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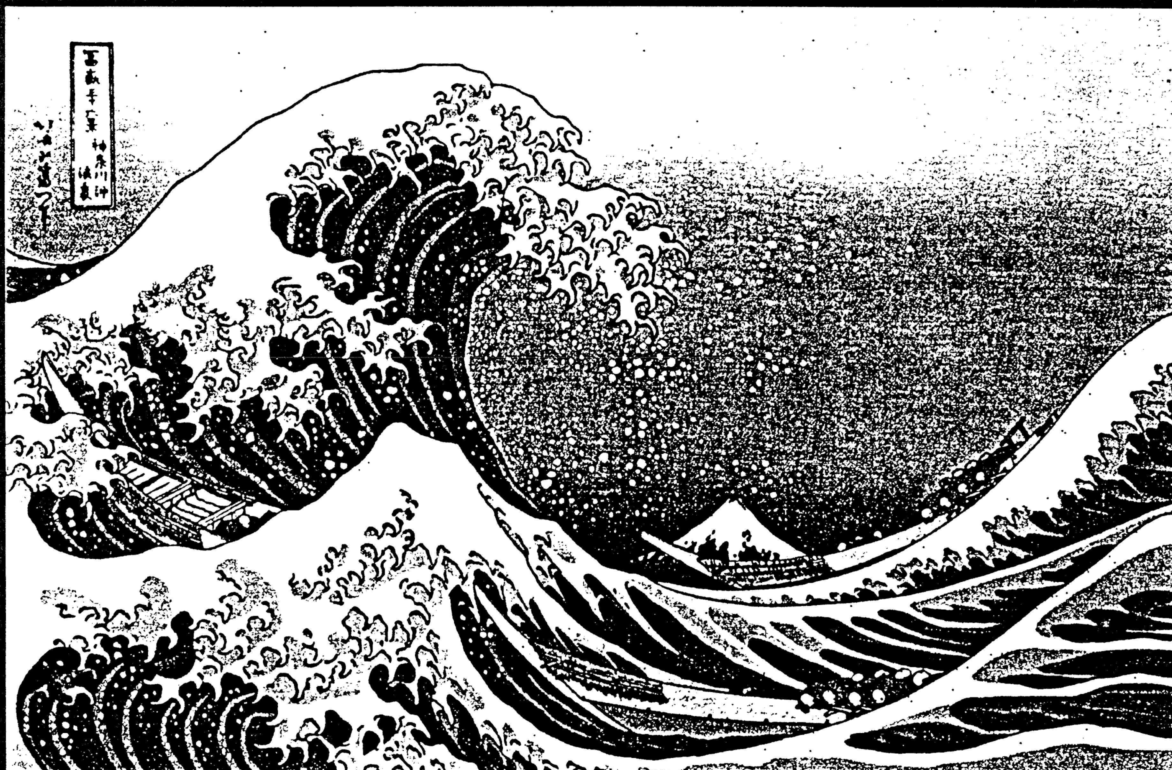

GREAT CASCADIA EARTHQUAKE TRICENTENNIAL

Seaside, Oregon
June 4-8, 2000

Convened by John Clague, Brian Atwater,
Kelin Wang, Yumei Wang, and Ivan Wong

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Penrose Conference
"Great Cascadia Earthquake Tricentennial"
Best Western Oceanview Resort
Seaside, Oregon
June 4-8, 2000

Program and Abstracts

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- Geological Society of America
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- Oregon Department of Geology and Mineral Industries
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This publication is informal and its contents have received little or no critical review

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Conference Summary

The year 2000 marks the tricentennial of the last great (magnitude 8 or larger) earthquake within the Cascadia subduction zone, which is located along the Pacific coast of North America from British Columbia to northern California. Coastal and offshore studies have confirmed that many great plate-boundary earthquakes have struck this region in the Holocene, and geodetic studies have shown that the subduction zone is accumulating strain that will be released in a future earthquake.

To commemorate the tricentennial, almost 100 geologists, geophysicists, engineers, and public officials gathered in Seaside, Oregon, in the first week of June 2000, to critically review current knowledge about great Cascadia earthquakes, clarify the hazards posed by these earthquakes, discuss appropriate strategies for reducing earthquake losses, and identify priority research directions. Further understanding of the great earthquake potential of the Cascadia subduction zone is required for seismic hazard characterization, engineering design, emergency planning and response, and other mitigation efforts in a region with a population of some 6 million people. Seaside was an appropriate place to hold the conference because much of the community, including the conference hotel, lies within the inundation zone of the tsunami of the 1700 earthquake.

The conference consisted of three days of indoor sessions, a one-day excursion to examine evidence of past Cascadia earthquakes, and a public forum. Two poster sessions complemented morning and afternoon oral sessions and discussion periods, and provided an opportunity for conference participants to showcase recent research on the Cascadia subduction zone, earthquake hazards, and mitigation.

Sessions on the first day dealt with earthquake hazards and their mitigation. These initial sessions provided focus for subsequent sessions on regional earthquake histories, tectonics, and present-day seismicity and strain accumulation. Evidence for past Cascadia earthquakes was examined and discussed during a canoe trip along the Niawiakum River in southwestern Washington and at a nearby park where lake, tidal marsh, and deep-sea cores collected during previous paleoseismological investigations were displayed.

A huge amount of progress has been made in understanding the behavior of the Cascadia subduction zone over the last two decades. Fifteen years ago, scientists were debating whether or not great earthquakes occur in Cascadia. Today, few scientists doubt that great earthquakes occur in this region; rather the discussion has shifted to questions such as the magnitude of the earthquakes and attendant tsunamis, the location and width of the seismogenic zone, and the involvement of crustal structures in plate-boundary rupture. These issues were topics of discussion and debate at the conference.

DAY 1

To provide focus and guidance, the first day of the conference dealt with hazards and losses posed by great Cascadia subduction zone earthquakes (session 1) and mitigation of those hazards (session 2). Public officials responsible for earthquake hazard mitigation, including several emergency managers, participated in this part of the conference.

Session 1, chaired by Ivan Wong (URS Greiner Woodward Clyde), consisted of four invited talks. The first three talks covered the range of hazards associated with great Cascadia earthquakes: ground shaking, tsunamis, coastal subsidence, liquefaction, and landslides. The fourth talk dealt with losses expected from a great earthquake.

Ivan Wong described the current state of knowledge on ground motions for Cascadia earthquakes of moment magnitude (M_w) 8 to 9. Two approaches have been used to estimate ground shaking in the Pacific Northwest: empirical attenuation relationships, which are compromised by the fact that they are not based on strong motion recordings of great Cascadia earthquakes, because none exist; and numerical modeling. Studies using these approaches indicate that ground motions from a M_w 9 earthquake will be very strong along the coast and will gradually attenuate to moderate, but still potentially damaging levels in inland areas such as the extensively urbanized Puget Sound region and Willamette Valley. Great earthquake ground motions will contain a significant amount of long-period energy, and strong shaking will last several minutes. Wong also discussed the key issues that must be resolved to reduce the large uncertainties in ground motion estimates, the most significant which is the location and geometry of the rupture planes of future great earthquakes.

The second speaker, George Priest (Oregon Department of Geology and Mineral Industries, DOGAMI), described the hazard of tsunamis generated by large subduction earthquakes. Priest pointed out that the greatest loss of life in a Cascadia earthquake could be from tsunamis. Efforts to mitigate this hazard can benefit greatly from accurate tsunami modeling. Such modeling requires as input characterization of the earthquake source and rupture process, particularly coseismic deformation of the sea floor, which is the largest source of uncertainty. Modeling techniques must also be calibrated with paleo-tsunami and paleo-deformation evidence. Accurate tsunami hazard evaluations will require interdisciplinary teams working together at a few strategic coastal sites.

Ground failure hazards – landslides, liquefaction, lateral spreading, and settlement – were discussed by Steve Kramer (University of Washington). Ground failures during great Cascadia earthquakes may be more severe and more extensive than those of historical earthquakes, most notably the 1949 and 1965 intraslab events in Puget Sound. In particular, landslide displacements may be greater and liquefaction more prevalent during great earthquakes because the strong ground shaking lasts a few minutes. Kramer completed his presentation by providing a perspective on the current technique of back-calculating the earthquake ground motions required to initiate liquefaction. This approach has been used recently to estimate the maximum ground shaking during the 1700 Cascadia earthquake. Liquefaction analysis is subject to considerable uncertainty, but the uncertainty can be incorporated in either a forward or backward manner into a probabilistic framework.

The final speaker in the session was Yumei Wang (DOGAMI and Chair of the Oregon Seismic Safety Policy Advisory Commission). She presented information on earthquake losses from large historical earthquakes and also reviewed a recent loss estimate for the State of Oregon from a M_w 8.5 scenario earthquake. Losses include deaths, casualties, building damage, and other economic losses. Wang estimates that direct financial losses to Oregon could exceed $12 billion and that casualties could exceed 13,000. More than 5,000 of the casualties would result from tsunamis and from damage to, or collapse of, unreinforced masonry buildings. Loss studies such as this are a powerful tool to promote risk-based mitigation efforts.

Four conference participants discussed key topics following the formal presentations of session 1. Bob Youngs (Geomatrix Consultants) presented in detail the database for his attenuation relationships. Ken Campbell (Vice President, EQE International) provided his perspective on subduction zone attenuation relationships. Dave Perkins (U.S. Geological Survey, USGS) and John Adams (Geological Survey of Canada, GSC) summarized how the Cascadia earthquake threat was being incorporated in national earthquake hazard maps of the U.S. and Canada, respectively. A topic of discussion was whether hazard information was being adequately conveyed from the earth scientists to public officials.

Session 2, chaired by Yumei Wang, included seven talks dealing with mitigation (risk reduction). The talks included an overview of mitigation and discussions of building codes, seismic design, transportation, lifelines, tsunami mitigation, financial perspective, and public policy.

Yumei Wang began the session with an introduction to earthquake mitigation. She noted that the Pacific Northwest is not prepared for the next great Cascadia earthquake, partly because an understanding of these earthquakes and their threat to society has only recently been gained and partly because a great earthquake has not occurred in historic times. Nonetheless, damages and losses during the next great subduction earthquake are expected to be very high and of great consequence. Thus, more mitigation, through a variety of means, is needed.

Michael Hagerty (Chief Structural Engineer, City of Portland) discussed the history and intent of building codes (i.e., to provide life safety). He stated that, due to Oregon's lack of code adoption in the past, 90 percent of the buildings in the state were constructed with no seismic design criteria and many are exceptionally vulnerable to earthquakes. The current Oregon code (1997 Uniform Building Code) is adequate for new buildings, which should be able to withstand three minutes or more of strong shaking typical of subduction zone earthquakes. Hagerty also discussed the new 2000 International Building Code, which has not yet been adopted.

Christopher Thompson (Principal, Degenkolb Engineers) reviewed seismic design issues. In addition to the expected long duration of shaking, dominant long-period (low-frequency) ground motions will influence the response of structures. Thompson described the structural engineer's pushover analysis, which is becoming more commonplace, and some newer mitigation measures (as opposed to the standards: cross-bracing, shear walls), including viscous dampers and base isolation systems.

Linda Noson (Senior Research Scientist, AGRA) reviewed transportation and lifeline systems. She concentrated on the past performance of interdependent lifeline systems during earthquakes and how communities can suffer long-term consequences from damaged lifelines. Predictive damage and loss assessments that include ground shaking characteristics and associated hazards, such as liquefaction and landslides, should be conducted to help reduce risk to communities.

Nobuo Shuto (Professor of Policy Studies, Iwate Prefectural University, Japan) described tsunami mitigation techniques employed in Japan and gave examples of their performance during past tsunamis. Mitigation involves public awareness, community evacuation drills, land-use restrictions, engineered solutions, vertical evacuation, and warnings (as soon as 7 minutes following the earthquake).

James Ament (Vice President of Operations, State Farm Insurance) provided a financial perspective. He pointed out the strong need for improved cost-benefit tools and case studies to provide incentives and promote mitigation. To reduce financial impacts, stakeholders (developers, designers, builders, financiers, and owners) must be engaged to develop balanced and rational decisions. He cited the "seat-belt" example in the U.S., where public awareness of risk reduction resulting from wearing seat belts has led to widespread behavioral change.

William Elliott (Manager, Elliott Consultants LCC) provided insights acquired from many years of experience in the public policy arena. He explained that more public policies spanning grass roots to national levels must be implemented to adequately reduce risk. He summarized the legislation that is being proposed by the Oregon Seismic Safety Policy Advisory Commission, requiring that schools (K-12 and higher) are life safe, that hospitals and fire stations remain in operation after earthquakes, and that annual earthquake drills are conducted.

A discussion session involving the speakers concluded that sound geologic data are required to develop reasonable and effective mitigation that can reduce the impacts of disasters and maintain healthy, economically sound communities.

PUBLIC FORUM

A public forum, "Surviving Earthquakes and Tsunamis on the Oregon and Washington Coasts", was held on the first evening of the conference. It attracted over 200 people and allowed conference participants to hear concerns of local residents. The forum was moderated by John

Beaulieu, State Geologist, Oregon Department of Geology and Mineral Resources and included three talks, remarks on public safety concerns by two Oregon State Senators (Joan Dukes and Gary George), and a question-and-answer period.

Kenji Satake (Geological Survey of Japan) summarized recent scientific discoveries that make scientists confident that great earthquakes have happened in Cascadia and will happen there again. The tsunami of the most recent great earthquake, on January 26, 1700, has been found in historical records for six towns along Japan's coast. The records suggest that the earthquake was close to M_w 9. Geodetic meaurements by global positional satellites (GPS) in northern Oregon, Washington, and British Columbia show that the coast is moving closer to the interior at a rate of many millimeters per year. The region is being shortened by convergence of the Juan de Fuca and North America plates, which are stuck together. The coast will lurch seaward when the plates become unstuck during the next great Cascadia earthquake.

Yumei Wang gave the second talk of the forum, entitled "What Will Happen If a Magnitude-8.5 Earthquake Hits Oregon?" An Oregon Department of Geology and Mineral Industries (DOGAMI) study estimates that thousands of casualties would result from damaged buildings and tsunami inundation during a great Cascadia earthquake. Damage to buildings in Oregon may exceed $12 billion. About 10 percent of the buildings will be destroyed or significantly damaged, and hundreds of bridges will be out of service. In addition, over 17,000 households will be displaced and more than 12,000 people will require temporary shelters.

George Priest (DOGAMI) gave the final talk of the forum – "Where Are the Tsunami-Prone Areas in Oregon and Washington?" Society can reduce losses from Cascadia subduction zone tsunamis through hazard assessment, planning, and public education. The main tool for hazard assessment is a map showing potential tsunami flooding. Generalized tsunami inundation maps have been produced for the entire Oregon coast. More detailed computer-generated maps are available for Eureka and Crescent City, California, the southern Washington coast, and the Oregon cities of Warrenton, Astoria, Gearhart, Seaside, southern Lincoln City (Siletz Bay), and southern Newport (Yaquina Bay). Similar maps are in production for Port Angeles, Washington, and Gold Beach and Coos Bay, Oregon. An initial tsunami wave is about the same size and shape as the sea-floor deformation accompanying the earthquake, but our ability to predict sea-floor deformation is in a primitive state. To complicate matters, wave heights can be increased by submarine subsidence, landslides, and unusual uplift along secondary faults and asperities. No modern Cascadia tsunamis have struck the Pacific Northwest, so verification of their size and accompanying earthquake deformation depends on geological studies of prehistoric tsunami deposits, buried soils, and present-day crustal movements.

After a lively question-and-answer period, the forum concluded with informal discussions between conference participants and local residents at poster displays.

Day 2

Following the hazard and mitigation sessions of Day 1, conference participants moved outdoors for a damp day devoted to the Holocene history of great Cascadia earthquakes (sessions 3 and 4). In morning drizzle they took an armada of 28 canoes down a muddy arm of Willapa Bay, Washington, where they looked at series of buried forest and marsh soils that record repeated, abrupt subsidence of coastal land in the past 3500 years (session 3). The trip was led by Brian Atwater (USGS) Eileen Hemphill-Haley (formerly with USGS), and Jonathan Hughes (Simon Fraser University). The uppermost of the buried soils was seen mantled with sand deposited by the tsunami from the 1700 Cascadia earthquake.

The outdoor day continued with a series of summaries of inferred earthquake history (session 4). A compilation of radiocarbon ages from dozens of sites between British Columbia and California highlighted difficulties in estimating rupture lengths of individual earthquakes (Alan Nelson, USGS). In British Columbia, tsunami deposits provide the most abundant evidence for great Cascadia earthquakes; widespread evidence for coseismic subsidence is limited to the 1700 earthquake (Ian Hutchinson and John Clague, both at Simon Fraser University). Probable tsunami deposits are also present in swales between beach ridges of coastal southern Washington and northern Oregon, and coseismic subsidence diminishes southward between this region and the coast of central Oregon (Curt Peterson and Robert Schlichting, both at Portland State University). Coseismic subsidence at a site on the southern Washington coast was greater, and was preceded by less preseismic submergence, than at a site on the northern Oregon coast (Ian Shennan, University of Durham). At least a dozen great earthquakes in the past 7500 years are probably recorded along the southern Oregon coast by evidence for subsidence of tidal marshes and by evidence for incursions of marine water into a coastal lake (Harvey Kelsey, Humboldt State University; Alan Nelson; Rob Witter, William Lettis & Associates; Eileen Hemphill-Haley). Along the northern California coast, earthquakes as much as 3500 years old have been inferred from signs of uplift, subsidence, surface rupture, and tsunamis (Gary Carver, formerly at Humboldt State University; Carrie Garrison-Laney, Virginia Tech; Hans Abramson, American School of Milan). New studies of deep-sea turbidites have potential for providing histories of great Cascadia earthquakes of the past 7500 years or more (Hans Nelson, Texas A & M University; Chris Goldfinger and Joel Johnson, both at Oregon State University). Hans Nelson and co-workers, building on the pioneering work of John Adams, have shown that large earthquakes triggered turbidity currents that have left a consistent sequence of deposits in submarine channels along much of the Cascadia margin.

The outdoor presentations concluded with displays of cores from beach-ridge areas of Washington and Oregon, a lake in southern Oregon, and the ocean floor off the Oregon coast. Viewed in intermittent mist beneath towering Sitka spruce, deep-sea turbidites showed a remarkable rhythmicity, and the lake cores a stunning assortment of layering and clasts.

Day 3

The morning of the third day of the conference, which was chaired by John Clague, was devoted to earthquake history topics (session 5). Four speakers addressed three topics.

Ian Shennan, with co-authors Sarah Hamilton, Antony Long, and Yongqiang Zong (all at University of Durham), reviewed techniques for discriminating coseismic and nonseismic relative sea-level change (RSL) from stratigraphic evidence. Five kinds of criteria must be evaluated when inferring regional coastal susidence due to great subduction zone earthquakes: the suddenness and amount of submergence, the lateral extent of submerged tidal wetland soils, the coincidence of submergence with tsunami deposits, and the degree of synchroneity of submergence events at widely spaced sites. Shennan suggested that microfossils in sediments at tidal marshes that are subject to coseismic subsidence during subduction zone earthquakes may record stages within the earthquake deformation cycle, i.e. post-seismic RSL, interseismic RSL, pre-seismic RSL, and co-seismic rapid RSL. A period of slow RSL in the late stage of an earthquake cycle may be a precursor of large subduction zone earthquakes.

Lisa McNeill (University of Leeds), Pat McCrory (USGS), and co-workers summarized their research on upper-plate structures and their contribution to Cascadia earthquake hazards. Faults and synclines beneath the inner continental shelf of southern Washington, Oregon, and northern California deform Quaternary sediments and project inland into many of the coastal lowlands where coseismically subsided marshes and forests have been described. McNeill hypothesizes that many coastal bays in this region are structurally controlled, lying within active synclines or on the downthrown side of active faults, and that coastal bay stratigraphy may incorporate both subduction zone and upper-plate permanent vertical motions. Support for this thesis is provided by McCrory's work, which documents Quaternary crustal faulting at the leading edge of the Coast Range block in Washington. An important implication of these studies is that upper-plate faults may pose a seismic hazard independent of plate-boundary rupture to coastal communities.

