, 1986) concerning this region tell us:

(1) *State-wide policies exist with respect to new construction.* The chief state-level policy action in Washington state is adoption in 1975 of a State Building Code which mandates state and local governmental adherence to seismic provisions of the Uniform Building Code (UBC) -- currently referencing the 1982 UBC provisions -- for nonresidential, new construction . Oregon also has a state-wide building code. Neither of these codes address existing construction.

(2) *The consensus seems to be that the current UBC provisions for this region have provided satisfactory state-of-the-art designs for construction of new "engineered" buildings.* While the delineation of the zones and peak acceleration estimates are subject to change as the USGS assessment findings are released, the current provisions appear to be unlikely to experience substantial change except possibly in a localized, site-specific cases. In assessing the impact of the NEHRP Recommended Provisions upon cost of construction, designs using the recommended provisions when applied to Seattle were found to be slightly less expensive than designs using the Modified 1979 UBC provisions which at that time were the applicable Seattle Code (reported in Weber, 1985).

(3) *Some local jurisdictions in this region are fairly advanced in their risk reduction efforts.* Seattle was cited by Holmes and Thurston (1985) in a FEMA-sponsored national review of private sector activities for its parapet ordinance and provisions for seismic upgrading when rehabilitating buildings. Land use practices in some jurisdictions reference seismic hazards, particularly secondary effects, as documented by discussions of the King County, Washington sensitive areas ordinance (Bolton et al., 1986). Tacoma requires a strong-motion recording instrument be installed and maintained in all buildings six stories or higher, funded through a city surcharge on building permits (discussed in Drabek, Mushkatel, and Kilijanek, 1983, p. 132).

(4) *The risks posed by existing construction are noteworthy in this region.* The problems of existing unreinforced masonry buildings in this region are similar to what has been reported nationally for high risk areas (FEMA, 1985a,b). Relatively little has been done at the state or local level to address the problem. The Washington Seismic Safety Council cited the particular problem of unreinforced masonry schools. Hawkins and Burke (1985), in a NSF-funded study of unreinforced masonry buildings in seven small towns in the Pacific Northwest, found the seismic problem to be acute in such small towns. Moreover, they judged the prospects for addressing the problems to be limited by a lack of local technical expertise and financial considerations.

Barriers to Policy Development and Implementation

The 1986 Washington Seismic Safety Council Report identified a number of barriers to policy development that apply at both state and local levels of government. The following were noted by us as continuing themes in discussions of earthquake reduction policy by officials in Washington state:

(1) *Inadequate planning information.* We cited a need for risk maps that are appropriate for guiding planning and building decisions. Such maps, or the capacity to produce and interpret them, exists in some jurisdictions. But in many jurisdictions, the capacity does not exist. Equally important, given the relatively low perception of earthquake risks among planning and policy officials, one might suspect there is little perceived need for such maps. *The dual challenge is to produce usable information and to create capable users of the information.*

(2) *Limited direct governmental control.* Ultimately risk reduction efforts entail changes in individual behaviors. Governments adopt and attempt to enforce regulations governing land use and building practices, but compliance decisions ultimately rest upon private citizens. In addition, enforcement of regulations typically entails multiple intermediaries. As such, governments have indirect means for influencing risk reduction practices.

Complicating the intergovernmental implementation problem is the fact that the Puget Sound/Portland areas contain multiple, overlapping jurisdictions. Within or overlapping the six counties of the Puget Sound area and the two counties of Portland are some 100 cities and towns, 365 special districts (e.g., recreation, utility, transit, drainage), 114 school districts, and 17 active ports. *The challenge is to develop policies that recognize the diversity of governmental entities and the complexity of intergovernmental implementation.*

(3) *Concern about costs.* Clearly, the costs of undertaking earthquake risk reduction programs is a major concern of policymakers. As such, *a high priority of the assessment effort should be both estimating costs and identifying ways to finance reduction programs.*

Unfortunately, as we noted in the Washington state policy report, the high costs and long time frames for risk reduction programs tend to blind policymakers to other more immediate and less expensive risk reduction efforts. Priorities should be placed upon identifying immediate, low cost actions.

(4) *Concern about liability.* A related concern we identified is a fear of increased governmental assumption of liability for earthquake damages and losses that might follow from documenting earthquake risks and public building vulnerability. As noted in the report and by others in this Puget Sound/Portland review session, there are several reasons for suggesting that such thinking is inappropriate. The fact is that in the event of a major earthquake, the state may already be held liable in some circumstances for damages or deaths. *The challenge is to identify risk reduction measures which appropriately address liability issues.*

Opportunities for Action

The lessons of the social science literature about policy formation and implementation establish the broad contours concerning earthquake risk reduction policy prospects. The listing of noteworthy barriers to policy development no doubt diminish expectations for enactment of far-reaching policy initiatives. Taken together these lists may suggest that any efforts to legislatively enact risk reduction policy reforms are fruitless. Unfortunately, such thinking seems to be all too common among state and local policymakers who have responsibilities for addressing the risks posed by earthquakes and other natural hazards.

One implication of this discussion is that rather than seeking comprehensive and expensive legislative initiatives, advocates should promote a more limited set of policy proposals for legislative enactment. In this respect, advocates need to become more entrepreneurial in taking advantage of windows of opportunity to insert seismic provisions where relevant into non-hazard specific policy initiatives. Even though the changes will be less visible and by definition more marginal, the cumulative impacts of inserting seismic considerations into rules, regulations, and guidance concerning state and local health and safety issues can be very important for earthquake risk reduction.

A second implication is that advocates of risk reduction should place greater emphasis on actions that do not require legislative action. One of the surprising findings of our work in reviewing state-level earthquake risk reduction practices in Washington state is that state agencies already possess most of the necessary authority for undertaking risk reduction programs. In this respect, several specific suggestions concerning immediate opportunities for advancing risk reduction practices come to mind:

(1) *Create a state-level agency working group.* As part of our review of seismic programs within Washington state, we found some activity in many state agencies and much activity in a few. While we judged the overall level of effort as shirking state leadership responsibilities, there is a clear potential for administrative action. A first step in promoting such action is to create an effective state-level agency working group. This does not require legislative action. Presumably, a similar effort could be undertaken in Oregon.

(2) *Anticipate policy-relevant questions.* As part of efforts to insert seismic provisions into existing legislation, rules, and regulations many questions will inevitably arise concerning costs, liability, and need. Without answers to these questions, there is little hope of even marginal additions to existing policies. It is remarkable how little prepared advocates or relevant state and local officials are to answer these questions. The USGS effort will help address some of these questions, but institutional mechanisms need to be created to make sure that the necessary answers are being developed. This requires an institutional capability to synthesize research results from the USGS effort. Such capability is provided in other states by seismic safety commissions.

(3) *Explore non-governmental avenues for risk reduction.* Most of the attention concerning earthquake risk reduction efforts is upon governmental policy as a means of mandating or otherwise inducing risk reduction behaviors. However, much risk reduction activity takes place outside of the governmental arena. Professional engineers participate in the development of local, regional and national standards or recommend appropriate modifications to standards. The insurance and banking community adopt their own standards or procedures for dealing with hazardous areas. Various companies deciding whether or not to locate in an area, or build facilities, have their own set of considerations.

Given these considerations, more attention should be given to the prospective role of the design professions in enhancing local earthquake risk reduction, rather than assuming risk reduction is necessarily accomplished through governmental actions. This requires an understanding the relationship between governmental policy -- the standards adopted by governments -- and professional recommendations of architects, planners, geotechnical and structural engineers, and other design professions concerning design standards and acceptable levels of risk.

As should be evident from this brief discussion, there are noteworthy behavioral and social science considerations at the heart of earthquake risk reduction efforts. Just as physical scientists use the Puget Sound/Oregon area as a laboratory for refining their theories about seismic events, socials scientists should be encouraged to test and apply relevant theories about policy formulation and implementation in the Puget Sound/Oregon political laboratory. Social science research is necessary to help answer inquiries concerning liability, costs, and risk acceptability. More basic social science research should also be encouraged concerning such things as the relationships among nongovernmental professional practices and governmental policies.

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Appendix

Washington Seismic Safety Council
1985-86 Accomplishments and Issues

Background

Established October 1985 as an *advisory* group to the Division of Emergency Management (DEM). Prior to its establishment, the Governor vetoed legislation establishing a commission and directed the DEM to carry out the functions of the proposed commission.

Funded through September 30, 1986 out of federal funds provided DEM by FEMA. (Supplemental funding provided by FEMA to publish the council report.)

Council membership included 12 members plus ex officio representation from DEM and FEMA.

Council Activities

Met nine times with monthly meetings held beginning November 1985. Attendance fairly good with alternates participating when necessary.

Background work by/for the council consisted of:

-Inventory of state agencies -- questionnaire asking about attention to seismic issues

-Questionnaire to selected professional associations

-Consultant report by Professor James Huffman, Lewis and Clark College, Northwestern School of Law on liability issues

Completed report in September 1986. Related slide presentation prepared by Carole Martens and Linda Noson. Related publication -- *Reducing Earthquake Risks: Seismic Safety Policy*, University of Washington, Institute of Public Policy and Management -- prepared by Peter May and Linda Noson.

Dissemination of Council Findings

Report issued to list of state agencies, legislators, and other relevant individuals.

Presentation made by Linda Noson to State Board of Education. Presentations to key legislative committees considering earthquake-hazard reduction related legislation. No specific legislation introduced because of the report.

Policy Notes publication being mailed to extensive mailing list of individuals within Washington state and local government (several thousand individuals).

Issues For Future Efforts

Future of Council -- FEMA funding expired, DEM has no state funding for continued Council activity. Council membership has agreed that without strong staff support and funding, there can be no follow up in terms of detailed studies, media events, and so on that are necessary for an effective Council. Issuing reports is not enough.

Staff support -- DEM provided staff support for the council. Several factors undermined the usefulness of the support: changeover in DEM personnel during council activities; physical separation of DEM from co-chairs limiting turnaround for clerical work; limited DEM capacity for carrying out background studies; and no specific budget assigned to council chairs for Council activities. Bulk of staff work carried out by the co-chairs.

State-level advocacy -- Getting action on the recommendations of this council or any subsequent effort requires strong advocacy among state agencies and the legislature. DEM and other state agencies are restricted in their ability to undertake such advocacy, particularly concerning legislative actions. The Council itself is limited because of the part-time, volunteer nature of its membership. Lack of this advocacy is a key barrier to implementation that needs to be addressed.

Capacity to undertake background studies -- The Council was only able to raise a number of issues that are central policy questions of state policymakers including such issues as the expected losses from major earthquakes, the costs of various recommendations, and liability. Any advisory council will not have the time or resources to carryout the detailed work required to address these issues. Yet, until answers are provided concerning these and related implementation considerations, we cannot expect significant legislative or agency action.

THE POLICY OPTIONS: THE LOS ANGELES EXPERIENCE

by
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The headline on the front page of the Los Angeles Herald Examiner on March 1, 1988 proclaimed "The Big One: Next major quake may hit East, not California, geologists warn." What had made front page news in California was a statement reported from a conference in New York City: many geologists believe that the next catastrophic American earthquake could well strike not in California but in the densely populated, highly industrialized and poorly prepared eastern United States.

Similarly, two years ago USGS Seismologist Bill Bakun told Canadian television viewers that there might be an earthquake along the B.C.-Washington-Oregon coast as big as that which broke the southern coast of Chile in the 1960s, and that the possibility of a very great earthquake must be taken seriously. The quake could be, Dr. Bakun surmised, OFF the Richter scale. So, the risk exists: the Pacific Northwest and the eastern United States, like California, are not immune from a massive catastrophic earthquake. In the article "The Prediction No One Wants to Hear: the great Earthquake," author Fred Cooper contends:

> Canadian and U.S. Scientists are predicting a mammoth earthquake along the B.C.-Washington-Oregon coast, but no one is paying much attention because it might not happen for another 200 years - but then again it might be a lot sooner. Those who think it might happen sooner want to prepare for the disaster, but they've got a big selling job to do first.

Apparently, the British Columbia-Washington-Oregon coastal areas, like the eastern United States and like California, are no more immune from earthquake apathy than they are from earthquakes.

Marketing and selling earthquake awareness and pushing people to take preparedness actions is a TOUGH SELL. Actually getting through to elected officials, bureaucrats, community groups, businesses, schools and families is a never-ending struggle.

Public officials can be an especially tough nut to crack, particularly elected officials if their concerns for their community's good tend to relate to periods of time bound at either end by an election. Programs are often more likely to get funded if they can produce visible, demonstrable results within four years. Winning over the City Hall power structure is no easy task. It requires some top level commitment.

Interest and active participation by key influential people such as the mayor, a city councilmember or county supervisor, a key legislator or respected corporate leader are absolutely essential in order to gain budgetary, bureaucratic, and community support for facing up to a most unpleasant task. In my experience, this is evident both within the Los Angeles basin, where you'd expect at least lip service to be paid to the need for earthquake planning and preparedness, and in communities across the country which have tried to enhance their local commitment to emergency preparedness.

In Los Angeles we live with the knowledge that Los Angeles is earthquake country. Most of us are convinced that someday we will be faced with an earthquake of magnitude 8.0 or greater. Some day people will get up expecting to go about their business, but it won't be business as usual any more. Because the earth will convulse and rupture, and parts of Los Angeles will never be the same again.

Perhaps we will have some sort of warning in the days, hours, minutes or seconds preceding the great shock. Perhaps we won't. So we're taking actions in LA to prepare for earthquakes, so we can save lives and property during a predicted or unpredicted event. And we're planning and setting policy for response to a short-term earthquake prediction or advisory, whether it culminates in an actual earthquake or not.

Just to make sure that the populace at large takes seriously both the earthquake threat and the need to prepare, we make certain that there are reminders every once in a while. Small to moderate earthquakes rock the LA basin almost daily. In fact, they occur so often that instead of spurring us to action they often lull us into complacency. And complacency and apathy are mighty deterrents to action. Nevertheless there exists in LA what has been called an "earthquake subculture." There are "earthquake groupies." We are not laughed at much, though, because our ranks include a number of our most prominent political, corporate and community leaders who are willing to put their money where their mouth is and support and fund earthquake preparedness efforts.

In the Los Angeles basin we had on October 1st one of those reminders which the earth sends us periodically to shake us out of our earthquake apathy. It was a 5.9 magnitude earthquake which caused $358 million in damage. It also did at least $1.6 million of good, because it instantly elevated the priority of earthquake preparedness and mitigation and it created the impetus for the Mayor and Council to authorize and fund a new $1.6 million preparedness program.

The City of Los Angeles certainly isn't unique in taking the earthquake threat seriously. However, the City takes it very seriously. And it is unique in having taken seriously the science and the art of earthquake prediction with all its policy implications. What successes Los Angeles has had in these efforts are probably attributable, more than anything, to three basic strategies we employ:

1. The demonstrated commitment of prominent persons
2. The team approach, and
3. Persistence and tenacity.

We do not make one shot attempts to educate, to influence, to make an impact; we just keep hammering away. There is really nothing new or unusual about our tactics, our approach, or even most of our specific programs. But we have enjoyed a considerable degree of success because of teamwork, leadership, and persistence.

Los Angeles has a dynamic organization for emergency planning and response which involves participation by all agencies of City government. Our first source of strength is the support of top officials: the Mayor, who is the director of the Organization, the City Council, and the heads of the City's major departments, such as Police and Fire, nine of whom form the Organization's Emergency Operations Board. Our second source of strength lies in our multi-agency approach, the active participation of mid-management and staff from both City and non-City agencies who work together with us, such as the Red Cross and volunteer groups, and the utilities. We use a team approach.

This multi-agency team approach is applied to emergency response as well as emergency planning. Our plans assign responsibilities and authority to various agencies prior to catastrophic events, because we believe that a time of crisis is not a good time to get to know people and to decide who is going to be responsible for what. So our emergency plans define and distribute responsibilities widely, among all departments, and we exercise and practice our response.

An example of how we have incorporated nontraditional providers of emergency services is the Department of Recreation and Parks, which manages and controls the Public Welfare and Shelter Division during a local emergency. The American Red Cross, the Los Angeles Unified School District, and other volunteer and governmental agencies assist in providing services and support. This division arranges for housing and assistance for persons rendered homeless as a result of a disaster. Services provided include food, clothing, shelter, registration, information on available assistance programs, and rehabilitation.

We use this multi-agency approach consistently throughout planning, exercising, and actual earthquake response. Of course it doesn't always work: some people do not like to take on additional, unwanted responsibilities. However, the Mayor's involvement coupled with persistent peer group pressure work wonders.

Los Angeles' methodology is that we have found that if we want the City's decision-makers to think BIG POLICY instead of day-to-day operational requirements, we take them out of their day-to-day setting, sequester them along with the chief executive in pleasant surroundings and create an environment in which the managers themselves bring up policy questions and deliberate over them. We did this first in 1984 at the National Emergency Training Center in Emmitsburg, Maryland, in preparation for the 1984 Summer Olympics in Los Angeles. In the fall of 1986 we held our first Earthquake Prediction Workshop at Monterey, California; and then in December 1987 we followed up with a second Earthquake Prediction Workshop and Exercise at Lake Arrowhead, California. This approach works very well for us because it ensures a participative planning process and encourages team building.

How we have approached what to do with the emerging science of earthquake prediction clearly reflects our approach to emergency planning and response. It is a team project (which means it has taken ten years to accomplish what one person could have completed in four months).

Earthquake Prediction Planning is old hat in Los Angeles. A landmark report was published in 1978, the Consensus Report of Mayor Bradley's Blue Ribbon Task Force. So truly, it has taken 10 years (so far) and it has been a real team effort.

The challenge of earthquake prediction is one which most local jurisdictions have ignored. A few in California have had to respond to an earthquake prediction or advisory unprepared. But the City of Los Angeles is not comfortable with the implications of inaction, of ignoring a challenge which has been issued by both the scientific community and our state government. When confronted with disaster or the potential for disaster, local government's responsibility, it seems to us, is clear: to protect lives and property. Local officials must be prepared to save the community from any calamity which could strike. Local government is where the buck stops.

Local government's responsibility for earthquake preparedness and prediction preparedness is considerable. We are responsible for translating theory into practice, and having the guts to implement costly seismic risk reduction strategies developed by engineers and others who do not have to be reelected to stay in their jobs. We are the ones who have to convince skeptical reporters and constituents that we are doing a good job. We are the ones who will have to answer for our actions or inactions based on earthquake predictions or forecasts which may or may not be scientifically based, properly evaluated, or communicated to us officially.

A direct result of the City's work on its Earthquake Prediction Response Plan was the realization that we had a long way to go to be prepared for the actual earthquake event. It became apparent that there were many response and prediction response issues requiring interdepartmental attention. We discarded the City's obsolete Civil Defense and Disaster Ordinance and created an Emergency Operations Organization, which is now the framework for all our emergency planning efforts.

In the years since 1978 we have worked on and off on various revisions of a draft Earthquake Prediction Response Plan. We had a plan, but we knew it did not address many important policy issues, so we scheduled a policy workshop for October 1986 at Monterey, California. We went to a nice place, fed everyone good food, and took three days to develop a policy which could have been written in two hours. There were 65 participants, including a dozen major department heads. The Policy was developed through a group process, so every participant "bought into it." There was considerable feeling that the workshop was invaluable in team-building and development of interpersonal relationships among top level City administrators and managers. That was probably more important than the actual Policy which was developed.

Having plans is fine but they are not much good unless they are tested, so we planned another Workshop for last October. The October 1 earthquake caused postponement and diversion from practicing our prediction response to practicing our response to the real thing.

When we finally made it to Lake Arrowhead last December, we held a slow motion exercise designed to raise and resolve policy issues rather than test the participants. The Mayor actively participated, setting the tone for the three days. Time was included for socializing and team building. At the end of the workshop, presentations and commitments were made by each department head regarding areas they will address in upcoming months. And we found again that our somewhat esoteric or obscure efforts in earthquake prediction planning helped tremendously in identifying and facing major problems in our overall disaster preparedness planning and response functions.

This team approach, with support and participation by top officials, is being applied to other projects as well. For instance, the City's Planning Director chairs a planning team which is preparing a policy-level workshop on the recovery and reconstruction issues we will face after our projected devastating earthquake. We will work on policies related to rebuilding and land use and economic recovery. The key to these kinds of efforts is that they are an ongoing process in which the City's policymakers are actively taking part. They are true team efforts.

GOVERNMENT LIABILITY AND DISASTER MITIGATION

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THE SIGNIFICANCE OF GOVERNMENT LIABILITY

The "liability crisis" of the last few years is not limited to the medical profession and big industry. The rapid expansion in legal causes of action for accident victims and the parallel growth in the size of damage judgments have also impacted upon governments at all levels. The result is that virtually every activity undertaken by government, including disaster mitigation, raises liability concerns which must enter into the policy decisions of government officials.

For many decades, governments, like hospitals, had the benefit of legal immunities protecting against the prospect of liability actions. However, many of these immunities have been gradually stripped away leaving governments subject to the same laws which affect the conduct of private enterprises and individuals. The rationale for exposing governments to liability is rooted in the logical proposition that accident victims should not have their ability to recover depend upon whether their injury has been caused by a governmental or private actor. The victim of a collision with a government owned vehicle is surely as entitled to recovery as is the victim of a collision with a privately owned vehicle.

Notwithstanding the logic of exposing governments to liability, at least where they engage in actions for which private parties are liable, the extension of liability to governments raises special problems of public policy because of the impact which these liability actions, whether or not successful, have upon the actions of government officials and the budgets of government agencies. In an era of large damage judgments, the best defendant is one with what personal injury lawyers refer to as "deep pockets." Governments, with the exception of some local units, are generally viewed as having perhaps the deepest pockets of all.

II. THE LAWYERS VIEW OF GOVERNMENT LIABILITY

First it is helpful to understand the basic elements of a tort action without the complicating factor of government involvement. There are various types of tort actions, indeed an expanding list, but it will suffice to focus on the common law action for negligence to illustrate the way lawyers and judges understand liability problems. There are four basic elements to be proven by a plaintiff in a private tort action for negligence:

1. failure to exercise reasonable care,
2. breach of duty to exercise such care,
3. foreseeability that harm will result, and
4. actual and proximate cause.

If the plaintiff proves these four things the defendant will be held liable unless the defendant can claim some form of immunity. The defendant might also seek to prove that third parties were responsible or that the plaintiff was contributorily negligent and thereby diminish the magnitude of responsibility.

When harmful government action is involved, the situation is complicated in several respects. There is a long history of special rules for government. These rules reflect an assortment of factors, both historic inertia and considered policy. The law with respect to government liability has been in rapid flux over the last several years. Several issues must be considered where harmful government action is involved.

First there is the issue of whether the government or the government official, or both, can be held responsible. In a private employer-employee setting, the law of vicarious liability makes the employer liable for the negligent and otherwise tortious acts of his or her employees where the employees are acting within the scope of their employment. The employer is held vicariously liable for the actions of the employee, but not to the exclusion of the employee's joint liability. The doctrine's importance rests not in relieving the employee of responsibility, but in giving the injured plaintiff a defendant who can reasonably be held responsible and will also have a good prospect of affording any damages assessed.

Obviously the same concern may occur to individuals injured by the actions of government employees. Although most government employees are reasonably compensated today, few are in a position to pay large damage judgments. However, the law of vicarious liability has not historically applied to government. The reasons are deeply rooted in our history.

SOVEREIGN IMMUNITY

American law inherited the doctrine of sovereign immunity from the common law of England. Although the content and rationale of the English doctrine is a subject of debate among legal historians, the bottom line was that the sovereign, which in American law means the state (in the generic sense), could not be sued in court without its permission. This doctrine was applied to the national and state governments. The doctrine was also applied to subdivisions of state governments and in some states to municipalities as well.

After several decades of Congressional foot dragging, the federal government waived some of its immunity in the Federal Tort Claims Act of 1946. Although the Act purports to be a general waiver of immunity in tort actions, it has exceptions which preserve significant immunities. Most states have adopted similar legislative waivers of immunity, although in a few states the doctrine has been overturned by judicial decision. The Washington Tort Claims Act was adopted in 1961. By its terms the waiver has no exceptions, but the Washington Supreme Court has held that the waiver is subject to a discretionary function exception. The Oregon legislature enacted a Tort Claims Act in 1967 which is a general waiver of immunity subject to express exceptions including one for discretionary functions. Both states apply their waivers of immunity to political subdivisions and municipalities.

In many states municipal governments have been subjected to special rules of immunity based upon a distinction between governmental and proprietary functions. In some states the immunity of municipalities has been eliminated by the courts on the theory that municipalities have none of the characteristics of sovereignty and therefore should have no immunities. However, the dominant view has been that municipalities have distinct types of functions, some of which require immunity in a democratic system.

OFFICIAL LIABILITY

Generally the law of government immunity has no impact upon the liabilities of individual government employees. One of the historic justifications for no vicarious liability was that tortious behavior by a public official was not within the scope of their official duties and therefore could not be the basis of government liability under vicarious liability doctrine. Even where the government can be held liable, however, the issue of official liability is an independent matter generally governed by the regular tort law except where there is a specific statutory immunity. For example, Washington law immunizes the elected officials of special purpose districts when they are acting within the scope of their official duties or employment. (RCW 4.96.040 [1981]) Another provision of the Washington Code immunizes anyone engaged in mine rescue or recovery work (RCW 38.52.198 [1985]). Of the most relevance to routine emergency work, if there be such a thing, is RCW 38.52.180 which immunizes emergency workers for harm resulting from their authorized emergency activities unless the result of wilful misconduct, gross negligence or bad faith.

Absent some statutory immunity like those noted, the application of which are subject to judicial interpretation, the public official is situated no differently than any private tortfeasor, except that the public official has also to cope with the possibility of legal action under Section 1983 of the Civil Rights Act.

SECTION 1983 ACTIONS

State and local officials are subject to liability for damages under federal civil rights legislation for the "deprivation of any rights privileges, or immunities secured by the Constitution and laws of the United States. Actions pursuant to this federal law have increased dramatically in recent years, and the courts have found officials liable for damages for actions which formerly appeared to have no constitutional relevance. Since 1978, municipalities have been subject to damage actions under the federal civil rights laws, and although the traditional immunities of the State protect it and its political subdivisions from liability, the State of Washington has accepted liability for damages levied against public officials acting in good faith within the scope of official duties.

STATE DEFENSE AND INDEMNIFICATION OF OFFICIALS

Having stated a picture of official vulnerability to lawsuits based upon negligent behavior in the performance of official's duties, I should hasten to point out that the Washington Tort Claims Act provides that state officials may request that the Attorney General defend an action brought against a state official when that official is acting within the scope of official duties. (RCW 4.92.060) The Act also provides that the state will be responsible for damages levied against state officials.