The fourth talk of the morning session, by David Perkins (USGS), dealt with probabilities of Cascadia subduction zone earthquakes. The short paleoseismic record and uncertainties and imprecision in dating past earthquakes make it difficult to determine the probability of the next event. Using Poisson and Weibull probability distributions, however, Perkins showed that the probability of a great earthquake occurring in Cascadia in the next 30 years is about 4-10 percent. He commented, however, that these values will higher if two or more earthquakes that cannot be discriminated using geologic evidence occurred over a short interval.

Session 5 ended with a panel discussion of the topics addressed by the morning speakers. The panel included John Adams, George Plafker (USGS), Ray Wells (USGS), and Robert Yeats (Oregon State University).

The focus of the afternoon session on Day 3 was a contentious issue in Cascadia paleoseismology – ground motion and paleoliquefaction. In earlier studies, Steve Obermeier (USGS) and Steve Dickenson (Oregon State University) have suggested that observed liquefaction features in Cascadia imply smaller ground motions than would be expected from great subduction zone earthquakes (i.e. no larger than moment M_w 8). According to Obermeier and Dickenson, the 1700 Cascadia earthquake failed to produce liquefaction features as large or abundant as those from the 1811-1812 New Madrid earthquakes or the 1964 Alaska earthquake and estimated that the shaking only exceptionally may have exceeded 0.25 g. Five speakers addressed this issue.

Ian Madin (DOGAMI) provided an overview of paleoliquefaction evidence in Cascadia. He noted that liquefaction features that can be definitely ascribed to great Cascadia earthquakes are not common; the best evidence comes from islands along the lower Columbia River, where sand dykes and sand blows linked to the 1700 earthquake have been found over distances of several tens of kilometers inland from the coast. Liquefaction features in other areas generally are not well dated thus their source is unknown.

Ivan Wong, the second speaker, talked about expected ground motion from great earthquakes at sites where paleoliquefaction evidence has been found. A critical factor in estimating ground shaking, whether using empirical or numerical modeling approaches, is the distance to the megathrust fault rupture. The most widely accepted model places the rupture generally offshore, but the rupture could possibly extend a considerable distance inland, in which case larger ground motions can be expected in both coastal and inland areas. Wong concluded that current studies indicate that a M_w 9 earthquake within the Cascadia subduction zone will generate strong to very strong ground shaking in the Pacific Northwest. Depending on the computational approach, surficial peak horizontal accelerations could exceed 0.5 g in coastal areas and up to 0.2 g and possibly much higher at inland locations such as Seattle or Portland. Long-period ground motions could also be large.

Yumei Wang, the third speaker, commented that further study is required before paleoliquefaction features can be used to constrain the magnitude of ground shaking during Cascadia subduction earthquakes. Environments in which liquefaction features may be preserved are relatively uncommon in the Pacific Northwest, which may explain why these features have been found in few areas. Accurate ground motion estimates require precise knowledge of the location of the earthquake source zone, and stress drop and attenuation during earthquakes. In the case of Cascadia, none of these is well known because no great earthquake has been recorded in the region.

Brian Atwater, the next speaker, argued on geologic grounds that liquefaction evidence in Cascadia is not inconsistent with the past occurrence of strong ground shaking and great subduction earthquakes. He stated that sand dykes and sand blows in favorable environments in Cascadia are as abundant as those in similar environments in the epicentral area of the 1964 Alaska earthquake. Further, liquefiable sediments and environments in Cascadia differ from those in the New Madrid region, upon which past conclusions about limited ground shaking have been partially based.

Rob Kayen (USGS) was the final speaker of the afternoon session 6. He gave a review of empirical and probabilistic techniques for estimating ground motion. Liquefaction thresholds depend on a large number of factors, including peak acceleration, duration of strong shaking, the thickness and physical properties of the liquefiable deposits, and the thickness of non-liquefiable deposits above them. It thus is generally difficult to determine peak acceleration or other measures of ground motion from the presence or absence of liquefaction features alone.

Day 3 closed with a panel discussion on ground motion and liquefaction. The panel comprised Ken Campbell (EQE International), Brian McAdoo (Vassar College), John Sims (John Sims & Associates), and Martitia Tuttle (M. Tuttle & Associates).

Day 4

The focus of the fourth day of the conference was geophysical issues, specifically subduction zone tectonics and present-day strain accumulation at the Cascadia subduction zone. Kelin Wang (GSC) chaired the two sessions.

Session 7, which included six talks, provided a systematic examination of the geophysical framework of the Cascadia subduction zone. The first two talks addressed the theme of seismogenesis of subduction thrusts from different perspectives. Larry Ruff (University of Michigan) reviewed the seismogenic characteristics of the world's subduction zones, emphasizing the diversity and complexity of earthquake processes as inferred from instrumental seismological records. Great earthquakes may rupture a very long segment of the subduction thrust at one time, but much smaller segments at other times. Roy Hyndman (GSC) summarized geophysical constraints on the seismogenic zone of subduction faults. Geodetic measurements provide good constraints on the extent of the interseismically locked portion of the fault, which is controlled primarily by temperature. It is important to recognize, however, that the interseismic locked zone may not be the same as the coseismic rupture zone. An important question to be addressed by future studies is whether a significant portion of plate convergence in Cascadia takes place aseismically.

The next two talks of the session were devoted to the kinematics and structure of the Cascadia subduction zone. Ray Wells discussed upper plate tectonics of the Cascadia margin and their effects on great earthquake processes. Motions of southern Cascadia forearc blocks make the effective plate convergence less oblique. Wells also pointed out the similarity in the distribution of forearc basins at the Cascadia and Nankai (southwest Japan) margins and the role these basin structures may have played in segmenting the Nankai subduction fault along strike, hence affecting the extent of earthquake rupture. Tom Brocher (USGS), with co-author Anne Trehu (Oregon State University), reviewed seismic survey and other geophysical studies along the Cascadia margin that constrain plate boundary fault geometry and forearc structure.

The final two talks of the session dealt with the thermal, hydrological, and petrological environments of great Cascadia earthquakes. Kevin Brown (University of California at San Diego) reported ongoing research on hydrological processes in the Cascadia accretionary prism and their implications for the seismogenic behavior of the seaward portion of the seismogenic zone. Observed temporal changes in fluid expulsion may indicate transient stress changes in the subduction thrust. Simon Peacock (Arizona State University) reviewed the thermal and petrological processes of the Cascadia subduction zone, which is a warm end-member subduction zone. He compared the thermal structure of the Cascadia subduction zone to the thermal structures of subduction zones off southwest and northeast Japan. It has been proposed that the downdip limit of the seismogenic portion of the plate interface is limited by temperature (350-450°C) for warm subduction zones. Dehydration of subducted sediments and igneous oceanic crust may elevate pore fluid pressures and weaken the subduction thrust fault. Metamorphic transition of basaltic rocks to ecologite is considered to be responsible for increasing slab dip and causing intraslab earthquakes.

Session 8, entitled "Present-Day Strain Accumulation and the Next Great Cascadia Earthquake", was devoted to monitoring and modeling contemporary interseismic stress and strain regimes in Cascadia, and included three talks. Garry Rogers (GSC) reviewed earthquake activity in the region. The lack of seismicity along the subduction thrust is believed to indicate that the fault is completely locked at present. Focal mechanisms of upper plate earthquakes indicate a low-stress plate boundary. Herb Dragert (GSC), with co-author Kelin Wang, provided a summary of geodetic observations and deformation modeling. Geodetic deformation along the entire Cascadia margin indicates a locked subduction fault and is consistent with clockwise rotation and northwestern translation of most of the southern Cascadia forearc. Three-dimensional elastic dislocation models describe the contemporary deformation reasonably well, but more realistic and complex viscoelastic models provide a better fit to GPS data. Takeshi Sagiya (Geographical Survey Institute) reviewed geodetic observations in Japan. The observations confirm the validity of the concept of great earthquake cycles.

The session ended with a panel discussion, "What do we know about the seismogenic zone and recurrence intervals?" One topic of discussion was whether paleoseismic data reveal a history of mixed full-length and segmented rupture of the Cascadia margin and how recurrence intervals could be reliably defined in such a situation. There also was considerable discussion on what controls the seaward limit of the seismogenic zone and the importance of this limit to tsunami hazard analysis. No local data exist to constrain the coseismic behavior of the frontal portion of the subduction fault and accretionary wedge, and, due to the large distance from the west coast of North America, Japanese tsunami records for the 1700 Cascadia earthquake cannot provide such detail. Discussions on the landward limit of the seismogenic zone centered mainly on observed interseismic and coseismic deformation as constraints. Uncertainties in paleoseismic data currently do not allow an unambiguous definition of the pattern of coseismic coastal subsidence for the 1700 Cascadia earthquake, but analytical techniques show promise to provide such a definition in the future.

The final activity of the conference was the drafting of a consensus statement on great Cascadia earthquakes. Conference participants, including the majority of scientists active in Cascadia earthquake research, as well as engineers and emergency planners, reached consensus on all key points. The landmark consensus statement, which has important implications for earthquake hazard assessment and risk reduction, is printed in full on the page 17.

Consensus Statement

- ***Damage, injuries, and loss of life from the next great earthquake at the Cascadia subduction zone will be great and widespread, and will impact the national economies of Canada and the United States for years or decades. Increased research, information exchange, public education, mitigation, and planning are needed to reduce risk.***

Damage from historical earthquakes and results of predictive damage and loss studies suggest that disastrous future losses will occur in the Pacific Northwest from a great Cascadia earthquake. Mitigation efforts in other seismically active regions and cost-benefit studies indicate that mitigation can effectively reduce these losses and helop with recovery. Accurate data acquired through geological and geophysical research, followed by information and technology transfer to key decision makers, will reduce risk to citizens of the coastal Pacific Northwest.

- ***The Cascadia subduction zone produces great earthquakes, the most recent of which occurred in 1700 and was of moment magnitude (M_w) 9.***

Geologic evidence from a large number of coastal and offshore sites from northern California to southern Vancouver Island and historical records from Japan show that most or all of the 1100 km length of the subduction zone ruptured about 300 years ago. Japanese accounts of a correlative tsunami suggest that this rupture occurred in a single earthquake, possibly of M_w 9, on January 26, 1700. The sizes of earlier Cascadia earthquakes are unknown. It is possible that some of them ruptured adjacent segments of the subduction zone over periods ranging from hours to years, as has happened historically in Japan and Colombia.

- ***Great Cascadia earthquakes generate tsunamis, the most recent of which was probably at least 10 m high on the Pacific coast of Washington, Oregon, and northern California, and up to 5 m high in Japan. These tsunamis threaten coastal communities all around the Pacific Ocean but would have their greatest impact on the U.S. west coast, which would be struck 15-40 minutes after the earthquake.***

Deposits of past great Cascadia tsunamis have been identified at numerous coastal sites in California, Oregon, Washington, and British Columbia. The distribution of the deposits and computer-based simulations of tsunamis indicate that many coastal communities in the region are partially to largely within the inundation zone of past Cascadia tsunamis. These communities are threatened by future tsunamis from great Cascadia earthquakes. Tsunami arrival times depend largely on the location of the rupture zone, specifically its distance from the coast.

- ***Strong ground shaking from a M_w 9 plate-boundary earthquake will last three minutes or more and will be dominated by long-period ground motions. Damaging ground shaking will probably occur as far inland as Vancouver, Portland, and Seattle.***

The large cities of Cascadia are 100-150 km from the nearest point on the inferred plate-boundary rupture zone. Although ground shaking at these locations will be less than that of a nearby large ($M_w \geq 7$) crustal earthquake, the shaking will last much longer and the long-period waves could damage many tall or long engineered structures. Shaking will be strongest along the Pacific coast, resulting in significant damage to coastal communities.

- ***The mean recurrence interval for great plate-boundary earthquakes in Cascadia is 500-600 years, but some of the past earthquakes had intervals less than the time that has elapsed since the 1700 earthquake.***

Intervals between successive great earthquakes range from a few centuries to about one thousand years. The number of well measured recurrence intervals is small – rarely more than five. The data show that great earthquakes have occurred at irregular intervals, but they do not show whether the earthquakes cluster or are randomly distributed in time. Because the recurrence pattern is poorly known, probabilities that the next earthquake will occur within particular intervals have broad ranges.

- ***The Cascadia plate boundary is currently locked, and the locked zone is offshore and widest off northwest Washington. The maximum area of seismogenic rupture is 1100 km long and 50-150 km wide.***

The location and size of the seismogenic portion of the plate boundary are critical for determining earthquake magnitude, tsunami size, and the strength of ground shaking. The landward limit of the "locked" portion of the plate boundary, where no slip occurs between the Juan de Fuca and North America plates during periods between earthquakes, has been delineated from geodetic measurements of the deformation of the land surface. However, few or no data constrain the seaward limit of the locked zone. In addition, the transition zone, which separates the locked zone from the zone of continuous sliding to the east, is also poorly constrained. Earthquake rupture may extend an unknown distance from the locked zone into the transition zone.

- ***Movement on some crustal faults near the coast may accompany plate-boundary earthquakes and increase the size of the tsunami and the intensity of local ground shaking.***

Detailed mapping along the coast of Cascadia on the adjacent continental shelf have revealed the presence of numerous folds and faults that were active during Quaternary time and perhaps remain active today. The question of whether some crustal faults slip during plate-boundary earthquakes, and thus are independent seismic sources, was debated at the conference. Movement on crustal faults does not explain the coastal coseismic subsidence evidence in some areas, which can only be interpreted as resulting from plate-boundary rupture. The evidence, however, does not disprove that some faults ruptured before, during, or immediately after great earthquakes. This issue is important for seismic risk assessment because moderate or large earthquakes might occur on crustal faults close to urban areas, and displacements of the seafloor along such faults could trigger tsunamis with very large waves.

Abstracts

SCULPTURING OF WAVE-CUT PLATFORMS BY TSUNAMI: PERSPECTIVE FROM CRESCENT CITY, CALIFORNIA

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Bedrock sculpturing of semilithified Miocene sandy mudstone exposed on a wave-cut platform has produced a variety of erosional forms that include grooves, which may be straight or sinuous. Straight grooves form by preferential incision of regional joints. Sinuous grooves are not fracture-controlled, are oriented parallel to wave run-up, and exist as closely-spaced subparallel, non-connecting, internally-drained grooves that are best developed on higher platform ramparts. Sinuous grooves have a mean length of 258 cm, mean maximum width of 14 cm, mean width/length ratio of 0.08. They are not as deeply incised as straight grooves, do not serve as conduits for low-tide runoff during winter months, and typically terminate by shallowing and narrowing in both seaward and landward directions. Sinuous appearance results from trains of linked comma-shaped depressions, commonly with the blunt, highly curved end of each being most deeply incised and oriented seaward.

While a seasonal cycle of beach aggradation and degradation combined with sediment transport and bedrock erosion accompanying low-tide runoff and high-tide wave motion accounts for form modification of sinuous grooves, it is unlikely to account for their origin. Groove genesis reflects corrasion of bedrock highs and/or cavitation associated with turbulent vortices during tsunami run-up. This interpretation is based upon a model has been proposed by E.A. Bryant and R.W. Young (1996) to explain the generation of similar features preserved in coastal bedrock platforms of southeastern Australia. Tsunami-emplaced sand layers are common within back-barrier bogs in coastal northernmost California, suggesting that wave-cut platforms have logically been subjected to supercritical flow engendered by tsunami inundation.

Since all coasts are potential sites of tsunamis due to earthquakes or ocean island or shelf margin collapse, efforts should be made to correlate tsunami sands in coastal bogs with bedrock platform erosional features and extensively reworked (hummocky cross-stratified) shelf sediments and/or tsunami-engendered sediment gravity-flow deposits of trenches and inner trench slope basins.

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SEISMIC HAZARD FROM GREAT EARTHQUAKES ON THE CASCADIA SUBDUCTION ZONE

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Previous Canadian seismic hazard models intended for the next National Building Code have used a deterministic (or scenario) representation to generate the shaking hazard from the Cascadia subduction zone by defining a line that represents the closest point of energy release and sliding a magnitude 8.2 earthquake along the line to generate hazard in the radial directions (using the Youngs *et al.* ground motion relation). A M8.2 earthquake was chosen as having substantially the same local shaking as the M9+ earthquakes we actually expect. We took the scenario event (of mean return period of 500 to 600 years) to represent the time-independent estimate of the 0.0021 p.a. (10%/50 year hazard), and we took the mean plus 1 sigma ground motions of the scenario event to (crudely) represent the 2%/50 year (0.0004 p.a. or 1/2500 year) shaking. The shaking is combined in a "robust" manner to give hazard maps - by taking the larger of the Cascadia and the probabilistic source zone hazard at each site. For sites near the subduction zone Cascadia usually dominates at most periods, for distant sites the probabilistic dominates at all except the longest periods, but where the contributions are sub-equal our robust approach underestimates the combined hazard.

Therefore we model great Cascadia earthquake motions probabilistically by: a) using the Flück-Hyndman-Wang definition of the seismogenic fault area; b) assuming a high fraction of the plate tectonic convergence rate across this area is released as seismic energy; c) assuming only great earthquakes which rupture the entire length of the zone; d) taking 500 years as the average return period; e) taking the range 300-800 years as the likely range in inter-event intervals, and then working backwards from the largest possible earthquake to smaller events until the plate tectonic slip rate is matched. We use a modification of the FRISK88 hazard code, a proprietary product of Risk Engineering Inc. The results are not very sensitive to the plate tectonic rate or the exact size of the largest events, but are sensitive to whether the zone fails in single M9 or multiple M8+ events. Moving from this "seismotectonic probabilism" to a "non-Poissonian probabilism" (terms defined by Muir-Wood) by incorporating stress loading from both plate motions and adjacent earthquakes will take a significant increment of knowledge.

Main question: What is the inter-event timing variability between great Cascadia events? This is tied in with the following, which may need to be solved first: Does every M>7.5 Cascadia subduction zone earthquake rupture the entire length of the plate boundary?

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EARTHQUAKE THREAT IN THE PACIFIC NORTHWEST: FINANCIAL PERSPECTIVE

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Earthquake, like other low frequency high consequence events, gets little respect. Many stakeholders refuse to recognize the potential financial impact of these events. Thus, developers continue to build projects in areas of high seismic risk that are otherwise attractive; financial institutions underwrite these developments and provide mortgage funds to buyers who willingly buy these properties. State and local governments do not discourage development (although they do attempt to establish and enforce minimal building codes).

The development of earthquake risk models has improved the availability of information regarding the likelihood and potential consequences of seismic events. This has not noticeably improved respect for the financial consequences of these events by most stakeholders. Further information regarding the efficacy of loss reduction and avoidance strategies is largely unavailable. This precludes the kinds of cost benefit analysis that might otherwise encourage improvements in construction, siting, etc.

The seismic community must partner with the design and building communities to improve understanding of both the potential financial impact of seismic events and the cost/benefit of reducing that impact. Steps need to be taken to better quantify for the various stakeholders (developers, designers, builders, financiers, and owners) the financial impact of these low frequency high consequence events with the ultimate goal of internalizing those consequences in order to drive more rational decision making.

QUESTIONS ABOUT USING LIQUEFACTION FEATURES TO ESTIMATE STRENGTH OF SHAKING IN THE 1700 CASCADIA EARTHQUAKE

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The 1700 Cascadia earthquake produced hundreds of liquefaction features now exposed along the Columbia River, 30-60 km inland from the coast. Some of these features, as much as 45 km inland, are vented-sand volcanoes that erupted onto a soil that subsided during the 1700 earthquake. To the north at Grays Harbor, deposits of the 1700 tsunami cap dikes that cut through such a subsided soil.