POLICY IMPLICATION OF GOVERNMENT LIABILITY

Public officials should be as concerned about the policy consequences of their actions as they are about the liability consequences. We have a tendency to look at the prospect of liability as an outcome to be avoided at all costs. In fact, I would suggest that liability has simply to do with the distribution of costs and with the existence of those costs. To some extent we can influence the existence of those costs by deterring negligent behavior. But to some extent those costs will occur either because we cannot avoid them or because they are incurred to avoid higher costs of another type. This is particularly true in the case of emergency services where the government is often seeking to avoid very large costs. Thus it is important to weigh the prospect that the best solution is government liability from the point of view of deterrence of negligent behavior as well as from the point of view of cost distribution.

With regard to the issue of whether the costs should rest with the government or with the public official, I would generally be of the view that with respect to negligence, as opposed to gross or wilful negligence, the government should bear the responsibility. Otherwise we risk losing the benefits of aggressive decision making. The government has ample means to assure that employees have incentive to avoid negligent conduct.

GLOSSARY

Accelerogram. The record from an accelerometer showing acceleration as a function of time. The peak acceleration is the largest value of acceleration on the accelerogram.

Acceptable Risk. A probability of occurrences of social or economic consequences due to earthquakes that is sufficiently low (for example in comparison to other natural or manmade risks) as to be judged by 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 is active if, because of its present tectonic setting, it can undergo movement from time to time in the immediate geologic future. This active state exists independently of the geologists' ability to recognize it. Geologists have used a number of characteristics to identify active faults, such as historic seismicity or surface faulting, geologically recent displacement inferred from topography or stratigraphy, or physical connection with an active fault. However, not enough is known of the behavior of faults to assure identification of all active faults by such characteristics. Selection of the criteria used to identify active faults for a particular purpose must be influenced by the consequences of fault movement on the engineering structures involved.

Attenuation. A decrease in seismic signal strength with distance which depends on geometrical spreading and the physical characteristics of the transmitting medium that cause absorption and scattering.

Attenuation law. A description of the average behavior of one or more characteristics of earthquake ground motion as a function of distance from the source of energy.

b-value. A parameter indicating the relative frequency of earthquakes of different sizes derived from historical seismicity data.

Capable fault. A capable fault is a fault whose geological history is taken into account in evaluating the fault's potential for causing vibratory ground motion and/or surface faulting.

Design earthquake. A specification of the ground motion at a site based on integrated studies of historic seismicity and structural geology and used for the earthquake-resistant design of a structure.

Design spectra. Spectra used in earthquake-resistant design which correlate with design earthquake ground motion values. A design spectrum is typically a broad band specturm having broad frequency content. The design spectrum can be either site-independent or site-dependent. The site-dependent spectrum tends to be less broad band as it depends at least in part on local site conditions.

Design time history. One of a family of time histories used in earthquake-resistant design which produces a response spectrum enveloping the smooth design spectrum, for a selected value of damping.

Duration. A description of the length of time during which ground motion at a site exhibits certain characteristics such as being equal to or exceeding a specified level of acceleration such as 0.05g.

Earthquake hazards. Natural events accompanying an earthquake such as ground shaking, ground failure, surface faulting, tectonic deformation, and inundation which may cause damage and loss of life during a specified exposure time. See earthquake risk.

Earthquake risk. The probability that social or economic consequences of earthquakes, expressed in dollars or casualties, will equal or exceed specified values at a site during a specified exposure time.

Earthquake waves. Elastic waves (P, S, Love, Rayleigh) propagating in the Earth, set in motion by faulting of a portion of the Earth.

Effective peak acceleration. The value of peak ground acceleration considered to be of engineering significance. It can be used to scale design spectra and is often determined by filterng the ground-motion record to remove the very high frequencies that may have little or no influence upon structural response.

Epicenter. The point on the Earth's surface vertically above the point where the first fault rupture and the first earthquake motion occur.

Exceedence probability. The probability (for example, 10 percent) over some exposure time that an earthquake will generate a level of ground shaking greater than some specified level.

Exposure time. The period of time (for example, 50 years) that a structure or facility is exposed to earthquake hazards. The exposure time is sometimes related to the design lifetime of the structure and is used in seismic risk calculations.

Fault. A fracture or fracture zone in the Earth along which displacement of the two sides relative to one another has occurred parallel to the fracture. See Active and Capable faults.

Focal depth. The vertical distance between the earthquake hypocenter and the Earth's surface.

Ground motion. A general term including all aspects of motion; for example, particle acceleration, velocity, or displacement; stress and strain; duration; and spectral content generated by an earthquake, a nuclear explosion, or another energy source.

Intensity. A numerical index describing the effects of an earthquake on the Earth's surface, on man, and on structures built by him. The scale in common use in the United States today is the Modified Mercalli scale of 1931 with intensity values indicated by Roman numerals from I to XII. The narrative descriptions of each intensity value are summarized below.

I. Not felt--or, except rarely under specially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway--doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body of striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink or clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V. Felt indoors by practially all, outdoors by many or most; outdoors direction estimated. Awakened many or most. Frightened few--slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes and glassware to some extent. Cracked windows--in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors and shutters abruptly. Pendulum clocks stopped, started or ran fast, or slow. Move small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees and bushes shaken slightly.

VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees and bushes shaken slightly to moderately. Liquid set in strong motion. Small bells rang--church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knickknacks, books, pictures. Overturned furniture in many instances. Move furnishings of moderately heavy kind.

VII. Frightened all--general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows and furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII. Fright general--alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly--branches and trunks broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse, racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls, cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changes level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipelines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures, remained standing. Destroyed large well-built bridges by the wrecking of supporting piers or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipelines buried in each completely out of service.

XII. Damage total--practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air.

Liquefaction. The primary factors used to judge the potential for liquefaction, the tranformation of unconsolidated materials into a fluid mass, are: grain size, soil density, soil structure, age of soil deposit, and depth to ground water. Fine sands tend to be more susceptible to liquefaction than silts and gravel. Behavior of soil deposits during historic earthquakes in many parts of the world show that, in general, liquefaction susceptibility of sandy soils decreases with increasing age of the soil deposit and increasing depth to ground water. Liquefaction has the potential of occurring when seismic shear waves having high acceleration and long duration pass through a saturated sandy soil, distorting its granular structure and causing some of the void spaces to collapse. The pressure of the pore water between and around the grains increases until it equals or exceeds the confining pressure. At this point, the water moves upward and may emerge at the surface. The liquefied soil then behaves like a fluid for a short time rather than as a soild.

Magnitude. A quantity characteristic of the total energy released by an earthquake, as contrasted to intensity that describes its effects at a particular place. Professor C. F. Richter devised the logarithmic scale for local magnitude (M_L) in 1935. Magnitude is expressed in terms of the motion that would be measured by a standard type of seismograph located 100 km from the epicenter of an earthquake. Several other magnitude scales in addition to M_L are in use; for example, body-wave magnitude (m_b) and surface-wave magnitude (M_S), which utilize body waves and surface waves, and local magnitude (M_L). The scale is theoretically open ended, but the largest known earthquakes have had M_S magnitudes near 8.9.

Region. A geographical area, surrounding and including the construction site, which is sufficiently large to contain all the geologic features related to the evaluation of earthquake hazards at the site.

Response spectrum. The peak response of a series of simple harmonic oscillators having different natural periods when subjected mathematically to a particular earthquake ground motion. The response spectrum may be plotted as a curve on tripartite logarithmic graph paper showing the variations of the peak spectral acceleration, displacement, and velocity of the oscillators as a function of vibration period and damping.

Return period. For ground shaking, return period denotes the average period of time or recurrence interval between events causing ground shaking that exceeds a particular level at a site; the reciprocal of annual probability of exceedance. A return period of 475 years means that, on the average, a particular level of ground motion will be exceeded once in 475 years.

Risk. See earthquake risk.

Rock. Any solid naturally occurring, hard, consolidated material, located either at the surface or underlying soil. Rocks have a shear-wave velocity of at least 2,500 ft/sec (765 m/s) at small (0.0001 percent) levels of strain.

Seismic Microzoning. The division of a region into geographic areas having a similar relative response to a particular earthquake hazard (for example, ground shaking, surface fault rupture, etc.). Microzoning requires an integrated study of: 1) the frequency of earthquake occurrence in the region, 2) the source parameters and mechanics of faulting for historical and recent earthquakes affecting the region, 3) the filtering characteristics of the crust and mantle along the regional paths along which the seismic waves travel, and 4) the filtering characteristics of the near-surface column of rock and soil.

Seismic zone. A generally large area within which seismic design requirements for structures are uniform.

Seismotectonic province. A geographic area characterized by similarity of geological structure and earthquake characteristics. The tectonic processes causing earthquakes are believed to be similar in a given seismotectonic province.

Source. The source of energy release causing an earthquake. The source is characterized by one or more variables, for example, magnitude, stress drop, seismic moment. Regions can be divided into areas having spatially homogeneous source characteristics.

Strong motion. Ground motion of sufficient amplitude to be of engineering interest in the evaluation of damage due to earthquakes or in earthquake-resistant design of structures.

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GROUND MOTIONS FROM SUBDUCTION-ZONE EARTHQUAKES

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ABSTRACT

A total of 258 horizontal components of accelerogram data recorded at soil sites during thrust, normal, and strike-slip earthquakes occurring in seven subduction zones around the Pacific Ocean were analyzed. The results of statistical analyses of 5 per cent damped pseudo-velocities (PSV), computed from these accelerograms at 10 periods (T) between 0.1 and 4 sec, indicated no significant differences in the average PSV levels of the thrust, normal, and strike-slip data from the Northern Honshu zone. Each of these groups of Northern Honshu data, which together comprised one-half of the total data base, were fit equally well by the same attenuation model. The analyses also revealed that at intermediate periods ($0.8 \leq T < 3$ sec), the PSV observed at stiff-soil sites within the Northern Honshu, Nankai, Kuril, Mexico, and Alaska zones were, on the average, significantly greater than the PSV observed at similar sites in the Peru/Northern Chile and New Britain/Bougainville zones. This observation indicates that differences in the source and/or travel-path characteristics between the two groups accounted for the differences in PSV. Independent evidence supporting source differences is the correlation noted between PSV in this period band and the characteristic source complexities for these zones, which Hartzell and Heaton inferred from the teleseismic data of the larger magnitude earthquakes. Certain anomalous tectonic characteristics of the New Britain/Bougainville zone were noted that may have contributed in some systematic manner to the relatively unusual spectral characteristics of the ground motions recorded on stiff-soil sites within this zone.

Some of the differences in the PSV among the zones at intermediate and long periods were probably the result of differences in local geologic characteristics. Geology greatly influenced the Mexican PSV data from soft-soil sites. To a lesser extent, geology probably affected the Alaskan data, which were recorded mostly on deep stiff soils, and the New Britain/Bougainville data recorded at Yonki, which is underlain by softer soil deposits.

INTRODUCTION

The characteristics of ground motions generated during subduction-zone earthquakes is a subject that has received little attention in the United States relative to studies of ground motions generated by transform-margin earthquakes in the Western United States and intraplate earthquakes in the Eastern United States. However, the recent suggestion of the possibility of a large subduction-zone earthquake in the Pacific Northwest (Heaton and Kanamori, 1984) and the well-documented occurrences of such earthquakes in Alaska and other regions of the world indicate the need for a better understanding of the ground motions from these earthquakes.

A considerable number of seismotectonic studies, many of which are referenced in the next section, have been conducted for subduction zones around the Pacific rim. Recently, sufficient ground-motion data became available to permit a systematic study and comparison of the ground motions among these subduction zones. For this study, processed and unprocessed accelerograms or their response spectra were compiled from various sources (Denham and Small, 1971; Prince *et al.*, 1976; Brady and Perez, 1977; Rascon *et al.*, 1977; Espinosa *et al.*, 1978; Crouse *et al.*, 1980; Mori and Crouse, 1981; Beavan and Jacob, 1984; Silverstein *et al.*, 1986; Anderson *et al.*, 1987; the Japan Port and Harbour Research Institute; and the U.S. National Oceanic and Atmospheric Administration). The unprocessed accelerograms were corrected using methods similar or identical to those described in Trifunac and Lee (1973). The 5 per cent damped pseudo-velocities (PSV), which were computed from the horizontal components of the corrected accelerograms at 10 periods between 0.1 and 4.0 sec, represented the ground-motion data base that was analyzed. Some accelerograms, recorded during the larger subduction-zone earthquakes, and their associated velocity time histories have been examined in a parallel study by Hartzell and Heaton (1985b) and Heaton and Hartzell (1986). They identified similarities between these strong motion records and the source-time functions derived from teleseismic data recorded in Pasadena during these events (Hartzell and Heaton, 1985a).

In this investigation, statistical studies of the PSV data, using regression analyses and analysis of covariance techniques, were conducted to determine: (1) the potential effect of focal-mechanism type on ground motion and (2) those subduction zones in which the recorded ground motions were similar or significantly different. Possible reasons for these differences were explored by examining the regional and local geology and the seismotectonic characteristics of the subduction zones.

Data Base

Sesimotectonic characteristics of the subduction zones. The locations of the seven subduction zones considered in this study are shown as wide lines in Figure 1. Certain seismologic, geologic, and tectonic characteristics of these zones are summarized in Table 1. The information comprising this table was compiled from many references; the principal ones are listed at the end of the table. Most of the column headings are self-explanatory, except possibly column 14 ("Q structure") and column 17 ("Seismic Slip"). The designation "Low Q" refers to zones of extremely high attenuation beneath the high plateau of Peru, beneath the Sea of Japan, and beneath the Sea of Okhotsk (Kuril zone). The other zones in these and other subduction zones have relatively low attenuation properties and have been designated as "Normal" in the table. However, it should be noted that little is known about the Q structure from 0 to 150 km beneath the Earth's surface, the depth range of nearly all of the earthquakes in this study. Because the paths of the seismic waves travel through this portion of the lithosphere and upper mantle before arriving at the recording stations, detailed information on the Q structure at these shallow depths eventually will be needed to better interpret the recorded ground motions. Nonetheless, the Q structure, as it is presently known, is provided in Table 1 for completeness. The values in the "seismic slip" column are the percentages of plate-convergence rates that are released as slip during major earthquakes.