Still far from certain, however, is how hard the ground shook. According to Obermeier and Dickenson (1997), the 1700 Cascadia earthquake failed to produce liquefaction features as large or abundant as those from the 1811-1812 New Madrid earthquakes or the 1964 Alaska earthquake. Citing Columbia River sites where they recognized no forcefully intruded sand, Obermeier and Dickenson (1997, p. 63) estimated that the shaking "only exceptionally might have much exceeded 0.25 g". These comparisons and estimates raise many difficult questions:

1. **Among areas of liquefaction from modern earthquakes of magnitude 8 or larger, which provide the closest analogs for liquefaction susceptibility along the Columbia River in 1700?** In the case of New Madrid, most of the liquefaction features came from sand beneath Mississippi River floodplains tens of kilometers wide, and the features resulted from a series of three or four earthquakes. The features along the Columbia River, by contrast, are located on islands rarely more than 1 km wide, and they probably resulted from a single earthquake.
2. **Are liquefaction features more abundant from the 1964 Alaska earthquake than from 1700 Cascadia?** In the sole numerical comparison, liquefaction features from 1964 along nearly 3 km of river banks near Portage (Walsh *et al.* 1995, Table 1) are about as abundant as the liquefaction features counted along 3 km of Columbia River banks 30-60 km inland from the coast (Atwater 1994, Fig. 6).
3. **Has erosion removed most of the liquefaction features that formed along the Columbia River in 1700?** Along the Columbia River, liquefaction features are best exposed along riverbanks that have retreated 100-300 m since the Columbia's nautical charting began in the 1870s. Near Portage in 1964, most liquefaction features formed within 300 m of rivers (McCulloch and Bonilla 1970, p. 54).
4. **By what engineering criteria, if any, does a lack of forceful intrusions set a reliable upper bound for the strength of shaking?** Obermeier and Dickenson (1997) used data of Ishihara (1985), who from two earthquakes obtained sharp thresholds for ground failure that depend on acceleration, the thickness of liquefiable deposits, and the thickness of non-liquefiable deposits above them. However, in a comparable study of ten other earthquakes, Youd and Garris (1995) found many examples of high acceleration that failed to produce the ground failure predicted by Ishihara.
5. **Which sand intruded forcefully and which rose passively?** If Ishihara's thresholds nonetheless apply to liquefaction along the Columbia River, they apply solely to sand that intruded forcefully, not to sand that welled up in lateral spreads. Obermeier and Dickenson (1997, p. 56) discounted many dikes along the Columbia River as lateral spreads, stating that most of the dikes "trend parallel to and increase in abundance toward the streambanks or the shoreline." This statement conflicts with available measurements of about 200 dikes; these dikes show little or no tendency to strike parallel to shorelines (Atwater 1994, Fig. 5).
6. **How much outcrop must be surveyed to confirm that forceful intrusions are absent?** As noted by Obermeier (1996, p. 70), "there is no well-defined procedure for determining the amount of outcrop that must be searched for liquefaction features in order to support a conclusion based on negative evidence." An intrusion-free outcrop along the Columbia

River, though 70 m long and 250 m^2 in area, overlies late Holocene deposits that contain many liquefaction features evident in vibracores (Curt Peterson, unpublished data, 1994).

7. **What are the engineering properties of sand beneath the intrusions?** Such properties have yet to be measured by standard engineering methods.
8. **Which subsurface sand liquefied in 1700, and how did the liquefaction affect the engineering properties that can be measured today?** Penetration data should be compared with signs of bedding and fluidization. Even then it may be difficult to identify the sand that liquefied in 1700, let alone infer its properties as of that time.

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EMERGENCY EVACUATION OF TSUNAMI INUNDATION ZONES: ALERTING AND INSTRUCTING AREA CROWDS OF PRIMARILY VISITORS UNFAMILIAR WITH OCEAN HAZARDS

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Oregon's oceanshore community populations fluctuate significantly, winter to summer, and on popular holidays. A good example of this is the Cannon Beach Fire District which extends along nine miles of popular recreational and vacation seashore only ninety minutes away from the constantly expanding inland Portland-Vancouver Metro Area. During summer and popular holidays, population of the District is eight to ten thousand. Of this, only 1700 are year-round residents who, generally, are well informed about tsunami hazards. The six to nine thousand other people thronging the area, having come for recreation from inland communities, if they've any awareness at all about tsunamis, broadly have little to no sense of personal reality about possibility of danger from the ocean suddenly flooding ashore to injure or kill them. Since 1988, the Cannon Beach Fire District has protected its residents and visitors against this low but very dangerous potentiality with a community warning system (COWS). The system is designed to be responsive to scientists' estimate of only a few minutes remaining between a significant earthquake and arrival of tsunami assault. COWS is programmed to sound ninety seconds of attention-getting alerting siren throughout the district's most hazarded, densely populated areas - the sirening is immediately followed by repetitive voice announcements explaining imminence of high-speed ocean flooding of all low areas. People in such areas are told to go quickly to nearest high ground away from the ocean. During peak-population periods, an estimated 6300 non-residents are in the local tsunami inundation zone. The system's ability to broadcast voice instructions avoids dangerous ambiguity of community emergency alarm such as experienced in Hilo, Hawaii, in May 1960 when a large proportion (44.5%) of residents misinterpreted meaning of the community's warning system using mechanical sirens to warn of the approaching Chilean tsunami (Lachman *et al.* 1961). Only 32% evacuated after the warning (Dudley and Lee 1998). Cannon Beach Fire District policy since September 1986 is to evacuate hazard areas immediately upon any locally experienced ground disturbance. An evacuation begun under that policy but found unwarranted by receipt of official evaluation that the disturbance isn't tsunamigenic can be halted by the system sounding "All Clear" and broadcasting an explanation throughout the hazard areas. In March 1993 and March 1996, local ground disturbance required precautionary evacuation, the system sounding the alarm and broadcasting its emergency instructions half an hour before official evaluation of the disturbances arrived advising they were not tsunamigenic. Community response to both events was positive, the precautionary evacuations being considered valuable practice of emergency actions.

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CASCADIA SUBDUCTION EARTHQUAKE AFFECTS ON BURIED PIPELINES – A COMPARISON TO CRUSTAL EVENTS

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Long-duration ground shaking from a moment magnitude (M_w) 9.0 subduction earthquake will have a much greater impact on buried pipeline systems than a short duration M_w 7.0 crustal event producing the same local shaking intensities. This will occur because of wider-spread liquefaction and larger permanent ground deformations (PGDs). It is important to consider the type/duration of earthquake when estimating pipeline damage caused by earthquakes.

Given the same ground shaking intensity, the probability of liquefaction occurring can double for a subduction versus a crustal earthquake. The relative Magnitude Scaling Factors (MSFs) can differ by as much as a factor of two between the two events. Similar shaking intensities would occur about 100 km from the subduction fault, and about 30 km from the crustal fault. For example, approximately the same shaking intensity would occur in Auburn, Washington from a M_w 9.0 Cascadia subduction earthquake as from an M_w 7.0 Seattle Fault earthquake. The probability of liquefaction could be double for the subduction event for a selected location in Auburn. Similar probabilities of liquefaction for the two events would occur in the Kent-Renton area about 15 km from the Seattle fault, even though the ground shaking intensity would be twice as strong from the crustal event. Note that the probability of liquefaction is also based on the distribution of soil liquefaction susceptibility. These estimates are based on Seed and Idriss's work (1982) as well as subsequent work by researchers such as Andrus, Stokoe, Youd, and Noble. There is a question about the validity of application of these MSF relationships for magnitudes this large. It may be that the MSF is not as extreme as described above.

When liquefaction does occur, the PGD resulting from lateral spreading could be more than seven times greater for an M_w 9.0 event 100 km away than for an M_w 7.0, 30 km distant, where the shaking intensity would be about the same. However, this estimate is based on Youd's Multiple Linear Regression analysis (MLR) (1999), which limits its application to a maximum M_w of 8.0. Hamada's proposed methodology relates PGD directly to the duration of strong ground shaking (1999). Application of Hamada's relationship results in similar estimates of increased PGDs when comparing the two earthquakes. It may be that the application of both the MSF and the MLR result in some double counting.

Buried pipelines are the primary component of lifeline systems delivering water, natural gas, and liquid fuel, and carry raw sewage away from population centers. These systems are vital to provide post-earthquake emergency response, and to allow society to continue to function following an event.

Buried pipeline failure rates are a function of the percent of the area that liquefies, and the net PGD of the ground. A "rule of thumb" is that the unit failure rate for pipelines is ten times higher in liquefied soils that undergo PGD compared to stable soils (Ballantyne 2000). For the same shaking intensity, the expected pipeline failure rates in liquefiable areas could double between a crustal and subduction event due to the higher percentage of the area that liquefies. For cast iron pipe, increasing the PGD by a factor of seven increases the unit failure rate by a factor of 50 (Ballantyne 2000). Cast iron pipe in soil with a PGD of 0.1m is estimated to have a failure rate of 1/km. Cast iron pipe in soil with a PGD of 0.7 m would in many cases require complete replacement.

Combining the increased probability of liquefaction, a factor of two, and the increased pipe vulnerability due to PGD, a factor of 50, would result in 100 times as many liquefaction/lateral spread-related pipeline failures for a subduction event compared to a crustal event in an area with similar intensities. We understand that MSFs and MLR-estimated PGDs for M_w 9.0 earthquakes are uncertain because of a lack of data. Even if the combined estimates are off by an order of magnitude, it is clear that a subduction earthquake will have a catastrophic impact on lifeline systems.

Further, if the subduction event breaks the entire length of the fault, not only will it have catastrophic effects within each community, but it will also impact lifelines in all population centers along its alignment, including Vancouver, Seattle, and Portland all at the same time.

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NEW GEOLOGY AND SEISMIC RISK REDUCTION

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As the International Decade of Disaster draws to a close we note some areas of the world where new discoveries in geology reveal seismic hazard far greater than our short incomplete historical record might suggest. It is not adequate in these areas to key risk reduction to historic records of earthquake activity.

In Cascadia where the challenge is to translate this new geologic knowledge into effective policy society initially viewed geologic information differently than it did historic experience. For example, where historic earthquakes are part of local memory it is relatively easy to promote the need for realistic efforts to avoid similar losses in the future. Where there is no historic record of earthquakes of large size, but there is a geologic record of such hazard, it is more difficult to sell the public on the reality of the hazard and the need to address it.

In Oregon we have learned that effective techniques for dealing with public acceptance involves two phases. First, the reality of the future earthquake hazard first had to be sold to the public and to policymakers. Second, was the need to select the appropriate level of risk reduction in appropriate forums.

Mechanisms for communicating the risk are diverse and include repeated presentation of the message in a variety of formats. These include workshops, symposia, videos, publications, media releases, newscasts, signs, brochures, and personal appearances. All presentations should be founded on adherence to credible data and interpretations, honesty with the public with regard to the uncertainties, and on practical information of value to policy discussions.

For Oregon new and practical information that drives policy discussions includes statewide probabilistic earthquake maps, local scenario earthquake maps, ground response maps on a statewide basis and a community basis, building inventories, and topical analyses addressing such things as lifelines and tsunamis.

In advancing this information it is wise for the scientist to recognize the difference between his role as a producer the data and a possible second role to assist in the selection of a balanced course of action for risk reduction. The second role includes valid economic considerations and value judgments beyond pure science.

We appeal to you, the scientific community to continue your work in the Pacific Northwest to continue to provide the data to more accurately characterize the hazard. We appeal to you also to assist in the more complicated discussions to select acceptable reduction of risk posed by the earthquake hazard while being mindful of the greater breadth of the discussion.

THE DILEMMA OF GREAT SUBDUCTION: *or* HOW I LEARNED TO LOVE POLITICS AND STOP WORRYING ABOUT THE EARTHQUAKE

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Our understanding of "giant" M_w 9 earthquakes on the Cascadia subduction zone has grown dramatically within the geoscience community within the last 10-15 ybp $\pm$ 5. The "Great Cascadia Earthquake Tricentennial" of the January 26, 1700 "giant" M_w 9 plate boundary rupture has refocused our attention on this megahazard: (Had the pilgrims landed at "Haystack Rock", near Cannon Beach, instead of Plymouth Rock; the historic memory of this last event would have no doubt been more strikingly instilled into our consciousness.) But Society's understanding of the threat (which includes not only building seismic safety but also tsunamis) and its willingness and preparedness to deal with such an event has lagged far behind (Bela 1992, Earthquake Spectra 2000).

Oregon has only had the requirement of one state-wide Building Code (based on the Uniform Building Code) since 1974. In about a quarter century, the state (including the coast) has gone from the "lowest" seismic risk (Zones 1 {V and VI } and 2 {VII}) to the "highest" (Zones 3 {VIII and higher} and 4 {proximity to major fault systems}). The decade between 1988 (a major rewrite of the UBC placing all of Oregon in Zone 2B) and 1998 (when the state begrudgingly upgraded the southern two-thirds of the coastline to Seismic Zone 4, ignoring the NEHRP 97 new seismic design maps) was turbulent and traumatic.

But the subduction zone earthquake introduced a whole new Ball Game into the local situation, which has proved very difficult to face up to in the present Building Code approach. Ground motion parameters derived for the subduction zone (pga) are mostly applied with regard to the California crustal earthquake model and experience, ignoring the long period energy content, duration of shaking, and the building code experiences of other places that routinely design with these parameters in mind (Japan, Chile, Mexico).

The reason for the dilemma created in transferring geologic knowledge into effective emergency response planning and public policy lies partly in the interdisciplinary aspects of the problem. No one segment knows "enough" about all the other elements or factors involved to *budge* comfortably very far from the "status quo". ("We all guess, but we all guess *differently*!") We're all (structural engineers, geologists, seismologists, geotechnical engineers) "in the same boat", but no one is in the "*Leader***ship**." "We're All [including politicians] *Subducting* In This Together." But mostly it's like watching the movie JAWS without the music! Why? Compounding the problem, since these groups are not used to communicating with one another, a real Leadership is yet to emerge. (At the recent USGS Seismic Hazards Mapping Workshop in Seattle, March 30-31, 2000; a well respected structural engineer who has been proactively engaged in building seismic safety for more than a decade asked: "*What's a turbidite?*") True Leaders have a consistent and persistent behavior and view of where they're going. "If you *don't* know where you're going, any road will take you there (or 'when you get there, you'll be lost!')."

Although "Risk" and "Hazard" are often used synonymously, it is useful to keep them apart (Peterson 1988). Risk = Value x Vulnerability x Hazard (probability). Keep in mind, however, that when we multiply (Geology) x (Politics) x (Economics) and then try to "square" it with (Structural Engineering)^2, we get something very different than Risk. Science is interested in the best explanation of a particular phenomenon. Politics, on the other hand, is "what people want".

The experience with the May 18, 1980, volcanic eruption of Mt. St. Helens just 20 years ago taught us that the scientific community has an ethical obligation to explain clearly their "conclusions" to responsible officials and the public, even if society resists:

"Although scientific understanding of volcanoes is advancing, eruptions continue to take a substantial toll of life and property. Some of these losses could be reduced by better advance preparation, more effective flow of information between scientists and public officials, and better understanding of volcanic behavior by all segments of the public. The greatest losses generally occur at volcanoes that erupt infrequently where people are not accustomed to dealing with them. Scientists sometimes tend to feel that the blame for poor decisions in emergency management lies chiefly with officials or journalists because of their failure to understand the threat. However, the underlying problem embraces a set of more complex issues comprising three pervasive factors.

"The first factor is the volcano: signals given by restless volcanoes are often ambiguous and difficult to interpret, especially at long-quiescent volcanoes.

"The second factor is people: people confront hazardous volcanoes in widely divergent ways, and many have difficulty in dealing with the uncertainties inherent in volcanic unrest.

"The third factor is the scientists: volcanologists correctly place their highest priority on monitoring and hazard assessment, but they sometimes fail to explain clearly their conclusions to responsible officials and the public, which may lead to inadequate public response. Of all groups in society, volcanologists have the clearest understanding of the hazards and vagaries of volcanic activity; they thereby assume an ethical obligation to convey effectively their knowledge to benefit all of society. If society resists, their obligation nevertheless remains. They must use the same ingenuity and creativity in dealing with information for the public that they use in solving scientific problems. When this falls short, even excellent scientific results may be nullified." (Peterson 1988)

A prestigious Committee on the Cascadia Subduction Earthquake Source Zone, patterned after the Committee on the Alaska Earthquake, National Research Council of the National Academy of Science (National Research Council 1973), could best provide the focus and *Leader***ship** necessary to ethically and honestly prepare and pre-plan for these truly awesome phenomena.

"In any moment of decision the best thing you can do is the right thing, the next best thing is the wrong thing, and the worst thing you can do is nothing." – Theodore Roosevelt

"The problem with doing 'nothing' is . . . that you never know when you're through."

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CRUSTAL STRUCTURE OF THE CASCADIA SUBDUCTION ZONE FROM SEISMIC REFLECTION AND REFRACTION PROFILING: RELATION TO EARTHQUAKES ON THE MEGATHRUST

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The Cascadia subduction zone is characterized by a very heterogeneous distribution of earthquakes in both the upper (North America) and lower (Juan de Fuca and Gorda) plates and by a conspicuous lack of historic earthquakes on the plate boundary since January 26, 1700. Controlled source seismic experiments completed since 1985 form a network of transects that image the crustal structure of the subduction zone. While most of these studies provide 2-D profiles, 3-D studies have been conducted for the most seismically active Puget Sound and Mendocino Triple Junction regions.

We combine available seismic profiles to construct a 3-D model for the geometry of the subducting plate and of the crustal blocks that compose the upper plate. Using this 3-D model, we infer variations in the geometry of and material property contrasts across the interplate boundary (the megathrust). Active source seismic experiments, complemented and extended by potential field data, delineate the depth extent of upper plate blocks having different physical properties, which may modulate the regional heterogeneity in stress resulting from the subducting plate geometry and thus may control the distribution of seismicity along the megathrust. Similarly, active source seismic data allow us to more precisely constrain the depth to the top of the subducted oceanic plate, confirming prior indications of upward warping of the oceanic plate beneath the Olympic peninsula and indicating downwarping of the subducted plate near the Mendocino Triple Junction.

Current research is focussed on refining velocity models for the interplate boundary and on understanding the implications of the variable plate boundary structure. Although along strike and dip variations in the apparent seismic reflectivity of the plate boundary suggest a megathrust having variable material properties in the shear zone, quantifying these variations requires detailed modeling of seismic waveforms to resolve features at scales of interest (10s-100s of meters) at depths up to 30 km. Similarly, such spatial resolution is needed to map variations in the thermal conductivity of the upper plate which may significantly influence the thermal state of the lower plate, as well as to find seamounts and/or buried ridges on the lower plate that may act as earthquake asperities or segmentation points on the megathrust.

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COULD TEMPORAL CHANGES IN FLUID EXPULSION PATTERNS FROM COLD SEEP REGIONS LOCATED ON FAULTS BE USED TO MONITOR TRANSIENT STRESS CHANGES IN THE SEISMOGENICALLY COUPLED REGION OF THE SUBDUCTION THRUST?

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We address here the possibility that changes in flow rates at cold seeps situated on deeply rooted fault zones could used as indicators of changes in stress in the forearc because of the modulation of fracture flow at depth. Existing evidence for transient flow in faults includes thermal and chemical anomalies in Ocean Drilling program bore holes in accretionary wedges including the Cascadia wedge (Davis *et al.* 1995). The potential that there is a linkage between transient flow and faulting episodes is intriguing, and the Cascadia margin is a good system to test this hypothesis. The accretion of thick incoming hemipelagic and turbidite sequences led to the rapid 30-50 km seaward growth of the accretionary wedge over the last 2 Ma. Off Oregon, the low angle taper of the recently accreted portion of the wedge changes to a higher taper angle further back in the forearc. An indirect inference can be drawn that the change to a higher taper angle reflects a change from a low degree of coupling near the toe greater coupling on the seismogenically active portion of subduction thrust. The high levels of hydrogeologic activity at the toe also suggest there is a linkage between the low taper and overpressuring at depth. Many of the cold seeps, methane gas vents, and significant methane hydrate deposits are situated along faults (Goldfinger *et al.* 1999, Suess *et al.* 1999). Could flow rates at such seeps be tectonically modulated? To date, there have been no long-term records of fluid seep rates that were available to evaluate whether such a hypothesis could be tested, given the right hydrogeologic setting.

Reported here are the results from recent long-term measurements of fluid expulsion rates that were made at major seeps regions at the summit of a faulted anticlinal ridge situated off Newport, Oregon, just above the potentially seismically coupled region of the décollement. The resulting record of flow rate and in some cases fluid chemistry, span approximately 30 and 50 days in 1998 and 1999, respectively. The measurements were made as part of the TECFLUX project, a collaborative research effort between several institutions including OSU, GEOMAR, and SIO during 1998 and 1999 (Torres *et al.* 1998, 1999; Bohrmann *et al.* 2000). Although this particular project's objectives were geared more towards understanding the dynamics of gas hydrate development and gas venting, rather than tectonic effects, they serve as a thought provoking example of the possibilities represented by long term measurements made at seeps.