The categories in Table 1 were selected because they are commonly discussed in the literature as having some bearing on the mode and mechanism of the subduction process or as being a direct result of the subduction. Some or all of this information may be indirectly related to the earthquake source and travel path characteristics, which in turn would affect the characteristics of the recorded ground motions. This

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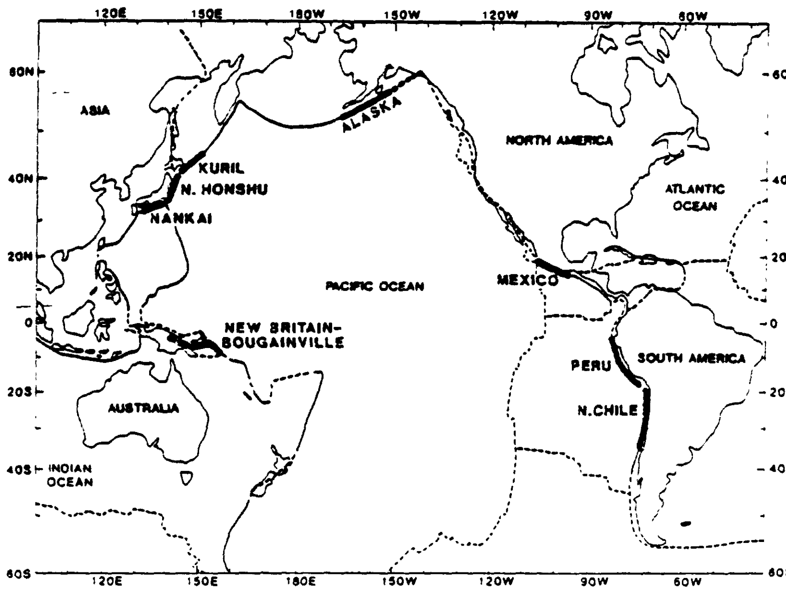

FIG. 1. Location map of subduction zones around the Pacific Ocean. Solid lines represent subduction zones with well-developed seafloor trenches; dashed lines indicate subduction zones without well-developed trenches or indicate other lithospheric plate margins. The labeled wide solid lines and wide dashed lines are the zones considered in this study.

possibility was explored to a limited extent in this study by examining possible correlations between the seismotectonic data and the ground-motion data.

Accelerogram data. The relevant information on the recording conditions of the accelerogram data base compiled for this study is given in Table 2. For all but two of the entries, the PSV from both horizontal components of the corresponding accelerograms were used in the subsequent analyses. The exceptions were the accelerograms recorded at Pajaritos, Mexico, and Santiago, Chile, for which only one horizontal component was available. The total of 258 components indicated in Table 2 were distributed among the various subduction zones according to type of focal mechanism (thrust, normal, and strike slip) as follows

	No. of Components			
Subduction Zone	Thrust	Normal	Strike-Slip	Total
Northern Honshu	98	22	8	128
Nankai	22	10	6	38
Kuril	14	4	4	22
Alaska	4	6	—	10
Peru/Northern Chile	13	6	—	19
Mexico	19	6	—	25
New Britain/Bougainville	12	4	—	16
Total	182	58	18	258

All earthquakes in the data base occurred within or near the Benioff-Wadati zone of the subduction-zone regions. Focal mechanisms were compiled for these earthquakes from the appropriate references listed at the end of Table 2. Although most of the earthquakes were thrust events, a significant number were normal. As expected, relatively few were strike-slip events. All great earthquakes ($M_w \geqq 8.0$) in

TABLE 1

SUMMARY OF SUBDUCTION ZONE CHARACTERISTICS*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Subduction Zone	Overriding Plate / Subducted Plate	Age of Subducted Plate†	Convergence Rate (cm/yr)	Dip*‡	Contact Width§ (km)	Convergence Angle	Arc Volcanism	Back-Arc Spreading	Seafloor Topography	Maximum Subduction Depth (km)	Maximum Historical Earthquake	Maximum Rupture Lengths (km)	Q Structure	Maximum Seismic Moments (dyne-cm)	Stress Drop (bars)	Seismic Slip (%)
Alaska	Continental / Oceanic	ET	6-7	15 / 40-50	200-400	Nearly perpendicular	Yes	No	Rough	250	$M_w = 9.2$ $M_s = 8.7$	100-1000	Normal	10^{29}-10^{30}	Low to very high (10-5000)	100 ?
Northern Honshu	Continental / Oceanic	LJ-EK	10	10 / 25	150	Nearly perpendicular	Yes	No	Rough	600	$M_w = 8.2$ $M_s = 8.7$	100-200	Low Q-normal	10^{27}-10^{28}	High (100-1000)	40
Mexico	Continental / Oceanic	EM-P	6-7	10-20 / 20-45	100-180	Nearly perpendicular	Yes	No	Rough	200	$M_s = 8.2$	100-200	Normal	10^{27}-10^{28}	Low (1-30)	40-80
Peru N. Chile	Continental / Oceanic	A-O	8-9.5	15 / 25-40	120-700	Nearly perpendicular	Partially	No	Rough	650	$M_w = 8.2$ $M_s = 8.4$	150-300	Low Q-normal	10^{28}	Low to moderate (10-100)	?
New Britain-Bougainville	Ocean-Semicont / Oceanic	M	6-10	20 / 45-90	75-100	Nearly perpendicular to oblique	Yes	No	Smooth	300 in W 500 in E	$M_w = 8.1$ $M_s = 7.9$	100-250	Normal	10^{27}-10^{28}	Low (10-20)	50
Nankai	Continental / Oceanic	EM	<4	15 / 15	115	Very oblique	No	No	Smooth	100	$M_w = 8.5$ $M_s = 8.5$	150-500	Normal	10^{28}	Low (30)	70
Kuril	Continental / Oceanic	EK	9-10	20-30 / 45	100-120	Nearly perpendicular	Yes	No	Smooth	670	$M_w = 8.5$ $M_s = 8.3$	100-200	Low Q-normal	10^{27}-10^{29}	Low to high (25-1100)	25

* The primary sources of these data include numerous maps and journal articles, many of which are compilations from other sources. The principal sources for each subduction zone are listed below:

Alaska: Archambeau (1978), Davies *et al.* (1981), Grow (1973), House and Boatwright (1980), Jacob *et al.* (1977), Jin and Herrin (1980), Lay *et al.* (1982), Pulpan and Keinle (1979), Ruff and Kanamori (1980), Spence (1977), Von Huene (1979), Von Huene and Shor (1969).

Northern Honshu: Archambeau (1978), Kanamori (1977), Lay *et al.* (1982), McCann *et al.* (1978), Ruff and Kanamori (1980), Sacks (1977), Yoshii (1977).

Mexico: Chael and Stewart (1982), Dean and Drake (1978), McCann *et al.* (1978), Molnar and Sykes (1969), Nixon (1982), Singh *et al.* (1981, 1984).

Peru-N. Chile: Archambeau (1978), Couch *et al.* (1981), Hussong and Wipperman (1981), James (1978), Lay *et al.* (1982), McCann *et al.* (1978), Nur and Ben-Avraham (1981), Ruff and Kanamori (1980), Sacks (1977), Stauder (1975).

New Britain-Bougainville: Denham (1973), Johnson and Molnar (1972), Lay and Kanamori (1980), McCann *et al.* (1978), Ripper (1982), Taylor (1979), Weissel *et al.* (1982), Wiebenga (1973).

Nankai: Ando (1975), Kanamori (1977), Lay *et al.* (1982).

Kuril: Archambeau (1978), Fedotov *et al.* (1982), Lay *et al.* (1982), McCann *et al.* (1978), Ruff and Kanamori (1980).

† Geologic age abbreviations: E = early; L = late; J = Jurassic; K = Cretaceous; T = Tertiary; A = Eocene; O = Oligocene; M = Miocene; P = Pliocene.

‡ Two dips are given; the upper number is the dip of the contact between the two plates at about 20-30 km depth; the bottom number is the dip of the subducted plate below the plate interface.

§ Refers to the downdip distance along which the brittle lithospheres of each plate are in direct contact.

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TABLE 2

EARTHQUAKE PARAMETERS FOR THE ACCELEROGRAM DATA BASE

Subduction Zone	Date (yr/mo/dy)	M	F	h (km)	Δ (km)	R (km)	Station
Northern Honshu,	56/02/14	6.0	N	45	21	50	TK024
Japan	56/02/14	6.0	N	45	23	51	TK024
	62/04/30	6.5	T	35	64	69	TH001
	63/05/08	6.1	T	40	53	63	KT001
	63/05/08	6.1	T	40	53	63	KT003
	63/08/04	5.1	T	39	35	52	KT014
	64/02/05	6.0	T	54	36	65	KT001-a
	64/02/05	6.0	T	54	36	65	KT001-b
	64/02/05	6.0	T	54	36	65	KT001-c
	64/11/14	5.1	N	69	8	69	KT001
	67/11/19	6.0	T	48	50	69	KT001
	68/05/16	8.2	T	20	90	129	HK003
	68/05/16	8.2	T	20	319	170	HK009
	68/05/16	8.2	T	20	159	56	HK013
	68/05/16	8.2	T	20	243	113	TH020
	68/05/16	8.2	T	20	187	71	TH029
	68/05/16	7.5	N	26	236	115	HK003
	68/05/16	7.5	N	26	75	90	HK013
	68/07/01	6.1	T	68	58	91	TK056
	68/07/05	6.4	T	44	62	76	TH005
	68/10/08	5.3	T	73	38	82	KT004
	70/01/21	6.7	T	25	46	51	HK003
	71/06/13	5.3	T	55	35	65	KT001
	71/08/02	7.0	N	45	196	201	HK004
	71/10/11	5.2	T	40	12	42	KT050
	72/02/29	7.1	T	50	259	240	KT004
	73/11/19	6.4	T	56	107	121	TH033
	74/03/03	6.1	T	49	39	63	KT036
	74/07/08	6.3	T	45	73	87	KT036
	74/09/04	5.6	S	52	42	67	TH029
	74/11/09	6.5	T	125	15	126	HK016
	74/11/16	6.1	T	44	38	58	KT036
	78/06/12	7.7	T	40	116	102	TH019
	78/06/12	7.7	T	40	120	102	TH033
	68-05-16	8.2	T	20	258	259	HK004
	68-06-12	7.2	T	31	189	192	TH029
	68-07-04	5.2	S	100	70	122	KT004
	68-09-21	6.9	T	57	196	204	TH029
	70-01-21	6.7	T	25	122	125	HK004
	70-04-01	5.8	T	75	101	126	TH029
	71-08-02	7.0	N	45	262	266	HK003
	72-02-29	7.1	T	50	285	289	Chiba-S
	72-02-29	7.1	T	50	304	308	TK056
	72-03-20	6.4	S	80	308	318	HK003
	72-03-20	6.4	S	80	55	97	TH029
	72-12-04	7.2	T	66	253	261	KT004
	72-12-04	7.2	T	66	402	407	Onahama-ji-S
	74-11-09	6.5	T	125	220	251	HK004
	75-10-30	6.0	T	60	174	184	HK003
	78-02-20	6.7	N	50	230	235	Onahama-ji-S
	78-02-20	6.7	N	50	205	211	Sakata-S
	78-06-12	7.7	T	40	173	178	Onahama-ji-S
	78-06-12	7.7	T	40	249	252	Akita-S
	78-06-12	7.7	T	40	273	276	TH029
	78-06-12	7.7	T	40	373	375	KT004

TABLE 2—*Continued*

Subduction Zone	Date (yr/mo/dy)	M	F	h (km)	Δ (km)	R (km)	Station
	81-01-23	7.1	N	130	225	260	TH029
	81-01-23	7.1	N	130	103	166	HK003
	82-03-21	7.1	T	40	137	143	HK003
	82-03-21	7.1	T	40	64	75	Tokachi-M
	82-07-23	7.0	T	30	118	122	Kashima-Zokan-S
	82-07-23	7.0	T	30	207	209	TK056
	83-05-26	7.8	T	14	107	108	Akita-S
	83-05-26	7.8	T	14	173	174	Sakata-S
	83-05-26	7.8	T	14	204	204	TH029
Nankai, Japan	65/04/20	6.1	S	40	21	45	CB002
	65/04/20	6.1	S	40	30	50	CB005
	66/11/12	5.5	S	20	19	28	KS005
	68/04/01	7.5	T	37	60	75	KS002
	68/04/01	7.5	T	37	123	135	KS003
	68/04/01	7.5	T	37	167	166	SK005
	68/04/01	7.5	T	37	80	88	SK006
	68/08/06	6.6	N	48	116	106	CG005
	68/08/06	6.6	N	48	14	54	SK006
	69/04/21	6.5	T	39	43	66	KS002
	70/07/26	6.7	T	47	21	51	KS002
	70/07/26	6.7	T	47	70	84	KS003
	70/07/26	6.1	T	47	21	51	KS002
	71/01/05	6.1	N	44	64	78	KK026
	75/04/21	6.4	N	12	41	37	KS014
	74-05-09	6.9	N	10	52	53	Shimizu-Sekitan-S
	78-05-23	6.7	T	160	141	213	Miyazaki-M
	78-07-04	6.2	T	120	226	256	SK005
	78-07-04	6.2	T	120	87	148	Miyazaki-M
Kuril, Japan	62/04/23	7.0	N	60	75	100	HK005
	65/10/26	7.1	T	159	162	227	HK004
	68/08/07	5.7	T	68	32	75	HK004
	72/05/11	5.8	T	63	33	71	HK004
	73/06/17	7.8	T	41	112	134	HK004
	69-01-19	7.1	N	238	231	332	HK004
	69-08-12	8.2	T	43	287	290	HK004
	73-06-24	7.1	T	30	194	196	HK004
	78-03-25	7.6	T	40	462	464	HK004
	78-12-06	7.7	S	100	284	301	HK004
	78-12-06	7.7	S	100	401	413	Tokachi-M
Alaska	75/01/01	6.0	N	58	81	100	2702 (Anchorage)
	75/01/01	6.0	N	58	82	100	2703 (Anchorage)
	75/01/01	6.0	N	58	79	98	2704 (Anchorage)
	79/02/28	7.6	T	13	75	59	2712 (Icy Bay)
	79/02/28	7.6	T	13	166	125	2728 (Yakutat)
Peru/N. Chile	66/10/17	8.1	T	38	236	239	4302 (Lima)
	70/05/31	8.0	N	43	372	300	4302 (Lima)
	71/11/29	5.3	T	57	127	138	4302 (Lima)
	74/01/05	6.6	N	98	74	123	4302 (Lima)
	74/01/05	6.6	N	98	73	123	4303 (Lima)
	74/10/03	8.1	T	13	86	70	4302 (Lima)
	74/10/03	8.1	T	13	91	70	4304 (Lima)
	74/11/09	7.2	T	6	95	70	4302 (Lima)
	74/11/09	7.2	T	6	103	70	4305 (Lima)
	71/07/09	7.5	T	59	140	152	Santiago, Chile