Our study utilizes a recently developed osmotically driven geochemical and aqueous flux instrument that is designed to quantify the fluid, and under some circumstances, chemical fluxes processes across the sediment/water interface of the forearc region. Both inflow and outflow rates on the order of 0.01 to 1500 cm/yr can be obtained together with fluid chemistry (Tyron *et al.* 1999a, b). Groups of flux meters were placed on different cold seep biological communities in order to ascertain whether these could be developed into a visual proxy to assist in providing semiquantitative estimates of flux. The results indicate that the fluid expulsion from the seeps is not a steady-state process either spatially or temporally, or even in direction on almost any time scale. Both the fluid chemistry and ecology of the seeps appears be controlled by or is responding to the nature of this variability. Temporal changes in both rate and direction were observed over short tidal type periods and longer periods of weeks or months. The shear complexity of the changes in rates suggests to us that that several non-linear processes are operating to modulate flow in this particular setting. Potential mechanisms generating transience at this locality include tidal effects, tectonic effects, subsurface movement of free gas and gas venting episodes, and hydrate growth and destruction. As this location is currently the site of large-scale methane gas migration and venting we currently favor these factors as the primary explanations for the transience. It does however raise the very intriguing possibility that other seep locations on faults connecting to the seismogenic zone (situated away form massive gas venting locations) could be used to monitor tectonic modulated flow and seepage.

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THE IMPACT OF UNCERTAINTY ON PROBABILISTIC AND DETERMINISTIC GROUND-SHAKING HAZARD FROM GREAT EARTHQUAKES ON THE CASCADIA SUBDUCTION ZONE

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An important issue concerning the characterization of seismic hazard in the Pacific Northwest is the large uncertainty in the size, recurrence interval, and expected level of ground shaking of great interface earthquakes on the Cascadia subduction zone (CSZ). For example, it is likely that the entire CSZ ruptured in January 1700 in a giant $M_w \approx 9$ earthquake (e.g., Satake *et al.* 1996). However, it has also been suggested that the CSZ can rupture in a series of smaller earthquakes of $M_w \approx 8$ to 8.5 (e.g., Geomatrix Consultants 1995). In order to bring the impact of this issue into focus, we have explored the difference in the deterministic and probabilistic estimates of strong ground motion that can be expected to result from reasonable estimates of the uncertainty in the seismotectonic characteristics of the CSZ. We did this by developing a set of credible scenarios regarding the location, size, frequency, and ground-motion attenuation characteristics of potential great CSZ earthquakes. We then evaluated how each of these scenarios impacts the expected ground shaking in the metropolitan areas of Seattle and Portland. These scenarios include differences in (1) the assumed down-dip and landward extent of the seismogenic rupture zone, (2) the magnitude and recurrence interval of the expected characteristic earthquakes, and (3) the attenuation relations used to estimate ground motion. We evaluated each of these scenarios deterministically. We also used these scenarios to construct a logic tree of alternative hypotheses from which we performed a probabilistic seismic hazard analysis (PSHA) using Monte Carlo simulation. The alternative scenarios are intended to capture the possible range in the key seismotectonic parameters of the CSZ that have been proposed in the literature (e.g., Atwater *et al.* 1995, Geomatrix Consultants 1995). All scenarios were given equal weight in the PSHA.

We used two hypotheses to characterize the uncertainty in the location of the seismogenic rupture zone (e.g., Hyndman and Wang 1995). The first hypothesis assumed that seismogenic rupture occurs only on the locked part of the plate interface (the locked zone). The down-dip edge of this locked zone is defined by the 350° isotherm, which from geophysical constraints is believed to occur at a depth of about 10 km. The second hypothesis assumed that seismogenic rupture occurs on both the locked zone as well as the transition zone between the locked and freely slipping part of the interface (the locked plus transition zone). The down-dip edge of this locked plus transition zone is defined by the 450° isotherm, which from geophysical constraints is believed to occur at a depth of about 20 km. We used two hypotheses to characterize the uncertainty in the magnitude of the expected characteristic earthquakes on the CSZ. The first hypothesis assumed that the entire CSZ ruptures in a single giant earthquake of about M_w 9.0. The second hypothesis assumed that the CSZ ruptures in a series of M_w 8.4 events (two are needed to fill the entire length of the CSZ).

We used two or three hypotheses to characterize the uncertainty in the recurrence interval of the characteristic earthquakes on the CSZ depending on the magnitude of the earthquake. For the M_w 9.0 event, we assumed a recurrence interval of 450 or 900 yr, consistent with the range of values derived from geophysical, paleoliquefaction, tree-ring, and turbidite-flow data. For the M_w 8.4 event, we assumed a recurrence interval of 225, 450, 900 or 1800 years. The first two hypotheses for the M_w 8.4 event account for the possibility that individual segments of the CSZ can rupture independently from one another and that each segment has a recurrence interval consistent with the available data. The latter two hypotheses account for the possibility that the smaller events can be clustered closely in time, where the cluster has a recurrence interval that is consistent with that of a single larger event. For example, two earthquakes with a recurrence interval of 1800 yr will have a total return period of 900 yr when modeled in the PSHA, which is consistent with a 900-yr recurrence interval for a single large earthquake. We used two hypotheses to characterize the attenuation of ground motion. The first hypothesis assumed that the Crouse (1991) attenuation relation is correct. The second hypothesis assumed that the Youngs *et al.* (1997) attenuation relation is correct. Both attenuation relations were evaluated for firm soil.

We evaluated the hazard for PGA and for 5%-damped response spectral acceleration at spectral periods ranging from 0.05 to 3.0 s. We used the spectral ordinates to calculate deterministic response spectra for each proposed scenario and to calculate uniform hazard spectra at return periods of 475 and 2500 yr and confidence intervals of 68% ($\pm 1\sigma$) and 90% ($\pm 1.5\sigma$) from a PSHA that incorporated all scenarios, each weighted by their likelihood of being correct. The deterministic results indicate that the largest ground motion for Seattle comes from a M_w 9.0 event rupturing the locked plus transition zone with ground-motion attenuation characteristics given by the Crouse attenuation relation. The largest ground motion for Portland comes from the same event but with attenuation characteristics given by the Youngs *et al.* attenuation relation. For both Seattle and Portland, the smallest ground motion comes from a M_w 8.4 event rupturing the locked zone with ground-motion attenuation characteristics given by the Youngs *et al.* attenuation relation. The difference in the ground motion from these two scenarios ranges from 153% to 167% for Seattle and 34% to 160% for Portland, depending on the spectral period.

The probabilistic results for Seattle indicate that the difference in the 475-year ground motion ranges from 127% to 208% for the 68% confidence interval and from 391% to 798% for the 90% confidence interval, depending on the spectral period. For the 2500-yr return period, this difference ranges from 38% to 85% for the 68% confidence interval and from 61% to 116% for the 90% confidence interval. For Portland, the difference in the 475-year ground motion ranges from 100% to 125% for the 68% confidence interval and from 301% to 580% for the 90% confidence interval, depending on the spectral period. For the 2500-yr return period, this difference ranges from 26% to 43% for the 68% confidence interval and from 48% to 68% for the 90% confidence interval. The larger uncertainty for Seattle is caused by the larger difference between the two attenuation relations and between the locations of the down-dip and landward edge of the locked zone and the locked plus transition zone. Smaller uncertainty is obtained for the 2500-yr return period because the scenario representing the largest ground shaking in each of these cities dominates this hazard. This latter result is important, since the 2500-yr ground motion is the basis for developing Maximum Considered Earthquake (MCE) ground-motion maps and design parameters in the 2000 edition of the *International Building Code* (IBC). The IBC has become the new unified standard for seismic design provisions in the United States, replacing all of the regional building codes that had previously been adopted in different parts of the country.

We conclude from the results of this study that the impact of uncertainty on deterministic and probabilistic estimates of ground motion from great interface earthquakes on the CSZ is significant and should not be ignored. Additional studies will help to reduce this uncertainty. However, until the results of these studies become available, the relatively large uncertainty that currently exemplifies our seismotectonic characterization of the Cascadia subduction zone should be explicitly factored into any seismic-hazard analyses that are done in the Pacific Northwest.

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PALEOSEISMIC GEOLOGY OF THE SOUTHERN PART OF THE CASCADIA SUBDUCTION ZONE

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During the last two decades geologic evidence of localized coseismic uplift, localized coseismic subsidence, surface fault rupture and tsunamis inundation has been identified at numerous coastal sites in northern California. This evidence, interpreted in the context of improved maps and models of the structure and tectonics at the southern end of the Cascadia subduction zone, provides a basis for characterization of repeated great earthquakes during the late Holocene.

The northern California coast differs from much of the rest of Cascadia in both its tectonic architecture and the type and structural context of the paleoseismic evidence. Between southern Oregon and the Mendocino triple junction the plate boundary is closer to shore and at a shallower depth beneath the coastline than it is along most of the Cascadia coast to the north. This places most of the northern California coastline west of the zero isobase in the region of general coseismic uplift. Additionally, a well developed fold-and-thrust belt, offshore along much of the northern part of the convergent margin, approaches the coast and extends onshore in northern California (Clarke and Carver 1992). Two systems of large seaward-vergent thrusts and associated folds, the Little Salmon and Mad River fault zones, make up the fold-and-thrust belt along the California part of the subduction zone. Late Quaternary slip on these thrusts and growth of the associated folds is reflected by progressive deformation of flights of raised marine terraces. Late Quaternary slip rates on these faults indicate they accommodate much of the plate convergence. Paleoseismic studies on several of these faults show they have repeated late Holocene displacements.

Raised Holocene marine terraces and elevated shore platforms are present where anticlines intersect the coastline. Cover sediments on the raised terrace at Clam Beach contain buried soils within dune sequences and landslide-ponded sediments that entomb fragile sedges in growth position. These sediments suggest the terrace was raised coseismically. Salt marsh stratigraphy with layers of peat, herbaceous salt marsh plants and trees buried by intertidal mud is localized in the cores of several large synclines. This stratigraphy, interpreted as recording coseismic subsidence (Jacoby *et al.* 1995), is absent at other places along the northern California coast. Radiocarbon ages for the raised Holocene terraces and the subsided marsh sequences are similar to ages for subsidence episodes along the subduction zone to the north (Atwater and Hemphill-Haley 1997). High-precision tree-ring series radiocarbon ages from buried trees and AMS ages for entombed salt marsh plants at the north end of Humboldt Bay show the most recent subsidence event occurred within about a decade of AD 1700 (Nelson *et al.* 1995).

Paleotsunami evidence is present in many wetlands along the northern California coast. The evidence includes sand sheets containing marine diatoms capped by woody debris layers and multiple fining-upward sand sequences indicative of successive wave pulses typical of large run-up locally generated tsunamis. Radiocarbon ages for the paleotsunami sands from the south part of Humboldt Bay, Lagoon Creek, and Crescent City for the last 5 events are indistinguishable at the 2 sigma level from ages for Cascadia earthquakes on the Washington coast (Atwater and Hemphill-Haley 1997). At several locations the tsunami sands are stratigraphically related to indicators of strong shaking including landslides and liquefaction and to sedimentologic, macrofloral and diatom evidence of coseismic subsidence.

At least two short subduction zone segments with slip histories different than the rest of Cascadia are present in the Mendocino triple junction region. These segments are kinematically defined by differences in convergence direction and rate resulting from the intersection of the subduction zone with the wide San Andreas and Mendocino fault - Gorda deformation zone transform systems (Tanioka *et al.* 1995). In 1992 the southern segment ruptured and produced the M_w 7.2 Petrolia earthquake and up to 1.4 meters of coseismic uplift on a ~24 kilometer long section of coast south of Cape Mendocino. Tree-ring series radiocarbon ages for subsided and buried trees in the Eel River delta on the northern segment indicate its last rupture occurred in the early 1800s. These segments constitute additional subduction earthquake sources at the south end of the Cascadia subduction zone.

Taken together, the paleoseismic evidence for Cascadia earthquakes in northern California suggests the subduction zone north of Humboldt Bay has a late Holocene seismic history that is similar to the rest of the Cascadia subduction zone in the Pacific Northwest. In northern California past great Cascadia earthquakes have included rupture of fold-and-thrust-belt faults, particularly the Little Salmon fault, and growth of associated folds. This upper plate deformation accommodated much of the plate convergence. Coseismic elevation changes along the coast have been associated with the upper plate structures. Coseismic subsidence has been confined to syncline axis while uplift occurred where anticlines intersect the coast. Large tsunamis were produced during each late Holocene event. The timing of the last 5 northern California Cascadia earthquakes can not be differentiated on the basis of radiocarbon ages from those originating further north along the Washington coast, suggesting most of the subduction zone may be unsegmented during most seismic cycles. Two short subduction zone segments with different slip histories are recognized in the Mendocino triple junction region. The southern of these ruptured in 1992, and the northern segment probably last ruptured in the late 1800s.

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TSUNAMI INUNDATION – FROM SCIENCE TO PREPAREDNESS

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Pacific and Grays Harbor Counties, on the Pacific coast of southwestern Washington, are at risk from both distantly and locally generated tsunamis. As part of the National Tsunami Hazard Mitigation Program, tsunami inundation modeling of those counties was completed in May 1999 (Walsh *et al.* in review). County emergency managers and local officials for public education and awareness and tsunami planning will use those maps. Prior to releasing the mapping information to the public, it became apparent that thoughtful planning by state and local officials was necessary for positive attention from the media, acceptance of inundation results by the public, and to avoid possible economic degradation. Meetings with elected officials, responders, and state agencies were held five months before the maps were released to the public.

-- Once the tsunami inundation areas were identified, planning the evacuation routes became a priority. It became clear that the inundation maps must be released in conjunction with the evacuation maps.

-- The GIS transportation layer was overlain on the inundation maps. That identified some communities with a single access road, thus increasing the time it would take to evacuate them. In other communities, safe nearby congregation areas was identified. Local emergency managers agreed that communities would have to work together to develop an evacuation plan within their areas.

-- With evacuation routes and congregation areas identified, state and county emergency managers ordered and installed tsunami evacuation signs. A tsunami brochure with tsunami safety tips, NOAA Weather Radio information, and tsunami evacuation maps was developed and printed for release with the inundation maps.

-- The inundation map further indicated that many communities could not evacuate within the required time. Officials embraced the book, *Surviving a Tsunami--Lessons from Chile, Hawaii, and Japan* (U.S. Geological Survey Circular 1187). This tool allows local officials to show that tsunamis are survivable if appropriate actions are taken.

-- The inundation maps were released at four local forums, two in each county. The presentations at these forums progressed from research findings and modeling by local scientists to community tsunami preparedness issues and planning.

-- Two months prior to the public forums, the local emergency managers launched an aggressive public education campaign. Radio, TV, and newspapers provided tsunami information addressing local community issues and preparing the public for the public forums and release of the inundation maps.

Lessons learned:

-- The media is a powerful tool that can provide public education and address controversial issues. The media must be part of any process that scientists or emergency managers address.

-- A partnership between scientists and emergency managers at the community forums provides a positive approach for dealing with hazards and allows scientific work to be credited and validated.

-- Holding multiple forums provides immediate feedback and allows presenters to restructure their message to the public. It also allowed the local media to carry coverage of forums that stimulated community participation in future forums. At the last public forum more than 300 citizens from that community participated.

-- The science and engineering communities need to work closely with emergency managers to identify and develop products that will reduce the loss of life and property in local communities.

TSUNAMI EVACUATION ISSUES AND STRATEGIES

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Tsunamis are probably the most life-threatening hazard of a Cascadia subduction zone earthquake. Coastal residents will have 30 minutes or less after the earthquake shaking stops to reach high ground. The important issues are: Where is high or safe ground? Which route(s) should people take? Where should they end up? Will there be enough food, water, and shelter at these destination sites? People on the coast should instinctively move to high ground when the shaking stops. This is why education is vitally important. Coastal counties and cities in coordination with the state, have been making good progress in raising awareness and educating the public about tsunami (and earthquake) hazards, as well as taking preparedness and mitigation steps beyond the education/awareness phase. The Oregon Department of Geology and Mineral Industries has produced tsunami inundation maps for the entire coast of Oregon. They restrict the construction of buildings, such as fire stations and schools, within the tsunami inundation zone. Schools within the zone are required to conduct tsunami evacuation drills yearly. These inundation maps, plus other detailed inundation maps developed for selected cities, have also been used as the basis for the production of tsunami evacuation brochures by several coastal jurisdictions, that were distributed to residents and tourists. The brochures include text and maps, which identify safe zones, evacuation routes, and/or evacuation sites. Many jurisdictions have installed tsunami hazard, evacuation route, and evacuation site signs. One town even purchased a large cargo container, placed it at a designated evacuation site, and stocked it with emergency supplies. These and many other efforts have been successful, because the coastal communities have been involved from the start and funding has been provided by local jurisdictions, the State of Oregon, and/or the National Tsunami Hazard Mitigation Program.

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MITIGATING THE NEXT GREAT CASCADIA EARTHQUAKE: EFFORTS ON CALIFORNIA'S NORTH COAST

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The Cascadia subduction zone is problematic for hazard mitigation. Recognition of the zone is less than two decades old and consensus on the general nature of the risk has emerged only recently. The last great earthquake occurred prior to European settlement, forcing the nonscientific community to rely on technical evidence to comprehend the risk. Events along the subduction zone recur infrequently by human standards and estimates as to when the next earthquake is likely vary widely. The Cascadia subduction zone also poses a previously unrecognized risk to West Coast residents, the near-source tsunami with travel times on the order of minutes. Although tsunami awareness has increased in coastal communities in recent years, there is still considerable public confusion over what a tsunami is, how quickly it can arrive, and the duration of potential hazard.

The Cape Mendocino Earthquake in 1992 (Oppenheimer *et al.* 1993) raised awareness of Cascadia earthquakes at the State and Federal levels, resulting in a FEMA-funded earthquake planning scenario describing the likely effects of a Cascadia earthquake (Toppozada *et al.* 1995). Since the release of the Planning Scenario, Federal, State and local agencies, businesses and other organizations have been working to mitigate Cascadia hazards. This has included:

• Redwood Coast Tsunami Working Group (RCTWG). The RCTWG, an organization of emergency managers, agencies and businesses from Humboldt, Mendocino and Del Norte counties, was formed in 1996 to promote public outreach projects and coordination of mitigation projects throughout the three county area. Current projects include a tsunami/earthquake education room at County Fairs. RCTWG's efforts resulted in a proclamation by the Humboldt County Board of Supervisors that the year 2000 is "Cascadia Earthquake Awareness Year".

• Planning exercises involving local, regional, state agencies responsible for emergency planning and response.

• Publications. Over 200,000 copies of an earthquake awareness/ preparedness magazine (Dengler and Moley 1999) have been disseminated in northern California and southern Oregon. A tsunami brochure for North Coast residents is available in both English and Spanish versions. A pamphlet "Living Safely in Your Schools" has been distributed to all teachers and staff in Humboldt and Del Norte Counties.

• Earthquake Education through Theatre Arts Project. A collaborative effort between a regional theater school, Humboldt State University and Humboldt county public schools has produced videotaped public service announcements on earthquake and tsunami safety. The program received an "Award in Excellence" from the Western States Seismic Policy Council (WSSPC) in 1998 for outreach efforts in education.

• Assessment. Four surveys have been conducted since 1993 on preparedness actions taken, perception of risk, and the effectiveness of education efforts. Since the initial survey, the percentage knowing what a tsunami is has increased from 78 to 92%, what the Cascadia subduction zone is from 16 to 29 %, and believing a future earthquake "very likely" in the next 10 years from 72 to 91%.

• Curriculum materials and teacher training. Professional Development Courses for teachers and students in the credential program are offered at Humboldt State University on tsunamis, earthquake education curriculum, and the faults of the Cascadia fold and thrust belt. The Humboldt Earthquake Education Center has developed a tsunami curriculum for K - 12 schools.

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RECENT MEASUREMENT AND INTERPRETATION OF CRUSTAL MOTIONS ALONG THE CASCADIA SUBDUCTION ZONE

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Over the past decade, the establishment of global and regional continuous GPS networks has provided the fundamental infrastructure to make geodetic measurements with extreme accuracy over distances of thousands of kilometers. Global networks (e.g. Beutler *et al.* 1998) are used to generate the precise GPS satellite orbits and the global reference frame needed to establish global positions at the sub-centimeter level; regional networks (e.g. Dragert *et al.* 1995, Bock *et al,* 1997, Miller *et al.* 1998) provide a continuous regional reference frame that facilitates the monitoring of relative positions at the level of a few millimeters. Over the past decade, this technology has been used in the active seismic regions of the northwestern U.S. and southwestern British Columbia to measure secular crustal motions associated with contemporary tectonics.

This unprecedented precision in geodesy is not without its problems. In order to integrate the increasing number of velocity determinations derived from both continuous and campaign GPS measurements within Cascadia (e.g. Khazaradze *et al.* 1999, Savage *et al.* 2000) careful consideration must be given to reference frames and data processing models used to determine site positions. For example, differences in nominal reference frames can alter velocity estimates by several millimeters per year giving rise to apparent block motions. Calculating regional principal strains from the horizontal velocity fields derived from common GPS data analyses removes reference frame discrepancies but leaves relative rigid block motions undefined. Because of its complexity, it is difficult to identify bias inherent in GPS data analysis. Estimates of height are particularly sensitive to processing models, and vertical trends based on even two to three years of continuous data can still be biased by non-tectonic processes.

In general, linear trends in successive solutions of position are the basis for estimates of tectonic motion. Even once these trends are accepted as being purely tectonic in origin, their interpretation is far from straightforward since the measured displacements over a given time period are a combination of elastic and non-elastic motions. The separation of these components is critical to understanding the plate margin processes and improving seismic hazard estimates. At present, the geodetic observations within Cascadia are still too sparse and fragmented to allow unambiguous resolution of interactive tectonic components such as contemporary plate convergence, variations in the geometry and coupling of the subduction thrust fault along the margin, viscoelastic effects and the temporal nature of the locked zone, and the residual northward motion of the Cascadia forearc.

Nonetheless, significant progress has been made through the generation of new kinematic and dynamic models constrained by the past decade of GPS measurements in the Pacific Northwest. Despite the large uncertainties, crustal velocities derived from GPS observations reveal two robust features: (1) seaward sites generally have larger velocities in the plate convergence direction than landward sites, and (2) the direction of the velocities generally becomes more northerly as we go south. The first feature has been accepted as evidence for the locking of the subduction fault. The northerly velocities have been attributed to a secular long-term northward motion and/or clockwise rotation of the forearc blocks (Wells *et al.* 1998). In other words, the convergence-parallel component of the GPS velocities is thought to reflect mainly interseismic elastic strain accumulation, but the margin-parallel component is thought to reflect mainly secular geological deformation. Geodetically determined strain rates indicate maximum contraction of the Cascadia forearc roughly in the direction of plate convergence, supporting the concept of elastic strain accumulation in this direction.

Elastic and viscoelastic models have been developed to explain the geodetic observations in terms of interseismic deformation. The geometry of the locked zone of the subduction fault in both types of models is constrained by the thermal as well as geodetic data (Hyndman and Wang 1993). Elastic dislocation models (Dragert *et al.* 1994, Flück *et al.* 1997) well describe the general pattern of the interseismic deformation, particularly land tilts, but predict a landward decrease of horizontal velocities more rapid than observed. Viscoelastic models (Wang *et al.* 2000) take into account the response of the "softer" mantle beneath the elastic lithosphere and provide a better fit to the observed GPS velocities. Work is in progress by various research groups in the PANGA (PAcific Northwest Geodetic Array) consortium (Miller *et al.* 1998) to model the secular deformation of the Cascadia forearc and the subducting plate and its impact on the interseismic deformation.

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THE IMPORTANCE OF SCIENCE IN PUBLIC POLICY: RECENT OREGON EXPERIENCE

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The scientific community represented at this conference has had a profound effect on raising the awareness of a wide range of stakeholders in the public policy discussion in Oregon, Washington and nationally. Examples abound in both regulatory and voluntary realms. Knowledge of the seismic threat has led to higher code requirements, and a wide understanding of our vulnerability. As a former chair of the Commission in Oregon concerned with public policy, I have seen advances in many areas. For example, bond measures to provide funds to strengthen public buildings such as schools, fire stations, and lifelines and passing in record numbers.

One of the key reasons is discussion like those we are having. A similar conference in 1995 was a spark to helping coastal communities prepare.

Kockelman presented a methodology in 1990 that helps show the parts of a successful program. They are the building blocks as follows: **EARTHQUAKE STUDIES** (geologic, geophysical, seismologic, engineering, other); **TRANSLATION ELEMEMTS** (likelihood, location, severity, format, other); **TRANSFER TECHNIQUES** (educational, advisory, review, other); **REDUCTION TECHNIQUES** (mitigation, preparedness, response, recovery, reconstruction); and **EVALUATION / REVISION** (studies, translation, transfer, reduction and program).

In Oregon we have been pursuing many of these elements. The attendees at this conference will have an opportunity to participate in a public forum one evening. The evening will be a window into how the public sees our efforts and how well they understand the situation.

As an engineer for a water utility and lifeline provider, I have witnessed an increasing level of activity in response to the "perceived problem". This brings us to the need to involve the other sciences in the equation, that of social and economic scientists. One of the meetings of the Oregon Commission included a presentation by Paul Slovik of the University of Oregon, who showed us where the earthquake threat stands in the minds of people. It is really high in their thinking, thanks in great part to the work of you here at this conference. My message to you is to reach out to the various stakeholders in every way open to you. Many avenues to take your study results to those who can help translate the message are vital. Supporters and critics alike are needed to keep the discussion moving so that we can move toward a culture of empowerment, and away from one of fear and loathing. Keep up the good work, and remember to keep us informed as you learn more.

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FARFIELD AND NEARFIELD TSUNAMI DEPOSITS IN SEASIDE, OREGON, USA

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Due to its location and low elevation, the city of Seaside, Oregon, has the potential to be substantially impacted by a nearfield tsunami resulting from a megathrust earthquake on the Cascadia subduction zone. However, a nearfield tsunami has not occurred in historic times, which would provide an indication of the shoreline inundation associated with such an event.

Significant damage to the City was caused by a farfield tsunami resulting from the 1964 Alaskan earthquake. Reported observations and deposits from that event provide a valuable record of the effects of a farfield tsunami. The 1964 event may also serve as a model for interpreting nearfield prehistoric tsunami deposits in the area, the most recent of which is believed to have occurred in AD 1700.

A reconnaissance subsurface exploration was conducted in the coastal wetlands of Seaside to identify the deposits of these farfield and nearfield tsunamis. The information gathered was used to map the inundation of the 1964 and 1700 events. The results may prove useful for evaluating potential mechanisms of inundation and maximum runup associated with future nearfield tsunami.

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3-D DISLOCATION MODEL FOR GREAT EARTHQUAKES OF THE CASCADIA SUBDUCTION ZONE

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There is good recent evidence that very large Cascadia subduction thrust earthquakes have occurred in the past and that strain is building up toward a future great event. Geodetic measurements along the coast form northern California to southern British Columbia show vertical and horizontal crustal deformation as expected for strain accumulation of a locked subduction thrust fault. The segment of the subduction fault that is locked and may rupture in future great events has previously been estimated by 2-D elastic dislocation modeling of interseismic deformation geodetic data. In this study, a general 3-D dislocation model has been developed that accommodates curved fault geometry, nonuniform interseismic locking or coseismic rupture, and variations in plate convergence rate (Euler poles of rotation for different plate segments). The model is based on the surface deformation due to shear faulting in an elastic half space presented by Okada (1985). The Cascadia subduction zone 3-D model calculates the surface deformation for a locked zone or a rupture zone of variable width along the margin. The bend in the margin trend and subducting slab end effects are included. There is a downdip transition zone between interseismic completely locked and free slip portions of the fault or between coseismic full rupture and no displacement, respectively. An initial 3-D model based on 2-D model results and geothermal constraints was adjusted to optimize the fit of the predicted interseismic surface deformation to current deformation geodetic data. The best-fit model has the thrust fault locked along the whole margin with smooth variations in width for the locked and transition zone. The 3-D dislocation model results are generally in good agreement with interseismic geodetic data and coseismic paleoseismic data. The northern (Explorer plate) and southern (Gorda plate) ends of the Cascadia subduction zone are complex and further work is needed to determine the Euler poles of rotation and the width of the seismogenic zone. The updip geometry of the locked zone is important for the generation of tsunamis, since the coseismic deformation of the sea floor corresponds approximately to the sea surface deformation. Assuming that the locked and transition zone approximate the maximum coseismic rupture area, these widths permit about a M_w=9.1 earthquake.

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DIATOM EVIDENCE FOR TSUNAMIS FROM A FRESHWATER MARSH, DEL NORTE COUNTY, CALIFORNIA

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Sand layers deposited in a freshwater marsh contain allochthonous marine diatoms, and record six tsunami inundation events during the last 3,000-3,500 years. Lagoon Creek is a 1000-m long freshwater marsh that extends up a narrow valley perpendicular to the shore. The seaward edge of the marsh is 300 m inland of the surf zone and the marsh is protected by a beach berm that is 5 m higher than mean higher high water (MHHW).

We collected 21 vibracores of up to 6 m of sediment from the marsh. These sediments record a gradual transition from slightly peaty mud to highly organic peat. Six sand layers that are inferred to be tsunami deposits punctuate this stratigraphy. The sand layers consist of landward-thinning, landward-fining, and normally-graded beach sands that extend as much as 1400 m inland of the beach berm. AMS radiocarbon dating and the identification of an ash deposit indicate that the oldest sediments in the section are between 3000 to 3500 years old.

Diatom analysis indicates that the oldest sediments (slightly peaty mud) were deposited in a fresh to slightly brackish water environment, while the younger deposits (organic rich peat) were deposited in an exclusively freshwater environment. The sand layers contain allochthonous marine diatom species both within and directly above each sand layer. Some of the fossil marine diatom species found associated with the sand layers were also found as living specimens on the adjacent beach. Marine diatoms were also used to determine that tsunami run-up exceeded the limit of sand deposition by at least 400 m for one of the events.

TECTONIC INTERPLAY BETWEEN OBLIQUE SUBDUCTION AND MENDOCINO TRIPLE JUNCTION MIGRATION ALONG THE SOUTHERN CASCADIA SUBDUCTION ZONE, OFFSHORE NORTHERN CALIFORNIA

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Driving forces including oblique subduction and the northward migration of the Mendocino triple junction create a complex tectonic environment at the southern end of the Cascadia subduction zone. Over 10,000 earthquakes in the last decade (Smith *et al.* 1993), Holocene faulting (Clarke 1992, Gulick and Meltzer 2000), debris aprons, slump blocks (Gulick *et al.* 1998), and a large-scale slumping event around ~250 ka are evidence of a seismically active margin (Gulick and Meltzer 2000).

Examination of multichannel seismic images of the Gorda plate, southern Cascadia accretionary prism, and Eel River forearc basin suggest varying degrees of strain partitioning between Gorda-North America and Pacific-North America relative plate motion (Gulick *et al.* 1998, 2000; Gulick and Meltzer 2000). Northward compression across the Mendocino fracture zone causes internal deformation of the southern Gorda plate along northeast-southwest oriented left-lateral strike-slip faults, resulting in clockwise rotation and plate fragmentation near the triple junction (Gulick *et al.* 2000, Levander *et al.* 2000). Northward migration of the triple junction has perturbed the southern end of the Cascadia margin by uplifting and tilting the southernmost forearc, rotating the southern Eel River basin eastward, and developing transpressional structures (Gulick and Meltzer 2000). Northeast-southwest oriented left-lateral strike-slip faults in the subducting Gorda plate (Gulick *et al.* 2000) contrast with northwest-southeast oriented structures that indicate both compression and translation in the overriding Eel River forearc basin (Gulick and Meltzer 2000), suggesting that the Gorda and North America plates are partially decoupled. Subduction-driven structures at the toe of the accretionary prism that vary in vergence direction, and Mohr-Coulomb analysis of the taper of the accretionary wedge suggest low basal shear-stress along the margin (Gulick *et al.* 1998). Seismic images offshore northern California show three major northwest-southeast oriented oblique-slip faults that may be driven by oblique subduction or could be related to the propagation of Pacific-North America plate strike-slip faulting into southern Cascadia (Gulick and Meltzer 2000).

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LOCAL BUILDING CODES IN RELATIONSHIP TO A LONG-DURATION SEISMIC EVENT

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Provisions addressing seismic hazards are a relatively recent development in building codes. Earthquakes in California in 1906, 1926, and 1933 demonstrated the need for more earthquake-resistant designs. Since earthquakes appeared to be a problem only in California, and did not generate a great interest in other parts of the country, it fell to the practicing structural engineers of California to develop earthquake design practices and building code provisions. In 1929 the Pacific Coast Building Officials, later called the International Conference of Building Officials (ICBO), published the first comprehensive set of earthquake design procedures.

Based partly on observing the behavior of contemporary structures under strong earthquake loads and partly on the theoretical understanding of earthquake phenomena and the response of structures to these effects, the building code provisions have continued to evolve.

The underlying philosophy of the seismic design provisions of building codes is three-tiered performance criteria, permitting buildings to resist: 1) minor levels of earthquake ground shaking without damage; 2) moderate level of earthquake ground shaking without structural damage, but with some damage to nonstructural elements; and 3) intense levels of ground shaking without collapse or endangerment of life safety.

While there are no explicit provisions in current codes that address long-duration earthquakes, there are implicit provisions that will help achieve the building performance criteria. Construction details that allow structural members to distort and absorb energy over many cycles of deflection will, in turn, allow the building to move and distort without collapse over a number of minutes.

Other phenomena associated with subduction earthquakes such as liquefaction, lateral spreading and tsunamis have only very recently been addressed in building regulations.

However, many states where the seismic risk was perceived to be small or non-existent, did not adopt the seismic provisions of the latest building codes. Consequently, most of the buildings designed and built under those codes do not have the construction details though essential to provide seismic safety under those older codes. In addition, some parts of the nation, such as the Pacific Northwest, have subsequently been determined to have a much higher seismic risk, than previously thought. When one considers that 90% of the standing commercial buildings in Oregon were built to standards which did not reflect either the minimum seismic considerations or the correct seismic hazard area, one realizes the large problem facing the people in this state with regard to seismic hazards.

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DISPLACED MARINE DIATOMS IN A COASTAL FRESHWATER LAKE: MICROFOSSIL EVIDENCE FOR HOLOCENE TSUNAMIS ON THE SOUTH-CENTRAL OREGON COAST

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At numerous sites from northern California to Vancouver Island, scientists working with low-tide estuarine outcrops or cores have identified anomalous deposits of coarse-grained sediment and microfossils, which they have attributed to deposition by tsunamis (Atwater *et al.* 1995, Atwater and Hemphill-Haley 1997). On the south-central Oregon coast where there are relatively few estuarine localities useful for detailed paleoseismic studies (Kelsey 1997, Witter 1999), low-lying freshwater lakes provide an additional means for studying Holocene tsunamis. After a reconnaissance study of several lakes, we focused on Bradley Lake, 28 km north of Cape Blanco. Our results show that it has a 7,400-yr record of freshwater deposition interrupted only by occasional, rapid lake-wide disruptive events that deposited coarse-grained sediment and microfossils. These disruptive depositional events, which we term "disturbance events" (DEs), occurred 17 times during the past 7400 years.

Diatoms are microscopic plants that secrete silt-sized siliceous hard parts. They proliferate in most aquatic environments, and are abundant in coastal and estuarine surficial deposits, and thus are incorporated with silt and fine sand transported by tsunamis (Hemphill-Haley 1996). For this study, the diatoms are divided into five groups: 1) Hm group – marine diatoms derived from modern surficial deposits; these diatoms are too delicate to have been eroded from nearby Tertiary diatomites; 2) HTm group – marine diatoms originating either from modern surficial deposits or Tertiary diatomites; 3) Tm group – extinct marine diatoms eroded from Tertiary diatomites; 4) BHC group -- brackish-water epiphytic diatoms; and 5) the freshwater group of *in situ* taxa. The Hm group provides the strongest evidence for tsunami inundation into Bradley Lake because these taxa encompass modern coastal-ocean assemblages at the time of the DE, and they are not the result of erosion from diatomaceous marine terraces located at the north shore of Bradley Lake.

The results of the diatom analyses show that:

1) Bradley Lake evolved from a freshwater marsh to a lake ca. 7300 years ago, following the oldest disturbance event (DE17). Freshwater diatoms are abundant throughout the record. Therefore, at no time in its 7400-yr history did Bradley Lake have an open connection with the ocean.
2) Where found, marine diatoms are very rare relative to *in situ* freshwater taxa. This indicates that they were deposited into the lake but could not survive to reproduce in the fresh water. The are confined to stratigraphic horizons in and immediately above the coarse-grained deposits of the DEs.
3) Hm group diatoms – the strongest diatom evidence for tsunamis – are prominent in 12 events: DE1 (250 yr BP), DE2 (960 yr BP), DE4 (1420 yr BP), DE5 (1900 yr BP), DE6 (1940 yr BP), DE7 (2800 yr BP), DE8 (3180 yr BP), DE11 (4110 yr BP), DE12 (4330 yr BP), DE13 (4550 yr BP), DE16 (6420 yr BP), and DE17 (7310 yr BP).
4) There is weak diatom evidence for tsunami inundation for two events: DE9 (3310 yr BP) and DE10 (3730 yr BP).
5) There is no evidence for tsunami inundation for 3 events: DE3 (1060 yr BP), DE14 (4670 yr BP), and DE15 (5460 yr BP).

6) Indirect evidence for earthquake-induced subsidence at Bradley Lake may be recorded for six disturbance events: DE5, DE8, DE11, DE12, DE13, and DE16. Abrupt increases in numbers of epiphytic diatoms (BHC group) following these DEs may reflect submergence of riparian plants along the shores of the lake, leading to an increase in preferred habitat for this particular group of diatoms, and boosting their productivity.

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INTEGRATION OF GEOLOGIC AND GEODETIC DATA INTO KINEMATIC MODELS OF CONTEMPORARY STRAIN IN THE PACIFIC NORTHWEST AND ACROSS THE CASCADIA SUBDUCTION ZONE

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Penetrative dextral shear combined with gravitational collapse-driven extension provide complex but coherent patterns of deformation within the interior of the western United States. We model geologic, neotectonic and GPS geodetic data to infer the western North America velocity and deformation field. Geodetic observations indicate 9-12 mm/yr of margin-parallel shear (with respect to stable North America) is located east of the Sierra Nevada and 3-5 mm/yr of west- to northwest-directed extension occurs in the central Basin and Range.

Our goal has been to resolve the horizontal velocity field and strain rate tensor within western North America and specifically in the Pacific Northwest. We use finite element modeling of deformation to incorporate available neotectonic and geodetic data. A finite element mesh defines the elements in which material properties are assigned, with properties chosen to produce desired deformation behavior. For instance, blocks are made rigid and deformation zones are weak. Block motion is then prescribed, and the resulting velocity field is compared to GPS velocities. The deformation field is then compared to geologic strain indicators. We adjust material strength and applied velocities in an attempt to eliminate conflicts between the modeled and observed fields. This modeling, though done with finite elements, is kinematic in nature. That is, we use finite element modeling to produce velocity and strain fields that are consistent with observations. We do not attempt to model the actual forces or rheologies active in the Earth. Finite elements are a means of producing relatively smooth fields (in this kinematic modeling, the modeled velocity field can be viewed as the weighted least squares best velocity field consistent with the prescribed velocities (Hearn and Humphreys 1998).

To summarize the results of our modeling, broadly distributed strain occurs throughout the region with transform rates being much greater and largely concentrated near margin while gravitational collapse drives extension and deformation of the interior. The Oregon Coast Range block is rotating rapidly clockwise with a pole of rotation in south-central Washington consistent with a model proposed by Wells *et al.* (1998). This accommodates both the northern motion of the Coast Ranges into the Olympic Mountains and Basin and Range extension in such a way that North America strain rate diminishes to the north and is very slight in Canada. It also increases subduction velocities, especially in Oregon. Eastern California shear zone strain "fans" broadly over the Pacific Northwest with several mm/yr of strain rate occurring in the Klamath Mountain region. This unexpected result finds support directly in the GPS velocity field; comparison of the velocity of a station at Quincy with that of Yreka shows a transfer of eastern California shear zone strain to the northern California coast, reducing the strain required in Oregon and Washington.