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TABLE 2—*Continued*

Subduction Zone	Date (yr/mo/dy)	M	F	h (km)	Δ (km)	R (km)	Station
Mexico	62/05/11	7.0	T	37	260	263	+Alameda Central, D.F.
	62/05/19	7.0	T	19	260	261	+Alameda Central, D.F.
	64/07/06	6.7	N	100	240	260	+E. M. Gonzalez, D.F.
	64/07/06	6.7	N	100	240	260	+P. E. Hidalgo, D.F.
	75/03/14	5.5	N	155	40	160	6529 (T. Gutierrez)
	78/11/29	7.7	T	18	299	300	+6518 (Minatitlan)
	78/11/29	7.7	T	18	329	330	+6520 (Pajaritos)
	78/11/29	7.7	T	18	119	120	6519 (Oaxaca)
	85/09/19	8.0	T	28	469	469	Sismex Puebla
	85/09/19	8.0	T	28	380	380	Tacubaya, D.F.
	85/09/19	8.0	T	28	381	381	+Sismex Viveros, D.F.
	85/09/19	8.0	T	28	389	389	+C. de Abastos F., D.F.
	85/09/19	8.0	T	28	385	385	+Sec. de Comm., D.F.
New Britain/Bougainville	70/10/31	7.0	T	45	154	160	+Yonki, Upper Ramu
	70/11/12	6.5	T	22	159	161	+Yonki, Upper Ramu
	71/07/14	8.0	T	43	200	205	Panguna
	71/07/26	8.1	T	43	298	301	Panguna
	71/09/25	7.0	N	111	43	119	Lae Base
	71/10/28	6.5	T	107	250	272	Rabaul
	72/01/19	6.6	N	100	203	226	+Yonki, Upper Ramu
	83/03/18	7.8	T	89	271	285	Panguna

Notes: M = magnitude (M_w, M_S, or M_{JMA}); F = fault type (T = thrust, N = normal; S = strike slip); h = focal depth; Δ = epicentral distance; R = center-of-energy-release distance. Station names preceded by a plus denote sites on soft soil. Data from the subduction zones were obtained from Anderson *et al.* (1987), Beavan and Jacob (1984), Boatwright (1980), Brady and Perez (1977), *Bulletin of the International Seismological Centre*, Chael and Stewart (1982), Crouse *et al.* (1980), Denham (1977), Denham and Small (1971), Dewey and Spence (1979), G. Dunphy (personal communication, 1985), Dziewonski and Woodhouse (1983), Dziewonski *et al.* (1983), Espinosa *et al.* (1978), Fujita and Kanamori (1981), Hartzell and Heaton (1985a), Ichikawa (1971), Jacob and Hauksson (1983), Kanamori (1971), Kasahara and Sasatini (1985), LeFevre and McNally (1985), K. McCue (personal communication, 1986), Molnar and Sykes (1969), Mori and Crouse (1981), Prince *et al.* (1976), Rascon *et al.* (1977), Silverstein *et al.* (1986), and Stauder and Mualchin (1976). For the three Japanese subduction zones, dates indicated with slashes (/) represent ground-motion data from Mori and Crouse (1981). Dates indicated with dashes (-) represent data supplied in 1984 by the Japan Port and Harbour Research Institute and Ann Mori of Kisojiban Consultants, Ltd. The four-digit numbers designating the Alaskan, Peruvian, and Mexican stations were assigned by the U.S. Geological Survey (Switzer *et al.*, 1981).

the data base, except one, were thrust events. The notable exception is the 31 May 1970, Peruvian earthquake (M_w = 8.0), a normal-faulting event which occurred near the Peru trench.

Note that approximately half of the components were recorded during earthquakes occurring in the subduction zone adjacent to the northern portion of Honshu Island, Japan. The number of components from the other zones is much smaller, and questions regarding the adequacy of the data sample size are certainly relevant. For every zone, the sample size could have been enlarged by admitting accelerograms that were recorded, for example, at sites on geologic media other than soil. Had rock-site records been considered, the Alaskan data base would have increased substantially, but the data base for the other zones would have only slightly increased. Thus, a decision was made not to use rock-site data in order to remove one variable from the analysis. Another example of accelerograms that were not selected were those generated by earthquakes definitely not associated with a Benioff zone, or earthquakes with magnitudes and epicentral distances well outside the range of most of the selected data. Partly for this latter reason and because of the small sample size, the eight horizontal components of the accelerograms recorded at Olympia and Seattle, Washington, during the 1949 and 1965 earthquakes, which occurred within the Juan de Fuca subduction zone, were not included in this study.

Accelerogram data recorded by the SMA-1 accelerograph network (Chang, 1984; Chang and Chiu, 1984) and the SMART-1 array (Bolt *et al.*, 1982) in Taiwan were also not included primarily because the causative earthquakes occurred in a region where the tectonics are complex and include both transform faulting and subduction. Thus, most of the earthquakes could not clearly be associated with either the transform faulting or the Benioff-Wadati zones.

Accelerogram data recorded during the 3 March 1985, Chile, earthquake (M_S = 7.8; EERI, 1985), which would have greatly enhanced the data base from the Peru/Northern Chile subduction zone, were not available for this study.

The accelerogram data used in this study were generally recorded on shallow, stiff soil and sedimentary deposits between about 5 to 25 m deep over Tertiary or older bedrock. The notable exceptions are some of the data from Mexico, which were recorded on deeper, much softer alluvial and sedimentary deposits in a basinal structural configuration. Other stations underlain by relatively soft and/or deep soil deposits or sediments include all the Alaskan stations and the station at Yonki, Upper Ramu, in New Britain/Bougainville. The stations at Anchorage, Alaska, are underlain by stiff alluvial material on the order of 100 m deep over Tertiary bedrock (Schmoll and Barnwell, 1984; Idriss, 1985; D. Cole, personal communication, 1987). Both the Yakutat and Icy Bay stations in southeast Alaska are underlain by generally stiff sediments, which are more than 200 m thick at Yakutat and probably much thicker at Icy Bay (Yehle, 1975; G. Plafker and B. Molnia, personal communications, 1987). The Yonki station is underlain by 110 m of poorly consolidated and unconsolidated lake sediments (K. McCue, personal communication, 1986). The potential effects from all of the above-noted differences in local geology were considered in the interpretation of the results of the data analyses.

The moment magnitude was used when known, which was generally the case for the larger earthquakes greater than magnitude 7.5. The moment-magnitude scale better represents the true size of great earthquakes, and its use in this study was preferred. When moment magnitudes were not available, surface-wave or Japan Meteorological Agency magnitudes were used. These magnitudes were used for the smaller earthquakes approximately less than magnitude 7.5. They were considered to be equivalent to the moment magnitudes based on Utsu (1982) and Heaton *et al.* (1986).

The center-of-energy-release distance was defined as the distance from the recording station to a point on the fault rupture where the energy was considered to be concentrated. For all earthquakes less than magnitude 7.5, this point was assumed to be the hypocenter. For most of the larger events, this point was the centroid of the fault plane defined by the aftershocks. If special studies of source characteristics and aftershock distributions were both available, the center-of-energy release was selected at a point on the fault plane corresponding to the location of greatest energy release. An example of the latter is the 16 May 1968, Tokachi-Oki earthquake off the eastern coast of Northern Honshu. Nagamune (1969) and Fukao and Furumoto (1975) determined that the source of major energy release for this event was located along the western edge of the fault plane. This point was a significant distance from either the centroid of the fault plane or the epicenter, which was located near the eastern edge of the fault plane.

The distribution of (1) magnitudes versus center-of-energy-release distances, (2) magnitudes versus focal depth, and (3) focal depths versus center-of-energy-release distances for the 128-component data base selected for Northern Honshu is portrayed in Figure 2. The three different symbols in each figure represent the three types of focal mechanisms. The data cover a magnitude range from 5.1 to 8.2, a focal depth range from 14 to 130 km, and a distance range from 42 to 407 km. The data are fairly well distributed over these ranges; thus, no strong correlation exists among the three pairs of parameters.

Generally, the data from the other subduction zones are distributed in similar fashions as shown in Figure 3. In these figures, different symbols designate subduction zones. Figures 2 and 3 show that the magnitudes and distances of the smaller data sets are generally within the magnitude and distance ranges of the Northern

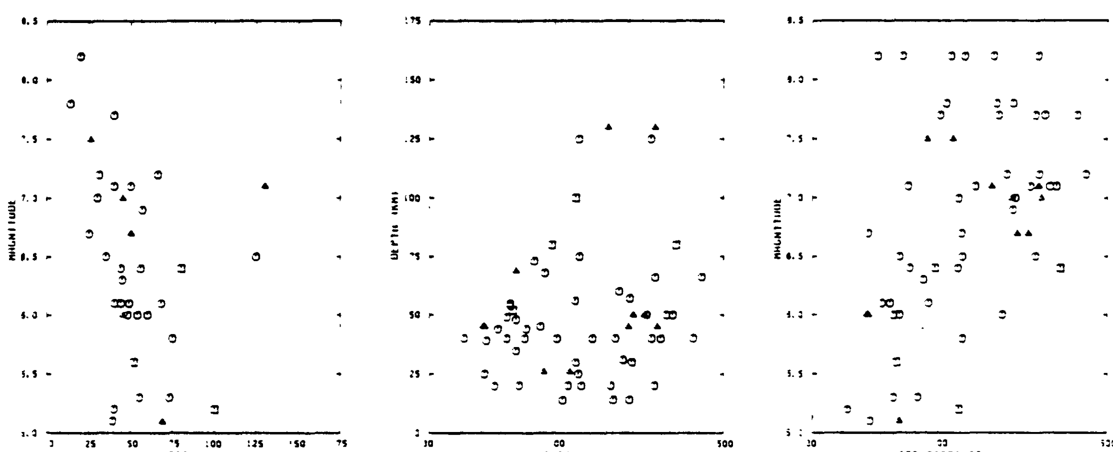

FIG. 2. Distribution of earthquake data in Table 2 for Northern Honshu subduction zone. Thrust = ○; normal = △; strike-slip = □; CER = center-of-energy release.

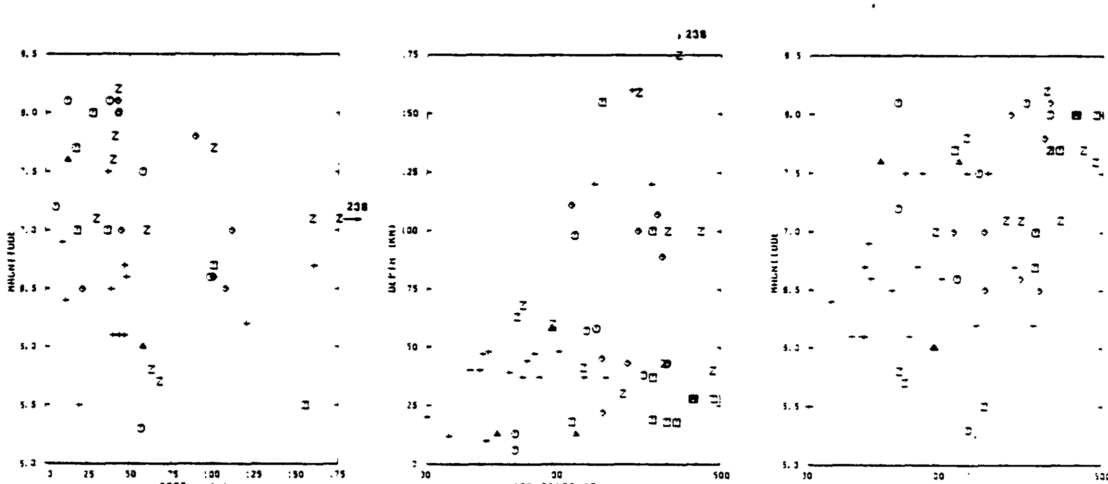

FIG. 3. Distribution of earthquake data in Table 2 for other subduction zones. Nankai = +; Kuril = Z; Alaska = △; Peru/Northern Chile = ○; Mexico = □; New Britain/Bougainville = ◇; CER = center-of-energy release.