The results also indicate that our current modeling is inadequate in some regards, and is substantially unconstrained throughout much of the Pacific Northwest. In particular, a prevalence of strike-slip deformation in the Great Basin results from a north-south contraction field that is too great. This problem may simply result from moving station DRAO (Penticton) in Canada at about 1 mm/yr to the northeast instead of 2-3 mm/yr consistent with recent observations. This slower velocity may prevent northeast Washington and northern Idaho from "getting out of the way" of the northwest-directed Basin and Range extension.

An additional result of our kinematic modeling is the determination of subduction velocity, which requires knowledge of the Coast Ranges and Juan de Fuca velocities. Older estimates used NUVEL-derived Juan de Fuca-North America velocities. The Coast Range is in motion relative to North America and importantly relative to the subduction zone. Juan de Fuca velocity estimates have uncertainties related to dependency on the Pacific plate velocity which is being refined, and appears to be several mm/yr more westerly than previously assumed (Antonelis *et al.* 1999) (Humphreys and Weldon 1994, DeMets and Dixon 1999), which reduces subduction velocities.

Finally, the Cascadia subduction zone serves as the outlet (window) for both transform and gravitational collapse driven deformation and the expansion of North America. Conversely, the transform margin prevents collapse from being accommodated in California. The result, over time, is that the expansion of the western U.S. has been redirected toward the Pacific Northwest as the transform margin has expanded and the length of the subduction zone has decreased.

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GIS CASCADIA HAZARD MAPPING: LINKING RESEARCH TO MITIGATION IN OREGON

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Timely and effective information transfer from Cascadia researchers to engineers, planners, and others who evaluate mitigation alternatives and allocate resources is critical for developing more hazard-resistant communities. GIS-generated hazard maps have been, and continue to be, one of the primary means for seismic information transfer. As GIS-generated hazard maps become increasingly pervasive, it is important that not only modelers but also users of hazard maps be familiar with capabilities and limitations in GIS modeling techniques.

GIS programs provide the power to overlay, combine, and analyze various layers of spatial information accurately and efficiently. Most GIS software packages also augment spatial data management with map layout and presentation tools, allowing for the development of visually effective map products. GIS-generated hazard map outputs are commonplace within the seismic community and, in many cases, serve as the primary means for conveying hazard data. Typical uses of seismic hazard maps include public education, emergency response planning, evaluation of regional building inventories, and selection of areas for more detailed site-specific evaluation (Spangle Associates 1998).

In general, the applicability of seismic hazard maps is limited both by uncertainty associated with the modeling algorithm(s) selected and the availability and quality of digital data inputs. Common spatial data inputs include seismic source locations, digital elevation models (DEMs) and surficial geologic and soils maps. Other sources that are often used to augment, or that are assigned to, the spatial data sets include seismic shear wave velocity profiles, laboratory and field collected soil properties, and seismic source characteristics. Though many efforts are underway to collect additional data and improve the quality of important Cascadia data sets, the low resolution and variability of input data remains an important limiting factor in the application of GIS analysis.

Another primary consideration in the application of GIS for developing hazard maps is the selection of relevant map scales and data resolutions for the modeling and final map presentation. There are a number of methods that explicitly incorporate uncertainty in the modeling, but oftentimes it is difficult, if not impossible, to track spatial errors propagated from original data sets. To at least partially account for regional modeling uncertainties, one can use the technique of aggregating outputs (usually numeric) to create relative zonation maps.

To address Cascadia earthquake hazards in the state of Oregon, the Oregon Department of Geology and Mineral Industries (DOGAMI) has utilized the relative hazard zonation approach to develop a number of regional hazard maps, focusing primarily on medium to large population centers (e.g., Priest 1995, Black *et al.* 2000, Hofmeister *et al.* 2000). Due in part to the large uncertainties in seismic source characterization, the majority of DOGAMI's map products have been relative hazard maps, focusing on expected response (including amplification, landslide, liquefaction, lateral spread, and tsunami inundation) based on assumed levels of fault rupture and seismic shaking. The methodologies used to develop these maps have varied over time, but the intent is to consistently develop the most accurate and appropriate maps the data can support. While this typically involves applying rigorous modeling tools throughout, the final outputs are simplified to more general hazard zones (e.g., low, moderate, high, very high).

DOGAMI's seismic hazard map products have been distributed to and used by planners, engineers, and others in Oregon interested in mitigating earthquake hazards. The maps have been used in conjunction with ground-shaking and infrastructure data to assess damage and loss and evaluate mitigation strategies (Wang 1998). It is hoped that these and other future efforts, recognizing the potential and limitations of GIS analysis, can lead to targeted mitigation programs and reduce the potential for damage and loss during the next Cascadia event.

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BOTANICAL EVIDENCE FROM NORTHERN CASCADIA FOR COSEISMIC SUBSIDENCE AND POST-SEISMIC REBOUND ASSOCIATED WITH THE AD 1700 SUBDUCTION ZONE EARTHQUAKE

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It is hypothesized that understanding the distribution of modern vascular plants and pollen in Cascadia tidal marshes will improve our ability to estimate coseismic subsidence and post-seismic rebound associated with great (magnitude 8 or larger) subduction zone earthquakes. In the study presented here, modern vascular plants and pollen are used to interpret fossil pollen sequences collected near Tofino, British Columbia. Pollen percentages and concentrations were determined for 16 fossil samples collected with centimeter resolution. Three types of sediment were sampled for fossil pollen: the top of the buried peat (7 cm), the overlying tsunami sand sheet (2 cm), and intertidal muds deposited following the earthquake and tsunami (7 cm). To calibrate fossil pollen assemblages to relative sea level, modern vegetation data from 294 plots were collected along 21 transects to establish the elevation distribution of vascular plants and the low, middle, high, and upper-high marsh zones. To establish that pollen rain is consistent with vascular plant distribution, 9 surface samples collected from a transect in close proximity to the buried sequence were analyzed.

The buried peat was characterized by Poaceae, Apiaceae, *Potentilla*-type, and *Achillea*-type pollen. Since *Angelica lucida*, the likely producer of the Apiaceae fossil pollen, is tightly correlated with elevation at all modern environments analyzed, its average and standard deviation (3.82 ± 0.07 m) are used to define the elevation of the site just prior to the earthquake. The sand sheet overlying the buried peat is dominated by tree pollen and spores and has lower concentrations of pollen than sediments above or below. The sand sheet also contains pollen indicative of a high marsh environment; this is interpreted to represent surface materials entrained by the tsunami.

Pollen from intertidal muds overlying the sand sheet indicates a low marsh environment established following the earthquake and tsunami. The low marsh pollen assemblage is characterized by relatively high concentrations of Cyperaceae (17-37%). *Triglochin maritimum* pollen is also elevated compared to the high marsh sediments below. This may suggest that *Triglochin* was an initial colonizer of the sandy substrate provided by the tsunami. At another area, approximately 4 km northeast of the site presented here, *Carex lyngbyei* is replaced by *Triglochin maritimum* as the low marsh colonizer where substrates are sandy. Regardless, the large spike of Cyperaceae pollen over several samples and the reduction or absence of high marsh indicators provides evidence that *Carex lyngbyei* became established following the earthquake at the site sampled. The average elevation of the upper limit of dense *Carex lyngbyei* (2.89 ± 0.15 m) is used to estimate the elevation of the site after tsunami deposition.

By comparing the two paleo-elevation estimates (3.82 ± 0.07 and 2.89 ± 0.15 m) and allowing for the 2 cm tsunami deposit, the amount of coseismic subsidence is estimated to be 0.95 ± 0.24 m. This assumes no unrecorded post-seismic rebound. If the Cyperaceae spike represents the lower limit of dense *Carex lyngbyei* (2.40 ± 0.09 m), the estimate for coseismic subsidence could be as great as 1.5 m. The range of values for coseismic subsidence presented here agrees with estimates made using sediment types (Benson *et al.* 1999) and foraminifera (Guilbault *et al.* 1996).

Pollen 4-7 cm above the tsunami deposit indicate a middle marsh environment, defined by a sharp decline in Cyperaceae and a rise in Chenopodiaceae (most likely *Salicornia virginica*) and Poaceae pollen. The average elevation and standard deviation for the top of the middle marsh (3.38 ± 0.15 m) is used as the paleo-elevation for sediments 6 cm above the tsunami deposit. This implies 0.49 m of relative sea-level decrease, where only 6 cm of sediment was deposited.

The remaining 0.43 m is most easily explained by post-seismic rebound. The elevation difference between the modern marsh surface and the inferred middle marsh elevation is 0.32 m. This includes 0.17 m of sediment, and consequently accommodates for 0.15 m of additional post-seismic rebound. This provides for a total of 0.58 m of post-seismic rebound, the majority of which occurred within the first 6 cm of sediment deposition following the tsunami. This is in agreement with the estimate of Guilbault *et al.* (1996) for post-seismic rebound using foraminifera.

Mathewes and Clague (1994) were the first to use palynology for earthquake history reconstruction. Shennan *et al.* (1996) expanded the use of palynology in Cascadia by incorporating modern pollen training sets and by introducing a multiproxy, microfossil approach. Atwater and Hemphill-Haley (1997) illustrated how useful plant macrofossils are for the reconstruction of former tidal marsh habitats. This study adds to the above by expanding the analysis of modern vascular plants to facilitate the interpretation of micro- and macrofossils. This research, and the research cited herein, directly contribute to obtaining reliable estimates of the magnitude, and hence severity, of seismic hazards in Cascadia.

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INVESTIGATIONS OF CASCADIA PALEOSEISMICITY IN SOUTHWESTERN BC AND NORTHERN MOST WASHINGTON STATE

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In areas closest to the convergent margin abruptly buried marsh soils indicate that coastal areas subsided by about 0.5 m during the last great plate-boundary earthquake in AD 1700. Marshes to the north of the Nootka fault zone on the west coast of Vancouver Island display tsunami deposits but no evidence of subsidence. This suggests that great subduction zone earthquakes do not propagate north of the Nootka fault zone. The eastern margin of the zone of coseismic subsidence lies some 120 km inland of the plate boundary and is demarcated by sites that show little evidence of land-level change during the AD 1700 earthquake. Tsunami deposits inferred to be the product of Cascadia earthquakes have recently been identified in marshes at the eastern end of Juan de Fuca Strait beyond the limit of coseismic deformation. Unlike coastal marsh areas to the south, where sequences of several buried soils are common features of marsh stratigraphy, all of the marshes in the zone of coseismic subsidence on Vancouver Island display only a single buried soil. In contrast, in sites at the eastern end of Juan de Fuca Strait a relatively long record of tsunami inundation can be reconstructed. Unlike areas farther south or east, relative sea level has fallen on the outer coast during late Holocene time at a rate of about 1-1.5 m per thousand years. Intertidal marshes consequently have a lifespan of 1000 years or less before they emerge from the intertidal zone. Present-day marshes therefore only record the events of the last millenium.

Low-elevation lakes on the outer coast may retain a longer record of inundation by Cascadia tsunamis. Between 1996 and 1998 we cored eight lakes on the outer coast of Vancouver Island, and one lake at the eastern end of Juan de Fuca Strait. Catala, Kanim, Deserted, and Kakawis lakes contain inferred tsunami deposits. The others are too far inland or are protected from tsunami penetration by barrier beaches or large outlet streams. A single tsunami deposit was found in Kanim Lake. The other three contain multiple tsunami deposits. Tsunami chronologies were derived from >70 radiocarbon ages on detrital material. Ages on some tsunami deposits are internally consistent, but in other cases the deposit contained reworked material. We suggest a tentative correlation between the tsunami deposits in the sampled lakes and the Atwater and Hemphill-Haley chronology from Willapa Bay. The sampled lakes have experienced uplift over the late Holocene. In order to calculate tsunami run-ups, we reconstructed lake paleoelevation on the basis of known crustal velocities and lake microfossil assemblages. Plotting tsunami deposits of known age against lake paleoelevation indicates that the mean Cascadia tsunami run-up limit on the outer coast of Vancouver Island is <4 m above mean sea level, compared to 7 m for model output.

CONSTRAINTS TO CASCADIA GREAT EARTHQUAKE RUPTURE AREA AND DISPLACEMENT: WHAT WE HAVE AND WHAT WE CAN DO FOR IMPROVEMENT

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To first order, great earthquake shaking at landward sites (e.g., Portland, Seattle, and Vancouver) is controlled by the closest approach of the rupture area, i.e., downdip landward extent of rupture. In contrast, the updip seaward limit of rupture has a strong effect on tsunami generation. What constraints do we have now on the downdip and updip rupture limits and what can we do for improvements?

A. Our primary quantitative constraints are from models for the "locked" (and transition) zones, constrained by geodetic measurements, i.e., pattern of deformation associated with great earthquake strain build-up.

The geodetic constraints are:

(1) <u>Vertical</u>- Repeated levelling, long-term tide gauges, microgravity and absolute gravity, GPS vertical.

(2) <u>Horizontal</u>- GPS horizontal, trilateration laser ranging, triangulation.

Some of the problems that need work are:

(1) <u>Modelling</u>- Better elastic dislocation (2-D and 3-D) and viscoelastic interseismic models; for example, there appears to be a slower fall off of horizontal velocity landward in GPS data than predicted by elastic models, and there may be a time dependence through the earthquake interseismic period.

(2) <u>Plate convergence</u>- The Juan de Fuca plate direction and rate are not yet known accurately; the Explorer and Gorda areas are deforming and the convergence with adjacent margins is very poorly known. Also, other elastic dislocation model parameters (thrust dip profile, convergence rates, elastic parameters); viscoelastic configuration and parameters could be better constrained.

(3) <u>Motion of forearc</u>- The motion of western Oregon and Washington with respect to stable North America (mainly coast parallel) is an important component of the subduction convergence direction and rate.

(4) <u>Vertical data are of low quality and open to interpretation</u>- Available levelling, tide gauge, and GPS vertical data are of low quality. Vertical data are a more sensitive and robust control than horizontal data, so are very important. The model locked and transition zones from vertical data are less sensitive to plate convergence rates and directions and to forearc motion, than from horizontal data. Can we acquire higher quality vertical data? i.e., reanalysis of old levelling, new levelling, better tide gauge analyses, absolute gravity, better GPS vertical?

(5) <u>GPS processing inconsistencies and reference frame problems</u>- There are still significant inconsistencies between the horizontal results from different GPS processing routines (a few mm/yr) and there are still problems with obtaining consistent reference frames (e.g., stable North America or reference stations).

B. The second type of constraint is associated directly with the coseismic great earthquake rupture (we need the coseismic rupture area, not just the "locked" zone).

(1) The primary available direct constraint is quantitative estimates of the coastal coseismic

subsidence from marsh data (not just depth to buried marsh top). The subsidence can be compared to the predictions of earthquake rupture dislocation models, with varying rupture displacements and extents predicted by models constrained by interseismic geodetic data.

The best estimates of subsidence come from the mean water depth just above and just below the buried marshes, based on depth zoning of intertidal organisms (also need earlier, deeper marshes). Also, the depth to the top of the 1700 marsh can be used, after correction for sea-level rise and postglacial rebound since the last event.

(2) Tsunami runup heights.

C. The third constraint is through theoretical models of what controls the downdip and updip limits of rupture.

For Cascadia the updip and downdip controls are argued to be temperature. The thermal downdip limits give general agreement with the limits from models of geodetic data (for many other subduction zones, the forearc mantle is argued to provide the downdip limit).

The main questions about this method are: (1) Are the proposed critical temperatures correct? Is temperature the only control? i.e., are pore pressure, composition, etc. important? (2) How accurate are the numerical thermal models used for estimating thrust temperatures? Can the numerical model parameters be improved? Does this method work elsewhere where there have been great events with known rupture limits?

POSTGLACIAL REBOUND AT THE NORTHERN CASCADIA SUBDUCTION ZONE

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Postglacial rebound is the response of the Earth to the decay of ice sheets. A postglacial rebound model explains crustal tilting and rapid uplift at the northern Cascadia subduction zone that occurred during retreat of the Cordilleran ice sheet (James *et al.* 2000). Observations explained by the model include the shoreline tilts of two proglacial lakes that formed at 13.5-14 ka (^{14}C years ago) (Thorson 1989) and rapid sea-level fall (land uplift) at 12-12.5 ka (Clague *et al.* 1982). Modeled mantle viscosity values range from 5×10^{18} Pa s to 5×10^{19} Pa s, and are consistent with previous viscosity inferences from observations of crustal deformation following subduction zone earthquakes (10^{18} to 10^{19} Pa s). No lower limit to subduction zone mantle viscosity is apparent from our model, but viscosity values equal to or larger than 10^{20} Pa s are definitely ruled out. Our modeled subduction zone mantle viscosity values are smaller than most upper mantle viscosity estimates derived from postglacial rebound studies of tectonically less active regions (10^{20} to 10^{21} Pa s), and should be incorporated into models of other Cascadia subduction zone processes (e.g., Wang *et al.* 2000). The rapid observed uplift at 12 ka requires, in addition to a low mantle viscosity, rapid unloading from a sudden collapse of remaining coastal portions of the southern Cordilleran ice sheet. The sudden collapse provides 0.18 m of global eustatic sea-level rise, approximately 0.7% of the sea-level rise associated with melt-water pulse IA. Predictions of a global postglacial rebound model (ICE-3G; Tushingham and Peltier 1991) with a 10^{21} Pa s upper mantle viscosity were previously applied to geodetic data from this region to isolate signals associated with the earthquake cycle (Hyndman and Wang 1993, Dragert *et al.* 1994). Owing to the low viscosity values, and resulting rapid recovery of glacial deformation, our model predicts present-day postglacial rebound uplift rates at least 10 times smaller than ICE-3G (less than about 0.1 mm/yr). Consequently, the landward tilt rate across Vancouver Island is about 40% less than previously concluded. This suggests a need for detailed studies of postglacial rebound when using vertical geodetic deformation data to constrain interseismic deformation in regions affected by the recent glaciation.

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POTENTIAL IMPACTS OF CASCADIA-MARGIN EARTHQUAKES ON THE FRASER RIVER (VANCOUVER) AND DUWAMISH RIVER DELTAS (SEATTLE)

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Large earthquakes generated along the Cascadia subduction zone pose hazards to greater Vancouver and Seattle, whose ports are built on the Fraser and Duwamish River deltas, respectively. Although located more than 100 km from the outer coast, the cities remain at risk due to local conditions that increase the potential of earthquake-induced ground failure. The accumulations of loosely consolidated delta sediment are up to 300 m thick and can significantly amplify ground motions. Dynamic motions with site periods vary from 0.2 to 0.5 seconds on the delta margins to 4 seconds in the delta center.

Extensive drilling programs by the USGS, GSC, and other agencies recently have examined the sedimentary framework of these urbanized deltas. The primary objectives were to determine the stratigraphic and geographic distribution of sandy sediment, which is susceptible to liquefaction, and to evaluate the potential impact of earthquakes on the region's industrial and transportation infrastructure. Sand-filled dikes, sills and other paleo-liquefaction features are commonly visually observed and suggest the occurrence of strong ground shaking in the past. Cone-penetration tests (CPT) and standard penetration tests (SPT) were used to characterize potentially liquefiable deposits. The sandy unit of principal concern on the Fraser delta is 8-30 m thick and interpreted to represent a complex of distributary channel sands. The youngest and most liquefiable deposits are located adjacent to the present Main Channel and delta front. Buried channels and laterally continuous layers of sand, probably derived from lahars (volcanic debris flows), also occur on the Duwamish delta. Based on modeled earthquakes, where ground acceleration may significantly exceed 0.2 g, there is a high potential for large strain disintegrative flow failure on the delta front and slope, potentially including the port facilities.

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IMPLICATIONS OF CASCADIA SUBDUCTION ZONE EARTHQUAKES ON LIQUEFACTION AND LANDSLIDES

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The status of the Cascadia subduction zone (CSZ) as a source of large earthquakes in the Pacific Northwest is now well established. There is little doubt that the CSZ has produced great earthquakes in the past, and that it will produce great earthquakes again in the future. While there is some debate over the specific details of future CSZ earthquakes, they will undoubtedly produce ground motions that are different than those produced by other seismic sources in the region; in particular, ground motions with long durations and strong low-frequency components.

Geotechnical seismic hazards can be divided into two categories – response hazards and ground failure hazards. Response hazards involve the modification (typically amplification) of rock motions by overlying soil deposits. Ground failure hazards, on the other hand, are characterized by permanent deformations of soil deposits. Landslides, liquefaction, lateral spreading, and settlement are primary examples of ground failure hazards. These hazards have been observed in past earthquakes in the Pacific Northwest and can be expected in future earthquakes, including great CSZ earthquakes.