Honshu data. The data for all subduction zones were selected in this manner to avoid excessive extrapolations of the regression equations that were used to compare the ground motions from the subduction zones.

ANALYSES

Statistical analyses were conducted on the PSV data collected for the seven subduction zones. The main objectives of the analyses were twofold: (1) to determine whether differences in PSV within a particular subduction zone for a given magnitude and distance were due to differences in the type of focal mechanism, and (2) to determine the subduction zones in which the recorded ground motions could be considered similar. For zones which had significantly different ground motions, possible physical reasons for the differences were considered.

The large number of components (128) for the Northern Honshu zone suggested that this data base first be used to determine the possible effect of focal-mechanism type, and then used as the basis for comparisons with data from each of the other zones. Standard analysis of covariance techniques (e.g., Dixon and Massey, 1983; Dixon, 1985) were used to test whether a linear attenuation model fit groups of data (e.g., groups representing different focal-mechanism types or groups representing different zones) equally well at some confidence level. Because the analysis of covariance in these references is based on linear models, preliminary analysis was conducted to determine whether such a model produced a reasonable fit to the data.

Selection of attenuation model. As a first step, all of the PSV data for the Northern Honshu zone were cast into a regression analysis and the coefficients a, b, c, and d in the equation

$$\ln[PSV(T)] = a + bM + c\ln[R] + dh \qquad (1)$$

were computed at each of 10 periods between 0.1 and 4 sec. In equation (1), $PSV(T)$ is the 5 per cent damped PSV in centimeters/second at period T, M is earthquake magnitude, R is center-of-energy-release distance in kilometers, and h is focal depth in kilometers. The values of the coefficients and the standard errors at each period are given in Table 3. Other trial regressions, assuming different functional forms for the PSV dependence on the magnitude and distance parameters, were conducted. These equations included a quadratic magnitude term, eM^2 and an anelastic

TABLE 3

RESULTS OF REGRESSION ANALYSES ON 128 COMPONENT DATA BASES FROM THE NORTHERN HONSHU SUBDUCTION ZONE [SEE EQUATION (1)]

Period (sec)	Regression Coefficients				$P(H_0/d)$*	S.E.
	a	b	c	d		
0.1	1.86	0.48	−1.02	0.0093	1.00	0.668
0.2	3.19	0.44	−0.98	0.0053	0.94	0.672
0.4	1.29	0.68	−0.84	0.0041	0.90	0.597
0.6	0.67	0.85	−0.95	0.0030	0.71	0.674
0.8	−0.38	0.96	−0.87	0.0017	0.44	0.703
1.0	−1.13	1.06	−0.83	0.0000	0.00	0.713
1.5	−2.79	1.18	−0.69	−0.0007	0.19	0.663
2.0	−3.04	1.26	−0.78	−0.0008	0.21	0.718
3.0	−3.46	1.34	−0.85	−0.0046	0.87	0.730
4.0	−4.09	1.39	−0.85	−0.0053	0.92	0.720

* $P(H_0/d)$ = probability of hypothesis, H_0; d is significantly different from zero.

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attenuation term, fR; however, these terms, although physically plausible, were not supported by the data according to the t test and were omitted. A regression was also performed on a nonlinear variation of equation (1), in which the term, $R = C_1\exp(C_2M)$, replaced R in the equation. Such a magnitude-dependent term in the geometric spreading term, $c \ln(R + C_1\exp(C_2M))$, has been used by others (e.g., OASES, 1978; Campbell, 1981; Hadley *et al.*, 1982) to account for the saturation of ground-motion amplitudes at short distances, R. However, the standard errors of this more complicated model were similar to those obtained from equation (1). Furthermore, the residuals (i.e., differences between computed and observed values of $\ln[PSV(T)]$) were uniformly distributed about their mean of zero throughout the range of each independent variable. These results suggested that near-field saturation effects were not significant for the Northern Honshu data. If data had been available at $R < 40$ km, such effects might have been observed; however, because there was no empirical basis for this effect, the nonlinear form of equation (1) was not considered further.

The purpose of the term, dh, in equation (1) is to account for any possible effect of focal depth. The term has some physical basis in that deeper earthquakes might be expected to produce greater short-period body-wave motions than shallower earthquakes of the same magnitude and hypocentral distance because the anelastic attenuation would likely be less and the stress drop would conceivably be greater (McGarr, 1984). On the other hand, shallow earthquakes tend to generate more long-period surface waves. The decreasing trend of the d values with increasing period in Table 3 tend to support these postulations. The inclusion of the dh term is supported to some extent by the data as indicated in Table 3, which also shows the probability that the coefficient d is significantly different from zero. These statistical tests suggest that d is significant at short and long periods. The insignificance of the coefficient at intermediate periods between 0.6 and 2.0 sec is expected because the values of d are closer to zero. In this period range, d is in transition from the relatively large positive values at short periods to the relatively large negative values at long periods. However, it should be noted that, at each period, the standard errors from regressions without the depth term are very similar to those in Table 3, indicating that the inclusion of the depth term does not substantially improve the fit of the model to the data. Regardless, linear models with the depth term [equation (1)] and without it were both used to test (1) the potential effects of focal-mechanism type on the PSV and (2) whether there were differences in the PSV among the subduction zones. Because the results using both sets of attenuation equations are similar, only the results based on equation (1) are reported in this paper.

Effect of focal-mechanism type. The analysis of covariance tests whether the mean values of the $\ln[PSV(T)]$ are equal among the various groups after adjustments are made for differences in the values of the independent variables among the groups. The main assumption of the method is that the regression curves for each group are parallel [i.e., for each group (i) the coefficients b_i are the same, the coefficients c_i are the same, etc., for a given period]. Another assumption is that the residuals of the regressions are normally distributed. This assumption was verified for data in each zone at several periods by plotting the residuals on normal probability paper and using the well-established Kolmogorov-Smirnov test. The fact that the residuals were found to be normally distributed is consistent with the findings of others (e.g., Donovan, 1973; McGuire, 1974; Campbell, 1981) who have studied the statistical distributions of United States ground-motion data. The final assumption is that the population variances about the regression lines are equal. Although this assumption was not formally tested, an examination of the sample variances indicated the assumption was reasonable.

The analysis of covariance was applied to the three focal-mechanism groups of Northern Honshu data. The equality of the coefficients, b_i, c_i, and d_i (where the subscript $i = 1, 2, 3$ denotes the group), as well as the equality of the adjusted group means of $\ln[PSV(T)]_i$, were tested at the 95 per cent confidence level by using the appropriate F ratio (Dixon and Massey, 1983; Dixon, 1985). The results indicated that, at this confidence level, the adjusted group means can be considered equal at all periods. The test for the equality of coefficients fails at only one period ($T = 1$ sec), but this isolated case is inconsequential.

The equality of the adjusted group means is consistent with the distribution of residuals and their averages for each of the three groups. At each period, the predicted PSV were compared to the observed PSV through the equation for the normal deviate

$$\phi_i = \frac{\ln(PSV)_{0,i} - \ln(PSV)_{p,i}}{\sigma_{\ln}} \tag{2}$$

where ϕ_i is the normal deviate for the ith datum at a given period; $(PSV)_{0,i}$ is the observed PSV at a given period; $(PSV)_{p,i}$ is the corresponding predicted PSV which was obtained by substituting the values of M, R, and h for the ith datum into equation (1); and $\sigma_{\ln}$ is the period-dependent standard error. The coefficients, a, b, c, and d, and the standard errors were taken from Table 3. A comparison of the ϕ_i and their averages, $\bar{\phi}$, is shown in Figure 4. The ϕ_i distributions of each focal-mechanism group are similar, and, in general, the $\bar{\phi}$ for each group are close to zero, which supports the results of the analysis of covariance. Thus, it appears that differences in the PSV data from Northern Honshu cannot be attributed to

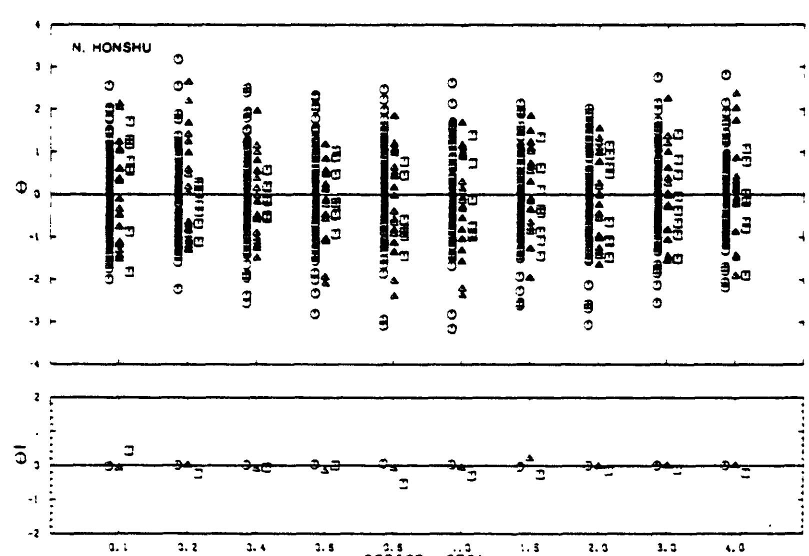

FIG. 4. Distribution of ϕ_i and $\bar{\phi}$ as a function of period and focal-mechanism type for the Northern Honshu subduction zone. Symbols for focal-mechanism type are given in Figure 2.

differences in the type of focal mechanism. With the exception of the thrust and normal data from the Nankai zone, the data from the other zones were not considered to be sufficient to test the effect of focal-mechanism type on the PSV. Nonetheless, although the effect of focal-mechanism type was not considered when the analysis of covariance was applied to the PSV data from the other zones, the separation of the data into the three focal-mechanism groups was preserved in the figures for each zone similar to Figure 4. Tests for differences in the Nankai thrust and normal data are reported in the following subsection in the paragraph where comparisons between the Northern Honshu and Nankai data are presented. Because these tests were also negative, the interpretations of the results for each zone assume that focal-mechanism type is not an important factor contributing to any differences observed in the PSV.

Comparisons of PSV among subduction zones. Statistical analyses similar to those presented in the preceding subsection were used to determine whether the PSV from the various subduction zones were similar. Rather than forming seven groups of data (one group for each zone) and testing them together, which would have produced many rejections of the null hypothesis that the adjusted group means were similar, the Northern Honshu group was compared with each of the other six subduction-zone groups individually. The results of the analysis of covariance are summarized in Table 4. The ϕ_i distributions and their averages for the PSV data from each subduction zone were also computed using equations (1) and (2); for each observed PSV, the corresponding M, R, and h values were substituted into the regression equation developed from the Northern Honshu data [equation (1) and Table 3] to obtain the predicted PSV datum, which was in turn substituted into equation (2) to obtain the corresponding ϕ_i. In equation (2), the period-dependent standard error, $\sigma_{\ln}$, was also obtained from Table 3. The resulting ϕ data are

TABLE 4
RESULTS OF ANALYSIS OF COVARIANCE

Index i	Subduction Zone	Period (sec)									
		0.1	0.2	0.4	0.6	0.8	1.0	1.5	2.0	3.0	4.0
1	Kuril	O	O	o	O	X	x	o	O	O	O
2	Nankai	X	X	O	O	X	O	O	O	O	O
3	Alaska*	O	O	O	O	O	O	X	O	X	X
4	Peru/N. Chile	x	o	o	O	O	x	x	x	o	o
5	New Britain/ Bougain-ville (all sites)	O	O	o	o	o	x	x	X	o	o
	Stiff-soil sites	O	O	x	x	o	o	x	x	o	o
	Soft soil site*	X	O	O	X	X	X	X	O	O	X
6	Mexico (all sites)	O	x	O	O	X	o	x	x	x	x
	Stiff-soil sites	o	o	O	O	O	O	o	o	o	o
	Soft-soil sites	o	X	O	o	x	x	x	x	X	X

Test of null hypothesis, H_0: adjusted group means of $\ln[PSV(T)]$ for Northern Honshu and the ith subduction zone are equal. Confidence level = 0.95. x or X = reject H_0; o or O = accept H_0. Lower case letter signifies that the equality of coefficients b_i, c_i, and d_i between Northern Honshu and the ith subduction zone cannot be accepted at the 95 per cent confidence level.

* Insufficient data to test equality of b_i, c_i, and d_i.

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summarized in Figures 5 through 10 for the other six subduction zones. Each figure contains two plots: the upper plot shows the distribution of ϕ_i for the thrust, normal, and strike-slip data as a function of period, and the lower plot shows the average $\phi_i(\bar{\phi})$ for each focal-mechanism group as well as the $\bar{\phi}$ for all of the data combined. For the New Britain/Bougainville and Mexico subduction zones, the data have also been separated into two soil classifications: the shallow stiff-soil sites and the soft-soil sites. The $\bar{\phi}$ for each of these soil classes is shown on the lower part of Figures 9 and 10 for these two zones. Results of the analysis of covariance for these cases are also presented in Table 4.