Earthquake-induced landslides involve permanent downslope deformation, the magnitude of which depends on the amplitude, frequency content, and duration of the local ground motion. Historical earthquakes in the Pacific Northwest have not produced catastrophic landslides. Noson *et al.* (1988) identified 14 earthquakes from 1872 to 1980 that are known to have produced landslides in Washington State. Sparse population and communication difficulties have likely contributed to the modest, and probably incomplete, record of earthquake-induced landslides in western Washington prior to 1949. Chleborad and Schuster (1998) provided a very complete review of landslides and other forms of ground failure in the 1949 and 1965 Puget Sound earthquakes. The ground motions expected to be produced by a great CSZ earthquake, however, will have different characteristics than those of the earthquakes known to have caused past landslides in the area. Most landslides tend to develop permanent displacements incrementally as pulses of acceleration temporarily exceed the limit (yield acceleration) for which the slope remains stable. The increased duration of great CSZ earthquakes means that more pulses capable of causing permanent displacement can exist; the increased strength of low-frequency ground motion components means that each pulse may cause more permanent displacement. The net result is that landslide displacements in great CSZ earthquakes may be considerably larger than in other earthquakes.

Liquefaction and lateral spreading result from the incremental buildup of porewater pressure in loose, saturated cohesionless soils. Historical earthquakes in the Pacific Northwest have caused a number of instances of liquefaction and lateral spreading. Chleborad and Schuster (1998) and Grant *et al.* (1998) summarized observations of liquefaction and lateral spreading observations in the 1949 and 1965 Puget Sound earthquakes. Recent paleoseismic investigations have also produced observations of liquefaction features in Vancouver, B.C. (Clague *et al.* 1997) and the lower Columbia River region (Obermeier 1993) that appear to be correlated in time. Dickenson and Obermeier (1998) observed numerous liquefaction features on islands in the Columbia River located 35 km to 90 km from the Pacific Ocean coastline. Because the buildup of porewater pressure in liquefiable soil depends on cyclic strain amplitude, and is particularly sensitive to the number of stress/strain reversals, liquefaction would logically be expected to be much more prevalent in great CSZ earthquakes than in smaller earthquakes.

Liquefaction is a complicated process and procedures for its evaluation are also complicated. Current procedures for evaluation of liquefaction potential are based on empirical evidence of the occurrence (and non-occurrence) of liquefaction. These procedures are based on a series of correlations between in-situ soil parameters (e.g. SPT resistance) and ground motion parameters (typically peak acceleration). Each correlation in this series is based on scattered data and consequently involves a degree of uncertainty. The conventional procedure of using ground motions to evaluate liquefaction potential, therefore, involves a considerable degree of uncertainty. Working in the opposite direction, i.e. using paleoseismic observations of liquefaction to identify ground motion parameters, leads to substantial uncertainty in the parameters.

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A SITE SPECIFIC PROBABILISTIC GROUND MOTION ASSESSMENT FOR TARHEEL DAM, COOS BAY, OREGON

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Seismic hazards to this site on the Coquille Reservation consist of shallow interface and intraslab earthquakes associated with subduction of the Juan de Fuca and Gorda plates, local faults, and randomly occurring upper crustal seismicity. Shallow interface events were assumed to be roughly equally distributed between magnitude 6.5 and 9.5. This "maximum moment" model contrasts with exponential or "characteristic" recurrence models, and accounts for the lack of interface events in the historic and instrumental records, with aftershocks as low as 6.5 (this lower magnitude cutoff is partially due to engineering considerations). A more accurate model would account for observed aftershock magnitude distributions from other subduction zones. Constraints from geologic recurrence data (abstracted from Geomatrix 1995) suggest effective slip rates between 7 and 25 mm/yr, with interface coupling factors of between 21% and 55%.

Intraslab events from intermediate (20-45 km depth) and deep (45-100 km) portions of the slab between magnitude 6.0 and 7.5 were modeled, though activity rates for these events are poorly constrained. Overall slab geometry was based on Flück *et al.* (1997), Parsons *et al.* (1998), and Harris *et al.* (1991). For return periods of 500 years and greater, shallow plate interface events contribute more than 80% to the peak acceleration hazard.

Uncertainties were incorporated by complete enumeration, allowing for complete posterior distributions of the results. Due to the lack of knowledge regarding appropriate magnitude distributions and recurrence times (as well as dispersion in the attenuation functions) uncertainties in the results are large: for a return period of 500 years, the computed mean peak horizontal acceleration is 0.33 g, with 16th and 84th fractile values of 0.17 and 0.41 g, respectively, for "soil" conditions. I will attempt to look at the sensitivity of the results to different magnitude and recurrence models.

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ASSESING THE IMPACT OF THE AD 1700 CASCADIA SUBDUCTION ZONE EARTHQUAKE ON NATIVE AMERICAN COASTAL PEOPLES: ARCHAEOLOGICAL EVIDENCE FROM THE NORTHERN OREGON COAST

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The geological realization that the Cascadia subduction zone periodically experiences extremely large (M_w 8-9) earthquakes has generated a great deal of interest among archaeologists working in the area. Earthquake-associated subsidence of low-lying coastal areas and flooding due to tsunami inundation have been linked to the abandonment of Native American villages along the coasts of northern California, Oregon, Washington, and British Columbia. In addition, these geological events have been associated with both the dearth of early Holocene archaeological sites along the Cascadia subduction zone in comparison to adjacent coastal areas, and the small number of archaeological sites compared to other heavily populated areas of Native North America.

While several archaeological sites submerged and buried by these events have been identified along the margins of estuaries in southwest Washington and northwest Oregon (Cole *et al.* 1996, Minor and Grant 1996), the impacts of the earthquakes upon Native American coastal peoples remains poorly understood. Sites are often poorly dated and lack detailed stratigraphic analyses needed to identify earthquake events and their impacts (Losey *et al.* 2000). However, the archaeological record offers excellent potential for understanding some of these impacts. Over 500 radiocarbon dates are available for Oregon coast archaeological sites alone, many of which are in locations highly susceptible to earthquake impacts. Also, most Northwest Coast archaeological sites contain large quantities of well-preserved human food remains. Many of these food items come from estuaries adjacent to the sites and potentially offer an extensive 'fossil record' of both environmental and human responses to earthquake events.

Radiocarbon dating of archaeological sites on Netarts and Nehalem bays on the northern Oregon Coast suggests that low-lying landforms like sandspits have undergone extensive reconfiguration during the late Holocene as a response to eustatic sea level rise, coseismic subsidence, and other factors. Despite the 3500 year existence of Netarts Bay (Darienzo and Peterson 1990, Shennan *et al.* 1998), for example, archaeological sites on Netarts sandspit appear to date only to the last 1100 years or so. Radiocarbon dating and excavation of several sites along the margins of Nehalem Bay reveals an inland and somewhat upland movement of people around AD 1700, possibly as a response to the earthquake and tsunami. Finally archaeological evidence from both Netarts and Nehalem bays suggests that some portions of the landscape were not chosen for intensive settlement until a few decades before AD 1700 and continued uninterrupted for many decades following the earthquake.

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SUBMARINE LANDSLIDES AS PALAEO-ACCELEROMETERS, NORTHERN OREGON CONTINENTAL SLOPE

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The lack of submarine landslides in the vicinity of Astoria Canyon presents a paradox at the base of the accretionary prism, offshore northern Oregon. In this region, normally consolidated slopes exceed 15°, which is very steep by underwater standards on passive margins, let alone an actively converging margin. Geotechnical data from shallow push cores, and the smooth morphology of the continental slope suggest that these slopes are normally consolidated, i.e. little erosion has occurred (McAdoo *et al.* 1996). If this is the case, seafloor sediment has been lifted from essentially flat on the incoming Juan de Fuca plate to 15° *without mass wasting*. Using the morphology of the few existing landslides imaged by multibeam bathymetry, with conservative ranges of sediment physical properties, I estimate the forces required to trigger existing slope failures, assuming they are seismogenetic, using a psuedo-static seismic regional slope stability model (Lee *et al.* 1999). An acceleration of less than 0.1 g could have caused the largest landslides, and a calculated acceleration of 0.06 g could have triggered most of the slides in the northernmost prism. These accelerations are surprisingly low considering the proximity to the locked portion of the subduction zone fault, where one might expect higher accelerations, hence increased landslide potential.

The majority of onshore data suggest that Cascadia is indeed seismically active (see review by Clague 1997). There are several possible explanations for the unfailed slope paradox in the northern Oregon accretionary prism, including a non-locked plate boundary fault beneath the prism (which is unlikely based on the subaerial evidence), a very slow earthquake source mechanism, or that a large earthquake occurred, and that somehow the prism did not shake enough to trigger widespread slope failure (e.g. McCaffrey 1983). I present reflectivity modeling data that suggest that weak and overpressured accretionary prism sediment (very low Q) may act as a seismic filter, where much of the high-frequency energy is lost to anelastic attenuation. The accretionary filter alone may not be efficient enough to remove all of the high frequency energy, but if the source mechanism is already lacking high frequencies (i.e. a slow earthquake), the prism may be effective at removing the portion responsible for high accelerations that could trigger failures.

The southern Oregon margin, however, is characterized by numerous overlapping slope failures, including three super-scale failures that involve the entire continental slope (Goldfinger *et al.* in press). The distinct differences in surface morphology between the southern and northern Oregon continental slopes suggests that different processes are at work. More work needs to be done comparing along-strike variability in the subduction zone to determine if the effects of a plate boundary earthquake will be homogeneous throughout Cascadia.

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EVIDENCE FOR QUATERNARY CRUSTAL FAULTING AT THE LEADING EDGE OF THE COAST RANGE BLOCK, WASHINGTON

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Determination of slip rates for the tectonic elements that make up the Cascadia subduction boundary is complicated by crustal-block motion within the continental margin. The structural pattern observed in coastal Washington cannot be attributed to simple subduction-driven contraction, but rather reflects deformation associated with northward motion of the Coast Range crustal block relative to the subduction-complex basement of the Olympic coast. The Coast Range block, a basaltic basement block approximately 125 km wide and 500 km long, translates north-northwest at 9-12 mm/yr relative to stable North America based on geodetic measurements (Ward 1990, McCaffrey *et al.* 1999). Block kinematics predict sinistral shear along its western boundary where it trends north-northwest through Willapa Bay, Washinton, and north-south contraction where this boundary trends east-northeast near Grays Harbor, Washington.

Crustal deformation observed at the boundary is localized within the more ductile subduction-complex basement rather than the more rigid basaltic basement. Specifically, seismic reflection data within Willapa Bay depict 10-12 m of vertical displacement (west side up) of a buried unconformity above the basement boundary (Wolf *et al.* 1998). This erosional surface projects to a pre-Holocene surface in a nearby Long Beach borehole that is radiocarbon-dated at *ca.* 21 ka (Smith *et al.* 1999), implying that the rate of vertical offset on the north-northwest-trending "Willapa Bay" fault zone is about 0.5 mm/yr. Further field investigation is required to resolve whether a component of strike-slip movement also occurs on this fault zone. New high-resolution, seismic reflection and sidescan sonar data image a 40-km-wide, east-west-trending zone of intensely folded and faulted strata on the continental shelf north of Grays Harbor that accommodates contraction within subduction-complex rocks adjacent to the Coast Range block. These contractional structures trend east-northeast and several extend onshore between Grays Harbor and Cape Elizabeth, where they offset Quaternary strata. We infer fault offset of Quaternary-age strata offshore by correlating stratigraphic units found in onshore and offshore wells (Rau and McFarland 1982) with units observed in seismic reflection profiles that cross the offshore well. We calculate a preliminary shortening rate of 2 mm/yr based on the degree of folding of Quaternary strata in this area. Some of the offshore faults vertically displace the seafloor 4-6 m, suggesting Holocene activity. These observations provide the first constraints on rates of Quaternary crustal faulting in coastal Washington. Radiometric dating of the deformed strata is critical for determining slip rates on these young faults and assessing their potential seismic hazard to coastal communities.

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THE EFFECTS OF UPPER PLATE DEFORMATION ON RECORDS OF PRE-HISTORIC CASCADIA SUBDUCTION ZONE EARTHQUAKES

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Geological and geophysical investigations of the Cascadia subduction zone during the last decade have increased public awareness of regional earthquake hazards from a subduction zone previously thought to be aseismic. Evidence for repeated abrupt subsidence in the last few thousand years is found in coastal lowlands along the active margin, in the form of rapidly buried marsh deposits and drowned forests (e.g. Nelson *et al.* 1995). These deposits are believed to result from coseismic subsidence and have been attributed to prehistoric subduction zone earthquakes, with the most recent event approximately 300 years ago. The extent and amount of such coastal subsidence have been used to infer characteristic rupture lengths, earthquake magnitudes, and recurrence intervals. Seismic reflection, SeaBeam bathymetry, sidescan sonar, and submersible observations of the submarine Cascadia forearc have revealed many active faults and folds in the North American plate which deform Quaternary sediments. Most structures are within the accretionary wedge, but some have also been identified on the innermost continental shelf close to locations of coseismic subsidence. The results of this study suggest that the record of coseismic subsidence may incorporate both widespread elastic strain release on the subduction zone and localized permanent upper-plate deformation, as documented by McNeill *et al.* (1998).

Inner shelf faults and synclines deforming Quaternary sediments are found to project into many of the coastal lowlands where coseismically subsided marshes and forests have been described. Examples include structures mapped near Grays Harbor, Willapa Bay, Nehalem Bay, Netarts Bay, Siletz Bay, South Slough, Coquille River, and Humboldt Bay (Clarke and Carver 1992). Onshore structures have also been mapped at Yaquina Bay and Alsea Bay (Kelsey *et al.* 1996). Many of these deform late Pleistocene marine terraces onshore (e.g., Kelsey *et al.* 1996). We hypothesize that many coastal bays are structurally controlled, lying within active synclines or on the downthrown side of active faults, and that the coastal bay stratigraphy may incorporate both subduction-zone and upper-plate permanent vertical motions. Permanent upper-plate deformation may also contribute to the preservation of buried marsh deposits, which require a relative sea level rise of 2-5 m in the last 2-4 ka. Late Holocene eustatic sea-level rise is thought by many to be negligible or minimal during the last 5 ka (P. Clark and W.R. Peltier, personal communication, 1997). In addition, recent modeling of isostatic rebound and hence forebulge collapse rates (James *et al.* 2000) suggest low mantle viscosity values and therefore minimal crustal motion (0.1 mm/yr or less) by the early Holocene. These results suggest that a permanent tectonic subsidence may make a significant contribution to preservation of the subsided marshes. Movement on these structures may be triggered by a subduction zone event, as observed in the forearcs of Nankai, southwest Japan, Alaska, and Hikurangi, New Zealand, and may lead to an increased apparent subduction zone rupture length and hence calculated earthquake magnitude. Alternatively, they may deform independently of subduction zone earthquakes as also observed on the Hikurangi margin of New Zealand. Regardless of which style of deformation predominates, the record of coseismic subsidence is likely to be affected. Interplate earthquakes may be of two types, as described in Nankai: (a) crustal structures are triggered and permanent deformation is recorded (Genroku); or (b) no crustal structures are activated and no permanent deformation is recorded (Taisho). If the Cascadia marsh stratigraphy is recording only type (a) earthquakes, subduction earthquakes may be more frequent than the record suggests. Modeling of subduction zone earthquake characteristics based on coastal marsh stratigraphy interpretations may be inaccurate in terms of: (a) total apparent rupture length and hence earthquake magnitude; (b) vertical movement and hence position of the locked zone; and (c) recurrence interval. Elastic dislocation modeling of the coseismic subsidence will also be affected by permanent deformation. Many of the inner shelf and coastal structures respond to north-south compression, in contrast to convergence-related northeasterly compression in the accretionary prism, but in agreement with the regional stress field. Despite low historical coastal and continental shelf seismicity, upper-plate faults may also pose an independent seismic hazard to coastal communities.

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TECTONICS AND DEPOSITIONAL HISTORY OF THE NEOGENE CASCADIA FOREARC BASIN: INVESTIGATIONS OF A DEFORMED LATE MIOCENE UNCONFORMITY

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An elongate late Cenozoic forearc basin, correlative to the Eel River Basin offshore northern California, underlies the continental shelf and upper slope of the Oregon Cascadia margin. This forearc basin was probably continuous in the early to middle Eocene but has subsequently been deformed and dissected into smaller basins, and eroded at its western margin. The basin stratigraphy contains several regional unconformities, suggesting a complex history of vertical tectonics, sedimentation, and eustatic sea level change. These include a regional late Miocene unconformity that could be traced throughout much of the central forearc basin and was used to construct a structure contour map from seismic reflection data. This unconformity may coincide with a regional and potentially worldwide hiatus at ~7.5-6 Ma (Neogene Hiatus 6 of Keller and Barron 1987). The surface is angular and probably subaerially eroded on the inner and middle shelf where it truncates the middle Miocene Columbia River Basalts, whereas the seaward correlative disconformity may have been produced by submarine erosion; alternatively, this horizon may be conformable. Rapid tectonic uplift resulting in this subaerial erosion, with possible coincident eustatic sea level fall, may have been driven by a clockwise rotation of Pacific and Juan de Fuca plate motion (Atwater and Stock 1998). The structure contour map of the deformed unconformity and correlated seaward reflector clearly outlines deformation into major synclines, including the Newport syncline where the unconformity reaches depths of 2.5 km below sea level, and uplifted submarine banks, including Heceta and Nehalem banks. The present-day continental shelf appears to be controlled by these major geomorphic features. Structural trends are in agreement with northeasterly to easterly plate convergence vectors, but closer to the coast structures reflect the regional north-south compressional stress field. The seaward edge of the Siletzia terrane does not appear to behave as the predominant backstop driving uplift of the outer-arc high which bounds the forearc basin, as might be expected from the lithological contrast across this boundary. Heceta Bank may be an exception, where the Siletzia margin and an accreted basement ridge may produce pronounced uplift. Regional margin-parallel variations in uplift rates of the shelf unconformity show agreement with coastal geodetic rates, suggesting that the geodetic signature may not be entirely elastic with some component of permanent deformation.

The shelf basin is bounded to the west by a north-south-trending structural outer-arc high. Forearc basin subsidence and outer-arc high uplift effectively trapped sediments within the basin, which resulted in a relatively starved abyssal floor and narrower Pliocene accretionary wedge, particularly during sea level highstands. Growth strata at the western edge of the forearc basin indicate that the forearc basin formerly extended further to the west, bound by an older outer-arc high. In the early-mid Pliocene, a truncational event removed this part of the basin and reduced the width of the forearc. The present outer-arc high began to form subsequent to this event. Older, eroded forearc sediments were consequently reaccreted and/or subducted and may be present at ODP Site 892. This truncation event may also explain the relatively narrow width of the present-day accretionary wedge. During the Pleistocene, the outer-arc high was breached following near-filling of the forearc basin, possibly contributing to incision of the Astoria canyon, the primary downslope conduit of Columbia River sediments. This event is supported by a change in sediment provenance from Klamath or Vancouver Island below to Columbia River above on the abyssal plain ~1.3-1.4 Ma, based on interpolated Astoria Fan stratigraphy.

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THE MENDOCINO TRIPLE JUNCTION: ACTIVE FAULTS, EPISODIC EMERGENCE, AND RAPID UPLIFT

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A complex zone of rapid Holocene surface uplift and deformation occurs at the Mendocino triple junction, the juncture of three plate-bounding faults: the Cascadia subduction zone (CSZ), San Andreas fault, and Mendocino fault. Within this mountainous structural knot, up to 1.4 meters of coastal emergence occurred during the 1992 Cape Mendocino M_s 7.1 earthquake. Surveying and radiometric dating of ancient marine strandlines (<8000 yr old) along the trace of the southernmost CSZ, over a 20-km distance between Cape Mendocino and Punta Gorda, indicate that the Holocene pattern of net surface uplift is very similar to the 1992 coseismic uplift pattern (Merritts 1996). Results of this investigation also indicate that episodic emergence occurred at least four times between about 600 and 7000 years ago, and that some past events might have resulted in larger amounts of uplift (~2.5 m) than the 1992 earthquake, perhaps during great earthquakes (M>7.5) along the CSZ megathrust. However, another plausible interpretation of the data is that multiple earthquakes resulting in smaller amounts of net surface uplift per event--similar to the 1992 earthquake--occurred closely spaced in time, giving the appearance in the geologic record of less frequent and larger events.