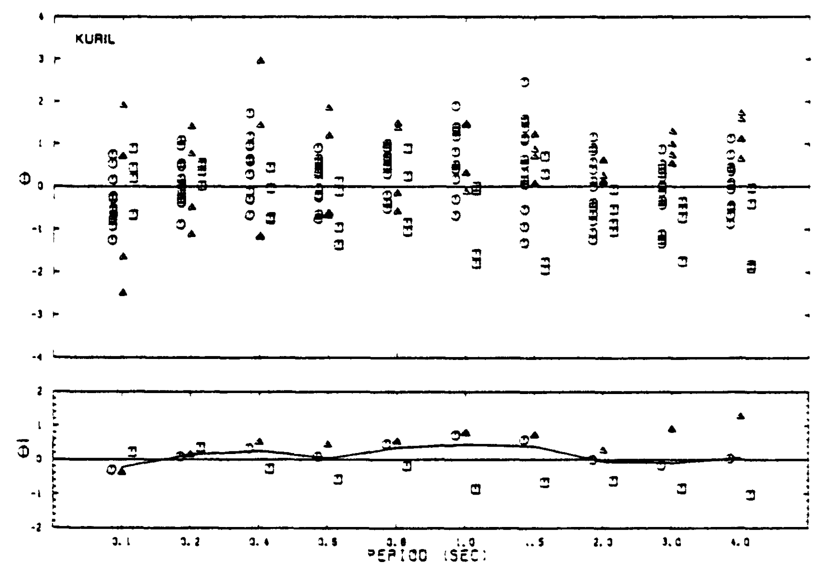

FIG. 5. Distribution of ϕ_i and $\bar{\phi}$ for the Kuril subduction zone. The line in the *bottom figure* passes through the average of all ϕ_i at each period. Symbols for focal-mechanism type are given in Figure 2. See text for details regarding calculation of ϕ_i and $\bar{\phi}$.

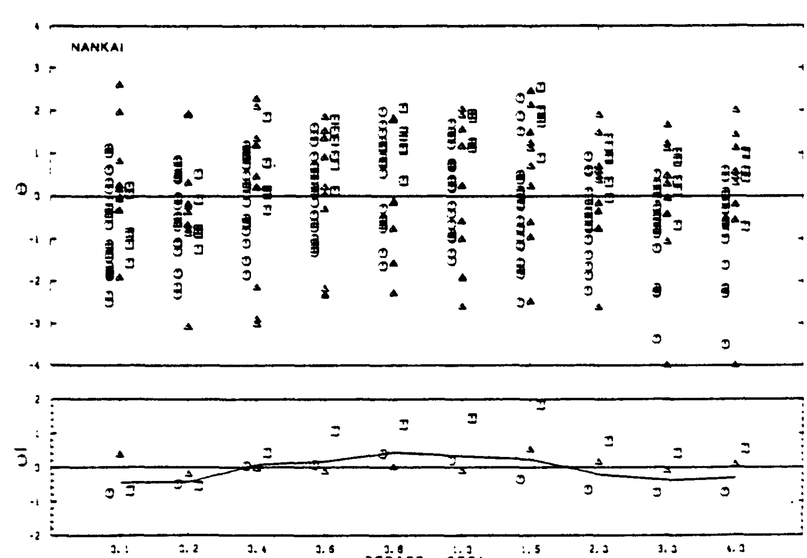

FIG. 6. Nankai subduction-zone data. See Figure 5 legend for explanation.

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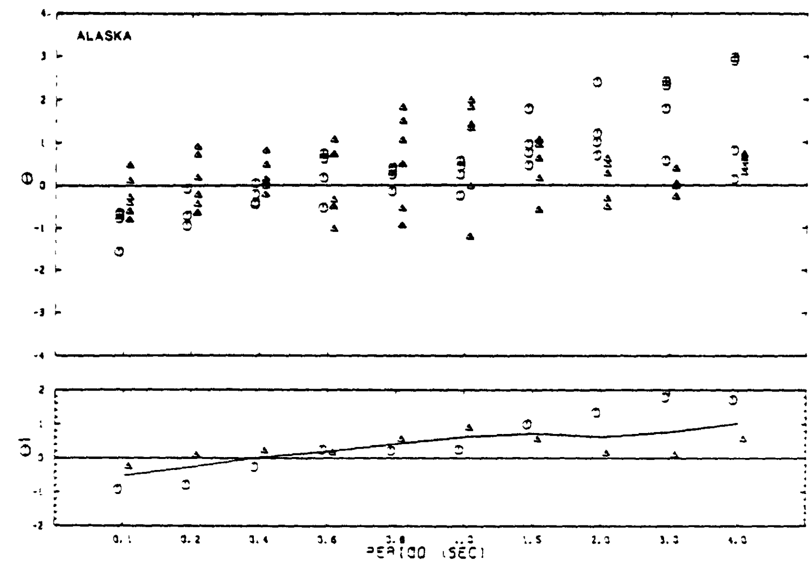

FIG. 7. Alaskan subduction-zone data. See Figure 5 legend for explanation.

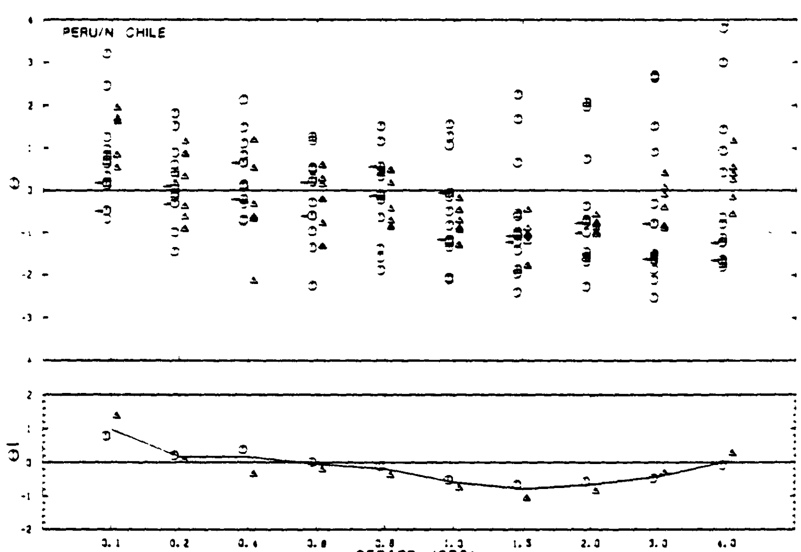

FIG. 8. Peru/Northern Chile subduction-zone data. The horizontal arrows in the *top figure* indicate the La Molina data. See Figure 5 legend for further explanation.

The results indicate that, in general, there are no significant differences in the data from the Northern Honshu, Kuril (Figure 5), and Nankai (Figure 6) subduction zones. For the Kuril versus Northern Honshu data, the independent variable coefficients (b_j, c_j, and d_j) can be considered equal at the 95 per cent confidence level at 7 of 10 periods, and the adjusted group means of $\ln[PSV(T)]$ can be considered equal at all periods except $T = 0.8$ and 1.0 sec (Table 4). At these two periods, the adjusted means for the Kuril zone are greater than those for Northern Honshu, which is apparent in Figure 5. At the three periods for which the independent-variable coefficients were not equal ($T = 0.4$, 1.0, and 1.5 sec), plots of the

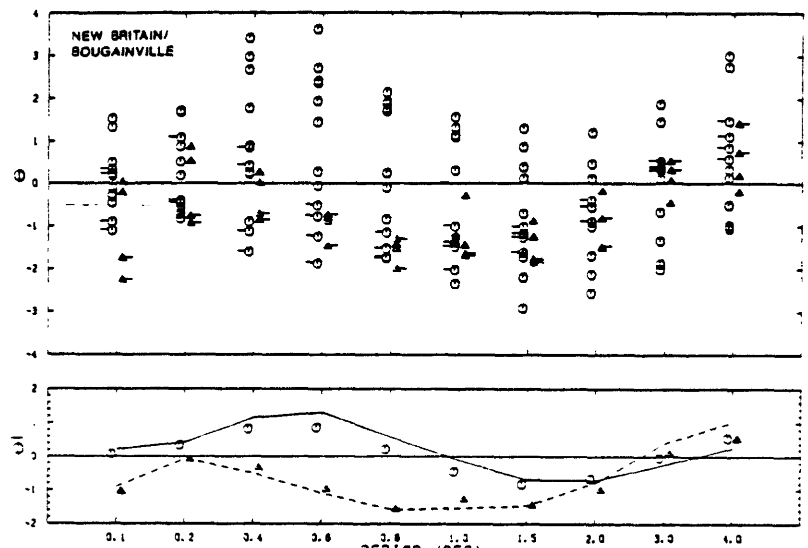

FIG. 9. New Britain/Bougainville subduction-zone data. The data from the soft-soil site (Yonki) are identified with horizontal bars in the *top figure*; the dashed line in the *bottom figure* represents the average of these data. The solid line represents the average of the stiff-soil data. Symbols for focal-mechanism type are given in Figure 2.

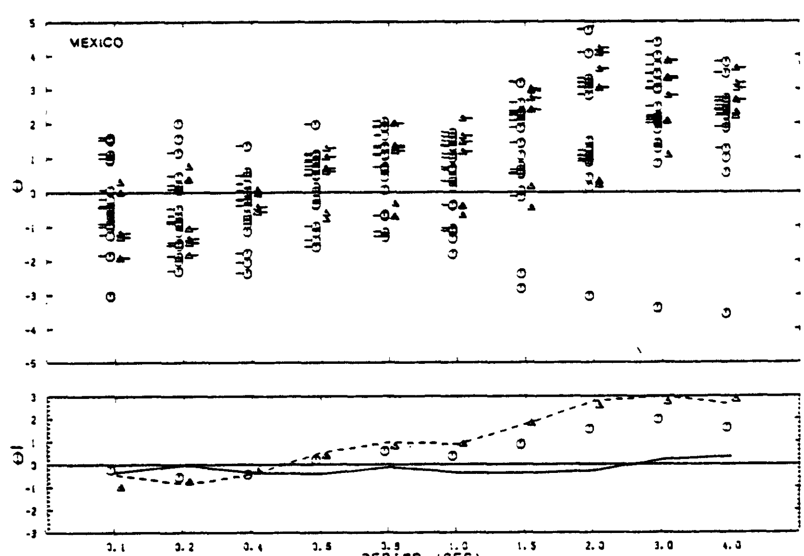

FIG. 10. Mexican subduction-zone data. Symbol explanations are similar to those in Figure 9 except that the soft-soil data [designated with bars (*top figure*) and dashed line (*bottom figure*)] are from more than one site.

ϕ_i versus each independent variable and the F values from the analysis of covariance were examined. For $T = 0.4$ and 1.5 sec, the plots of φ_i versus distance, R, generally showed the ϕ_i were greater than zero for $R < 200$ km and generally less than zero for $R > 200$ km. At $T = 1.0$ sec, the ϕ_i show no striking trends with any of the independent variables; the ϕ_i are mostly greater than zero, as previously noted.

For the Nankai versus Northern Honshu data, the independent variable coefficients can be considered equal at all periods. The adjusted group means can be considered equal except at very short periods ($T = 0.1$ and 0.2 sec) and again at $T = 0.8$ sec. At the short periods, the Northern Honshu adjusted group means are greater; at $T = 0.8$ sec, the Nankai adjusted group mean is greater (Figure 6).

The data in Figure 6 also suggest some differences in ground motion due to focal-mechanism type. However, when an analysis of covariance was performed on the thrust and normal data, the two larger groups of data within the Nankai data base, the equality of adjusted group means could not be rejected at the 95 per cent confidence level for all but two periods ($T = 2$ and 4 sec).

The data from each of the other nonJapanese subduction zones are generally different from the Japanese data, although undoubtedly some of these differences can be traced to differences in the local geology between the typical Japanese site and some sites from other zones. In other instances, the differences appear to be more related to intrinsic differences in the earthquake source characteristics.

The Alaskan data, according to the results in Table 4, are not significantly different from the Northern Honshu data for $T \leqq 1.0$ sec. At longer periods ($T =$ 1.5, 3, and 4 sec), the differences are significant at the 95 per cent confidence level. At these periods, the adjusted means for the Alaskan data are greater than those for the Northern Honshu data. It should be noted that the lack of Alaskan data did not permit a test of the equality of the coefficients b_j, c_j, and d_j. However, plots (not shown here) of the normalized residuals, ϕ_i, for the Alaskan data versus each independent variable did not show any correlation or trends with any of these variables. The results in Table 4 are consistent with the residual plot in Figure 7. The interesting feature of this figure is the gradual increase in the ϕ_i and $\bar{\phi}$ with increasing period. This trend can be attributed to differences in local geology between the Alaskan and Northern Honshu sites. The sites in both areas are underlain by relatively stiff sediments, but the sediments at the Alaskan sites are much deeper, as noted in the previous data base section. The increase in PSV with period at sites with deeper soil deposits has also been observed in the ground-motion data from the Western United States by Seed *et al.* (1976) and Trifunac and Lee (1979), for example. Taking this effect into consideration, the Alaskan data would then more closely agree with the Northern Honshu data at longer periods.

The Peru/Northern Chile data are not significantly different from the Northern Honshu data except at $T = 0.1$, 1.0, 1.5, and 2.0 sec (Table 4 and Figure 8). At the three longer periods, the adjusted means of Peru/Northern Chile are significantly less. Table 4 reveals that the equality of the coefficients b_j, c_j, and d_j is not generally satisfied at the 95 per cent confidence level, but an examination of the residuals versus each independent variable does not indicate any obvious trends for $T \leqq 1.0$ sec. For $T > 1.0$ sec, trends are not apparent if the data corresponding to the $M =$ 5.3 event, the smallest earthquake in the Peru/Northern Chile data set, is ignored. This event accounts for the two largest residuals, ϕ_i, at these periods.

Unlike the Alaskan data, the differences between the Peru/Northern Chile and Northern Honshu data at the longer periods are not thought to be primarily due to any differences in local geology. All sites in the Peru/Northern Chile data set except station 4305 in Lima (the La Molina site) are underlain by Cascajo, a dense to very dense sandy gravel deposit less than about 20 m in depth (Lastrico and Monge, 1974; Repetto *et al.*, 1980). The La Molina site is underlain by about 25 m of stiff silty clay, sandy silt, and dense sandy gravel. Thus, this site and the Cascajo sites are similar in depth and stiffness to the Northern Honshu sites. Although Repetto *et al.* (1980) show that the long-period ground motions at La Molina are somewhat greater than those recorded at the Cascajo site during the 9 November 1974 earthquake and that this difference may be due to the local geologic differences at both sites, the residual data in Figure 8 do not indicate that the local geology is the primary factor for the $\bar{\phi} < 0$ trend at the longer periods. The two La Molina data points, identified by the horizontal arrows in the top half of Figure 8, follow the average trend dictated by the Cascajo data shown in the bottom half of the figure.

The trends at long periods observed in the Peru/Northern Chile data are also seen to some extent in the data from New Britain/Bougainville. Taken collectively, the adjusted means of the New Britain/Bougainville data are similar to those from the Northern Honshu data except at $T = 1.0$, 1.5, and 2.0 sec, at which periods the adjusted means of the New Britain/Bougainville data are significantly less. Because 6 of the 16 components in this data set were recorded at Yonki, a known soft-soil site, the data were separated into stiff-soil and soft-soil categories and the analysis was repeated. The results (Table 4 and Figure 9) show that the stiff-soil data are greater than the Northern Honshu data at short periods ($T < 1.0$ sec), while the opposite trend is observed at longer periods. This trend at longer periods is similar to that noted in the Peru/Northern Chile data. The fact that the coefficients b_j, c_j, and d_j did not pass the equality test at $T \geqq 0.4$ sec at the 95 per cent confidence level does not affect these observations within the ranges of the independent variables for the stiff-soil data. This was verified by examining plots of the residuals versus each of these variables.

Another interesting observation in Figure 9 is the similarity in the $\bar{\phi}$ for the stiff-soil and thrust data and for the soft-soil and normal data. These apparent correlations are more of a coincidence rather than reflecting possible biases in the soft-soil and stiff-soil data due to focal-mechanism type or vice versa. Twice as many thrust components (4) were recorded at Yonki, the soft-soil site, but the ϕ_i for these data are similar to the ϕ_i for the two normal components at this site, as shown in the top half of Figure 9. This comparison further emphasizes the differences in the Yonki data due to local geology. The remaining stiff-soil data have approximately the same ratio of thrust to normal components (8:2) as the Northern Honshu zone (98:22) to which it is compared. Thus, the distinct differences between the stiff-soil New Britain/Bougainville and Northern Honshu data are not the result of any differences in the relative numbers of thrust and normal events between the zones.

The results of the final comparison with the Mexico data are presented in Table 4 and Figure 10. Because of the large disparity in the local geology between the stiff-soil and soft-soil categories, the results from the combined data base are not too informative. The adjusted group means of the stiff-soil data are similar to the Northern Honshu data at all periods; however, some caution must be exercised in interpreting this result because the test for the equality of coefficients b_j, c_j, and d_j failed at the short ($T = 0.1$ and 0.2 sec) and long ($T \geqq 1.5$ sec) periods. At each of these periods, the inequality in the c_j coefficient was the reason that the hypothesis regarding the equality of the three sets of coefficients was rejected. A linear trend was observed between the residuals and $\ln[R]$. At the two short periods, the residuals decreased with increasing $\ln[R]$, and at the long periods the opposite trend was observed. Of particular interest are the data recorded in or near Mexico City at Tacubaya and Sismex Puebla during the 9 September 1985, earthquake. These data were recorded at the longer epicentral distances within the stiff-soil group. The residuals, ϕ_i, of these data are between -3 and 0 at the two short periods and between 0 and +2 at $T \geqq 1.5$ sec. At these longer periods, these residuals are much less than those for the soft-soil sites, as illustrated in Figure 10. Although the equality of the coefficients b_j, c_j, and d_j for the soft-soil data was rejected at most periods, the reasons were not apparent when the residual plots were examined. Clearly, most of the residuals were substantially greater than zero at the longer periods, regardless of the values of the independent variables.

The local and regional geologic characteristics, i.e., soft soils and large sedimentary basins, are responsible for the large PSV of these Mexico accelerograms. Approximately half of the Mexico accelerogram data listed in Table 2 were recorded in Mexico City, which is situated on the bed of a Pleistocene lake that occupied the basin of the Valley of Mexico (Tsai, 1969). The basin is composed of soft alluvium and lake sediments, which amplified the ground motions at the longer periods (Tsai, 1969; Anderson *et al.*, 1986). The Minatitlan and Pajaritos accelerograms were recorded near the eastern coast of Mexico adjacent to the Bay of Campeche. This back-arc region is part of a large alluvial basin, and this basin is probably responsible for the large, long-period motions observed in the PSV of these two accelerograms, which were recorded near the middle portion of this basin. By contrast, the accelerograms from the other subduction zones were generally recorded in the fore-arc regions at the edges of sedimentary basins, where the sedimentary layers are much thinner than those in the middle of the basins. Long-period motions at the edges of the basins are usually not as pronounced as those in the middle, as demonstrated during the 1971 San Fernando, California, earthquake (Hanks, 1975; Liu and Heaton, 1984). During this event, sites at the edges of the Los Angeles and San Fernando Valley basins did not experience large, long-period motions, whereas sites near the middle of these basins did experience them.

The results of the analyses of the PSV data were compared to the characteristics of the subduction zones to gain some further physical insights for the differences observed in the ground motions among the seven subduction zones. Plots of nine of the parameters in Table 1 (age, convergence rate, dip, contact width, maximum subduction depth, maximum historical earthquake—M_w, maximum rupture length, stress drop, and seismic slip) appear in Figure 11. The two groups of the subduction zones from left to right along the horizontal axis of each plot are in order of decreasing strength of ground motion at stiff-soil sites for periods greater than about 0.8 sec. The braces beneath the zone abbreviations lump those zones together in which the strength of motion at these longer periods are similar. This grouping was based on information presented in Figures 5 through 10 and in Table 4.

Correlations are not readily apparent between most of the variables plotted in Figure 5 and the observed long-period ground motions. If the limited Mexican stiff-soil data are ignored, weak correlations are seen in the stress drop and M_w plots. The maximum stress drops and M_w are somewhat higher for the Alaska-Nankai-Kuril-Northern Honshu group than for the Peru/Northern Chile-New Britain/Bougainville group. Although some physical interpretation could be advanced to explain the stress drop observation, the stress drop variations are large, and the values reported in the literature are probably not consistently determined by one procedure with the same type of data to warrant any such interpretation.

The most anomalous subduction zone in terms of the characteristics listed in Table 1 is New Britain/Bougainville, the zone with the smaller long-period ground motions. This small subduction zone involves a complex interaction of four lithospheric plates and, consequently, is more complex tectonically than any of the other zones. Compared to the other six zones, the New Britain/Bougainville zone has the steepest Benioff-Wadati zone below the plate interface and has the smallest contact width. Although there are many anomalous characteristics of the New Britain/

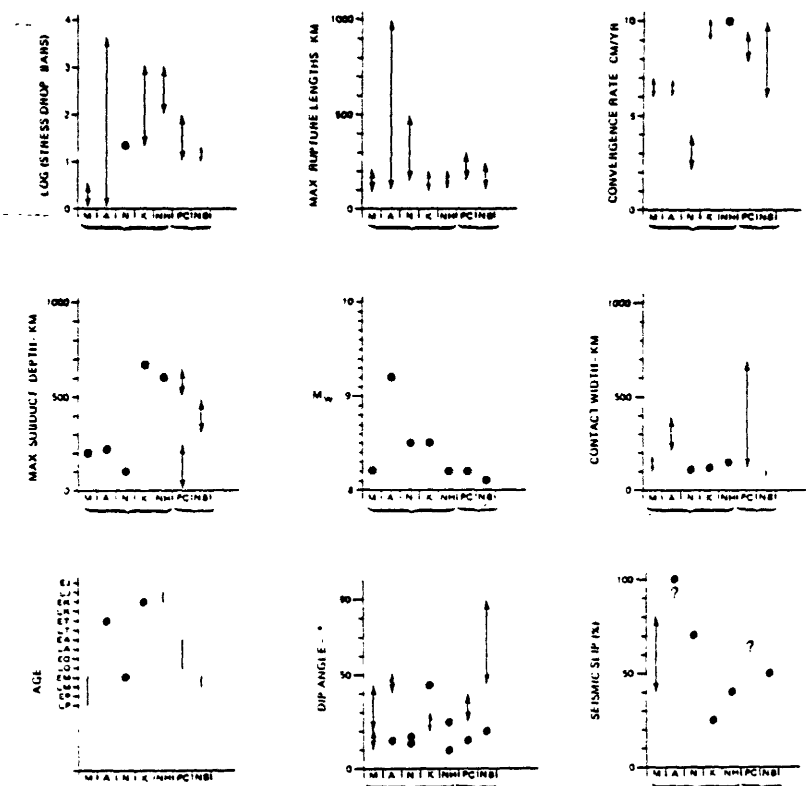

FIG. 11. Subduction-zone parameters from Table 1. The grouping of subduction zones from *left* to *right* along the horizontal axis is in order of decreasing strength of ground motion for periods of 0.3 sec and greater. Braces beneath zone abbreviations lump those zones in which the strength of motion is similar. M = Mexico; A = Alaska; N = Nankai; K = Kuril; NH = Northern Honshu; PC = Peru/Northern Chile; NB = New Britain/Bougainville.

Bougainville subduction zone, the potential physical link between them and the ground motions is not clear.

DISCUSSION

The general lack of correlation between the PSV data and the seismotectonic characteristics of the subduction zones, as indicated in Figure 11, may not be surprising. Variables such as convergence rate and age of the subduction zone, although they may correlate with the maximum magnitudes of earthquakes that have occurred in the subduction zones (Ruff and Kanamori, 1980; Heaton and Kanamori, 1984), may have little or no bearing on the ground motions generated by an earthquake of a given moment magnitude. Detailed information, which would be relevant, such as local and average stress drops for many earthquakes, asperity sizes and distributions, and seismic velocity and Q structure in the upper 150 km, is not available for these regions. Some information on source complexity, multiplicity, and roughness, which may be useful, was obtained in a parallel study by Hartzell and Heaton (1985a).

Hartzell and Heaton analyzed data from large magnitude ($M_w > \sim 7.5$) subduction-zone earthquakes and found no correlation between the teleseismic source-time functions, trench age, and convergence rate. This finding is analogous and perhaps consistent with our observations concerning the general lack of correlation between the ground motions and the subduction-zone parameters listed in Table 1, two of which are the age of the subducted plate and convergence rate. However, the source-time functions derived by Hartzell and Heaton exhibited similar characteristics for different earthquakes in the same subduction zone. These characteristics tended to vary for different subduction zones. Hartzell and Heaton grouped the zones according to source multiplicity and source roughness as follows

1. South Chile, *Alaska*
2. Aleutians, Kamchatka, *Kuril*, Colombia, *Nankai*
3. *N. Honshu, Japan*, Tonga-Kermadec, Central America
4. *Central Chile, Peru, Solomon Islands* (*New Britain/Bougainville*), New Hebrides.

The grouping is in order of decreasing multiplicity and roughness, and the italicized zones are those considered in our study. Central America has not been italicized because our Mexico zone is northwest of the area studied by Hartzell and Heaton. A comparison of Figures 5 through 10 with the above groupings indicates that there is little correlation between the short-period ground motions less than about 0.8 sec and the zone grouping. However, at intermediate periods around 1 sec, some correlation is apparent. For example, the ground motions from Peru/Northern Chile (Central Chile, Peru, of Hartzell and Heaton) and New Britain/Bougainville (Solomon Islands of Hartzell and Heaton) are smaller on the average than those from Northern Honshu. Likewise, the Northern Honshu ground motions are smaller on the average than those from Nankai and Kuril, although the differences between the Nankai and the Northern Honshu motions were only statistically significant at a period of 0.8 sec. This apparent correlation may be a coincidence because the correlation breaks down at periods around 3 and 4 sec. At these periods, one would expect the correlation to be just as strong or possibly stronger because the teleseismic data contain some information at these periods (the period band of the teleseismic data is 2.5 to 50 sec). A stronger correlation at these periods would have offered more persuasive evidence that the source (rather than travel-path) characteristics at intermediate periods are potentially different in some zones and are thus contributing significantly to the differences in the observed ground motions.

The effect of local and regional geology was found to be an important factor also despite the initial attempts to select as much accelerogram data from stations (other than those from Mexico) with similar local geology. Geology obviously affected the Mexico ground-motion data, and it probably affected the Alaska data and the ground motions recorded at Yonki in New Britian/Bougainville.

The evidence suggesting that local geology affected the New Britain/Bougainville accelerograms recorded at Yonki is based on a comparison between these data and those recorded at stiff-soil sites within the same zone (Figure 9). Denham *et al.* (1973) also observed a characteristic shape of the response spectra from the Yonki accelerograms. The spectra exhibit a peak centered at 0.2 sec, and Denham *et al.* (1973) suggest that the local geology may be the primary factor responsible for this peak. However, the PSV levels observed in the Yonki spectra at the longer periods are much smaller than the PSV levels generally associated with other softer and/or deeper soil sites (e.g., Alaska and Mexico). Furthermore, it is interesting to note the sinusoidal character of the average residuals, $\bar{\phi}$, in Figure 9 for both the Yonki and stiff-soil data. This evidence indicates that other factors, such as the source and/or travel-path characteristics, are contributing to the spectral characteristics. The anomalous tectonic environment of the New Britain/Bougainville zone, as discussed in the preceding section, may be influencing these factors in some systematic manner.

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