Long-term rates of uplift obtained from consideration of platform ages range from 1.9 to 3.0 m/ky, consistent with estimates of uplift rates obtained from late Pleistocene marine terraces in the area (Merritts and Bull 1989, Merritts *et al.* 1991). The oldest and highest Holocene platform between Cape Mendocino and Punta Gorda has an age of 5930-6685 yr BP (mussel cemented to the platform at inner edge at Mussel Rock). The next lower platform is broad, with two pholad shell ages of 2990-3460 yr BP and 3300-3485 yr BP at Cape Mendocino (Pholadidae *Penitella penita*; sampled in original growth positions). This platform is overlain by 1.2 m of coarse marine cobbles containing a 2345-2720 yr BP charcoal log (Merritts *et al.* 1991). A sharp contact exists between the coarse cobbles and up to 2 m of overlying beach and eolian sands interstratified with Indian middens formed about 400-2500 yr BP (Merritts *et al.* 1991). The next lower platform has not been dated, but pholads in growth position from the fourth and youngest platform yield an age of 610-955 yr BP, and a debris flow deposit overlying this platform yields shell debris with an age of 135-215, or 260-465, yr BP (calibrated age has two possible solutions).

This sequence of platform ages can be interpreted relative to a rising, post-glacial sea level. As sea level rise decelerated during the mid-Holocene, coseismic uplift at 5930-6685 yr BP raised the first wave-cut platform (#1) above sea level (present platform altitude +9 m). If it formed at an altitude of 0 to -0.5 m (from the New Zealand sea level curve of Gibb 1986), it has been raised 9 to 9.5 meters in ~6.3 kyr, yielding a long-term uplift rate of about 1.5 m/kyr. Most of this platform was destroyed by rising sea level before the next lower preserved platform (#2) was elevated at 2990-3485 yr BP, forming a buttress to protect it from further wave trimming. Platform #2 remained within the intertidal zone for up to 1000 yr, as beach gravels were deposited on it until at least 2345-2720 yr BP. Assuming it formed at 0 meters, its inner edge has been raised 6 meters, yielding a long-term uplift rate of about 1.9 m/kyr. Shortly after 2345-2720 yr BP, emergence well above the wave zone occurred, resulting in the stratigraphic discontinuity between near-shore gravels and wind-blown sand overlying platform #2, as well as emergence of a lower undated platform (#3). For this reason, the minimum age of platform 3 is estimated to be 2345-2720 yr BP. A fourth platform was raised above sea level about 610-995 yr BP. This platform is generally narrow, and the thin deposits overlying it consist of terrestrial debris-flow gravels or wind-blown sand rather than near-shore beach sediments, indicating it was raised well above mean sea level during a time of decelerating or no sea level rise. Finally, in 1992, coseismic uplift raised all terraces at Cape Mendocino and Mussel Rock an additional 1.2 to 1.4 meters.

Analysis of emergent wave-cut platforms is used to estimate the amounts of uplift and recurrence intervals between events for paleoearthquakes. Five earthquakes resulting in emergence might have occurred at about 6.3, 3.3-3.4, 2.5, and 0.8 kyr BP, as well as in 1992. Recurrence intervals since 3.3-3.4 kyr BP range from ~800 to 1700 years. Maximum uplift per event was 0.9-2.5 meters for prehistoric earthquakes, but only 1.4 m for the historic event. A time-predictable model of earthquake recurrence, which predicts the time of the next event from the amount of slip in the most recent event, can be used to estimate when the next earthquake will occur. Estimates range from 940 to 1290 years, depending on which platform is used to obtain a prediction.

Although the existence of prominent risers and inference of substantial prehistoric coseismic uplift (up to 2.5 meters) at the MTJ suggest great earthquakes might have occurred along much of the CSZ, the dates of paleoseismic events in the MTJ region do not seem to correlate with those obtained farther north along the CSZ. At least five subsidence events due to great earthquakes might have occurred along the CSZ in northernmost California in the past 1600 years (Clarke and Carver 1992), but only one prominent emergent platform (#4, 610-955 yr BP) in this age range occurs in the MTJ region. Estimated age ranges of two of the CSZ events overlap that of platform #4. A better correlation exists between ages of CSZ subsidence events and debris flow deposits, as the ages of the oldest and youngest of the CSZ events are coincident with those of two debris flow deposits in the MTJ.

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ASSESSMENT OF FUTURE CASCADIA TSUNAMI HAZARDS USING A FINITE ELEMENT MODEL: TOOLS AND APPROACHES

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Designing hazard mitigation strategies for Cascadia subduction zone earthquakes and tsunamis involves integrating tools from multiple disciplines. Geological evidence provides clues as to what may happen in future events by telling us what signatures were left behind by the cycle of past earthquakes and/or tsunamis. Integrating such evidence along with current geophysical measurements can help guide estimates of how the ocean floor will deform during the next strong subduction earthquake. Finally, modeling tsunamis (Myers and Baptista 1998) from potential deformation scenarios can facilitate our understanding of the propagation and inundation of the generated waves. The latter two components, estimating the deformation from likely future scenarios and modeling of ensuing tsunami waves, have been the focus of our research, the results of which have been integrated with local, state, and federal approaches to evaluating hazards in communities along the western coast of the United States.

Using a technique developed by Flück *et al.* (1997) that computes the deformation as the integration of multiple point sources distributed throughout the subduction zone, we developed eight scenarios of how the deformation may occur in a future event. This method of computing the deformation allowed the three-dimensional geometry of the subduction zone to be represented, and slip magnitudes and directions computed using convergence rates were imposed at each of the point sources. The finite element model ADCIRC (Luettich *et al.* 1991) was modified and used to simulate tsunamis generated from each scenario. Using topographic and local bathymetric data gathered by local and state officials in Oregon and Washington, unstructured grids were extended into coastal communities at risk to tsunami inundation. Propagation patterns between the seismic source and the coast showed that bathymetric features such as banks, valleys and canyons affected the focusing directions of the waves approach to the coastline. The waves generally arrive later in the northern portion of the study, but with larger amplitudes. The inundation and wave activity in communities remains significantly strong for many hours after the earthquake. The local inundation patterns and the timing of their arrival have been analyzed in detail by state officials to develop hazard maps for Oregon and Washington coastal communities (Priest *et al.* 1997, 1998). The development of these maps has involved synthesizing the results in the context of the uncertainties involved with each phase of the project, physical factors such as tides that would affect overall inundation patterns, and the underlying geological evidence from past events.

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INTEGRATION OF VERTICAL DEFORMATION CONSTRAINTS AND GPS RESULTS FROM THE CASCADIA MARGIN

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We present a new elastic model for interseismic strain accumulation along the Cascadia subduction zone based on updated constraints on relative plate motion, GPS observations, and vertical deformation from tidal gauges and first-order leveling. This model has several important advances: (1) Convergence amount and direction are consistent with a revised Euler pole for Pacific-North America relative plate motion (DeMets and Dixon 1999) that has been propagated to North America-Juan de Fuca motion (Miller *et al.* 2000). (2) The fault plane model of (Flück *et al.* 1997) is adopted, but the width of the locking and transitional zones are varied to best fit the vertical deformation field. In southern Washington, vertical data permit two different interpretations of locking zone width; horizontal deformation constraints are more consistent with a model which extends the locked zone about 10 km farther inland than is generally accepted. The vertical deformation constraints yield a Cascadia subduction zone locking model that is more complex than those in common usage.

This model is used to predict horizontal deformation rates that can be attributed to coupling of the subduction zone. These rates are then subtracted from GPS observations of deformation (Miller *et al.* 2000, Savage *et al.* 2000). The residual velocity field, a proxy for permanent deformation, also includes important contributions from other sources.

This residual velocity field has three distinctive features: (1) In southwestern Oregon and northwestern California, northwestward motions indicate a strong response to Pacific-North America motion and to impingement of the Sierra Nevada block on the Pacific Northwest. (2) Coastal central Oregon and Washington show northward-decreasing migration of the fore-arc. The migration is inferred to result from oblique convergence and the decrease in velocities is consistent with geologic constraints that show north-south shortening within the Washington fore-arc. This deformation decreases at the latitude of Puget Sound and the Olympic Mountains, and is not evident in British Columbia. (3) Finally, there is a small but significant north and northeast-directed residual motion of the back arc region, far to the east of expected interseismic deformation.

The northward residual motion is fit with an Euler pole that lies 113.5, 43.5, -0.2°/my. This Euler pole may have little tectonic significance: it may include contributions from unmodeled differential crustal block motion, discrepancies between Juan de Fuca – North America plate circuit constraints and actual convergence of the fore-arc and the downgoing plate, and possible flaws or inconsistencies in reference frame realization. Systematic errors related to these ambiguities have distinctive spatial patterns. Mismodeling of plate boundary effects will have little effect on stations in the back arc. In contrast, flaws in reference frame realization will contribute less to the larger overall velocities in the fore-arc. Thus, refinement of the subduction zone model will rely on densification and refinement of the velocity field in the fore-arc; understanding regional residual motions relative to the stable continental interior are will be best resolved in the back-arc as reference frame uncertainties stabilize.

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SEISMIC MICROZONATION MAPS OF GREATER VICTORIA, BRITISH COLUMBIA, CANADA

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Victoria is in one of the most seismically active areas of Canada, and is susceptible to damage from crustal earthquakes (magnitude 6-8) as well as very large (magnitude ~9) earthquakes on the Cascadia subduction zone west of Vancouver Island (Rogers 1998). The Greater Victoria seismic microzonation maps show the relative variation in earthquake hazard due to amplification of ground motion, liquefaction, and slope instability.

The initial step in evaluating earthquake hazards was preparation of a geological map that reflects the thickness and distribution of Quaternary stratigraphic units (Monahan and Levson 2000). Map units are defined in terms of the stratigraphic profile present rather than solely on the sediment exposed at the surface. This map is based on several thousand geotechnical borehole and water well logs, several thousand engineering drawings for municipal sewer and water line excavations (which commonly show where bedrock was encountered), airphotos, and large-scale topographic maps. In areas where borehole data were sparse, the subsurface conditions were inferred from topographic and geomorphic evidence. Subsurface control points are shown on all maps.

The amplification of ground motion hazard was estimated by assigning U.S. National Earthquake Hazard Reduction Program (Building Seismic Safety Council 1994) site classes to each geological map unit defined above. Site classes were assigned on the basis of a shear-wave velocity model for the Quaternary sediments developed from 15 seismic cone penetration tests and 4 spectral analysis of surface waves tests (Monahan and Levson 1997). The amplification hazard is greatest in areas underlain by thick deposits of soft late Pleistocene glaciomarine clay, particularly where capped by peat and organic soils (Monahan *et al.* 1998, 2000c).

The liquefaction hazard was quantified by combining the Seed method for determining liquefaction susceptibility with the probabilistic seismic model developed for the National Building Code of Canada. Layer-by-layer probabilities of liquefaction calculated by this process were then adjusted by a depth weighting function to provide a measure of the severity of the liquefaction hazard in each map unit (Levson *et al.* 1998). Although liquefiable deposits are not widespread in the Victoria area, the liquefaction hazard is high in areas underlain by Holocene beach sands and in artificial fills. The latter are common in port facilities and other shoreline areas (Monahan *et al.* 1998, 2000b).

The slope instability hazard for soil slopes was assessed by estimating the yield acceleration of typical slopes, considering the slope angle and strengths of the geological units present. The yield acceleration was combined with the probabilistic seismic model developed for the National Building Code of Canada to estimate the probability of slope failure. The slope instability hazard is greatest along sea cliffs where sediments are exposed and along valleys and gullies deeply incised into these deposits. Most rock slopes appear to be relatively stable, although the potential for very small rock falls exists, and some areas of less stable bedrock occur in mountainous areas west of the city (Monahan *et al.* 1998, McQuarrie and Bean 2000).

The amplification, liquefaction, and slope instability hazards were combined into a composite hazard map to summarize the earthquake hazard for regional planning purposes (Monahan *et al.* 2000a). Because the amplification hazard is the most widespread in the Victoria area, the map is colour coded to reflect this hazard, and areas of moderate and high liquefaction and slope instability hazards are shown by superimposed cross hatching and shading. The intent of this map is to flag those areas of moderate and high hazard, the nature of which can be determined by reference to the individual hazard maps.

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GEOSLICER: A NEW SOIL SAMPLER FOR PALEO-TSUNAMI STUDIES

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This paper introduces a new soil sampler named Geoslicer (Nakata and Shimazaki 1997, 2000). Geoslicer enables us to extract thin vertical wide sections of unconsolidated Quaternary sediments. So it works effectively for sampling of tsunami deposits on coastal lowlands as well.

Geoslicer has a very simple structure. It is composed of a sampling box and its shutter made of steel or stainless steel. The sampling box looks like a big dustpan, having openings at its two sides. To collect soil sections, we firstly intrude the sampling box vertically down into the ground using a vibro-hammer and then its shutter sliding along the thin slits attached to both sides of the box, and pull out them together. Several devices are implemented to the box and shutter, such as wedge-shaped sidewalls and a stopper at the bottom of the box to prevent samples from slipping off. To reinforce the box and shutter strong enough to bear the stress cause by hammering, L-shaped angles are welded on their back.

We made several different-sized Geoslicer and tested them successfully in the field (Haraguchi *et al.* 1998). Extracted soil layers are surprisingly undisturbed and show almost the same features as observed on trench walls close to the extraction sites. For tsunami deposits sampling, we use a Geoslicer 40cm wide, 4m long (deep) and 7-10cm thick. Since we can directly observe sedimentary structures on ground immediately after sampling, this method is much effective than thin-wall tube sampling commonly used for paleo-tsunami studies. Extracted sections can be taken to a laboratory for cross-examination or can be displayed at a meeting or even easily stored for future reexaminations.

This sampling method is, however, still under improvement in many ways. To upgrade rather complicated and time-consuming sampling process, and to avoid possible deformation of sampled layers by vibro-hammering, we are trying to make sampling system simpler for better performance in high-resolution paleoseismological studies.

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OXCAL ANALYSES AND VARVE-BASED SEDIMENTATION RATES CONSTRAIN THE TIMES OF ^{14}C-DATED TSUNAMIS IN SOUTHERN OREGON

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Low-lying freshwater lakes above the reach of storm surges contain records of local tsunamis that can be used to reconstruct the history of great earthquakes along the Cascadia subduction zone. A 7300-yr record from Bradley Lake, formed when a dune blocked a stream 28 km north of Cape Blanco, contains 17 lake disturbance events (DEs), at least 12 of which probably record tsunami inundation of >5.5 m. We dated the 17 DEs in Bradley Lake with 57 AMS ^{14}C ages measured on detrital plant fragments from disturbance event beds in 11 of the 21 described piston and vibracores from the lake. Most fragments were probably deposited within a few hours of each DE.

To evaluate the stratigraphic consistency of the ages we used the sequence analysis feature of the program OxCal with the INTCAL98 radiocarbon calibration data set. Ages were grouped in stratigraphic order using 19 phases; the ages within each phase (DE) were unordered. Ages similar enough to be considered from the same population at the 95% level were averaged. Calibrated-age distributions were calculated for means and single ages within each phase. In the sequence analysis, ages that had probabilities of <10% of being in the correct stratigraphic order were eliminated from further analyses.

In later sequences analyses, we added estimates of the minimum and maximum number of years between DEs to further constrain the age distributions for DEs 2-16 (Fig. 1). The estimates were calculated by dividing mean sediment thicknesses between DEs by sedimentation rates determined by counting varves in finely laminated, 1-to-7-cm-thick beds of clay-gyttja overlying each DE. Varve preservation is favored by anoxic, brackish conditions at the bottom of the lake that lasted for decades following many DEs. As suggested by the r^2=0.99 for the linear regressions of Figure 1 (dashed lines show 95% confidence limits), ages for DEs derived by summing the number of years (estimated from sedimentation rates) for each interval between DEs compare favorably with the ^{14}C ages for the same DEs. The consistency in the two types of independently derived ages supports our inference that light-dark couplets in finely laminated beds above DEs are varves. OxCal restrictions or shifts in the age distributions for DEs 8 and 11-14 may be partly the result of unrecognized erosion of lake sediment or changing sedimentation rates. Age distributions for DEs 15 and16 are too widely separated in time from each other and DEs 14 and 17 to be affected by the sequence analyses.

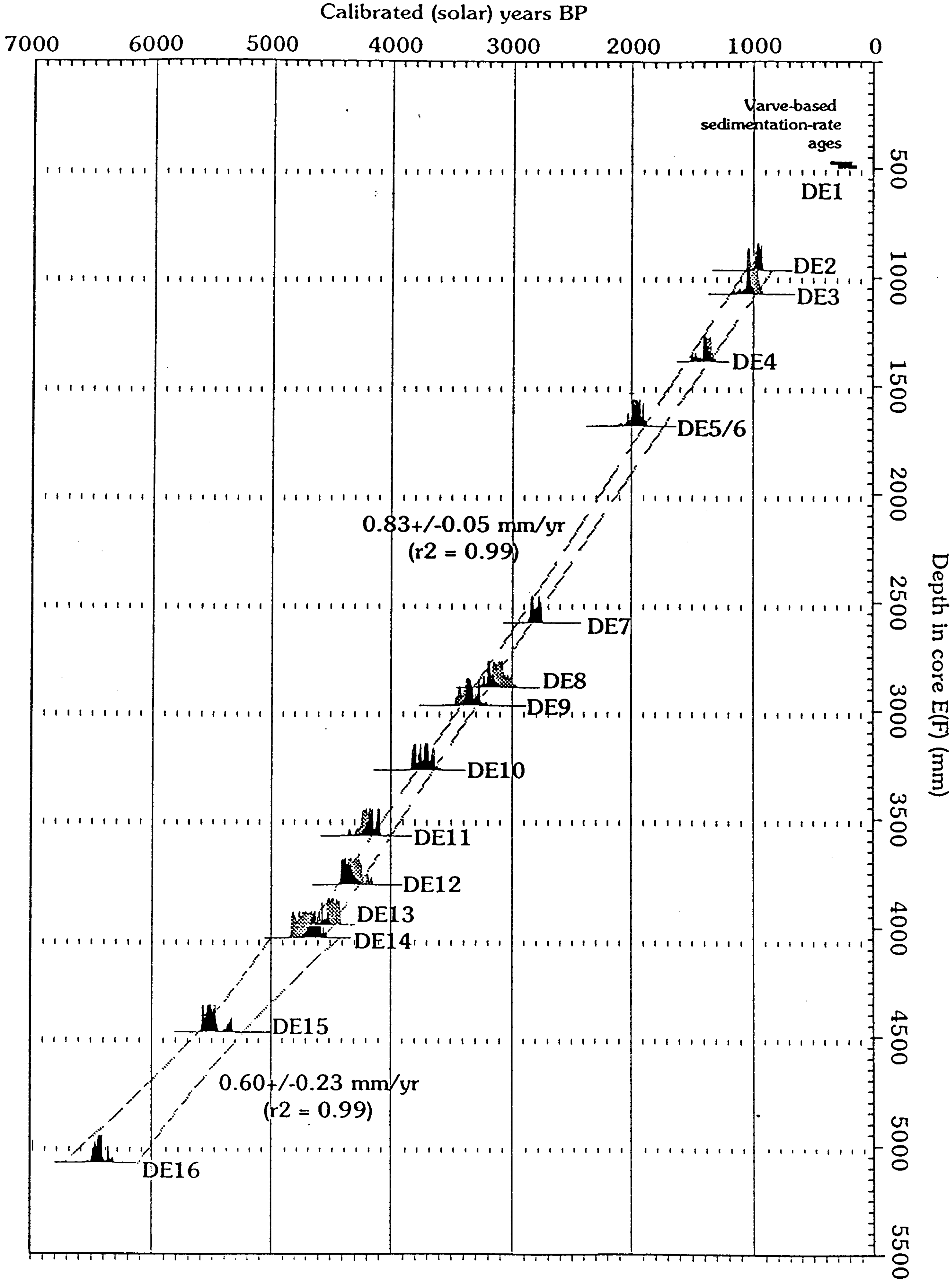

Figure 1. Calibrated-age distributions for DEs (disturbance events) in Bradley Lake determined by OxCal. Initial distributions (gray) were restricted or shifted (final black distributions) with estimates of the number of years between DEs derived from varve-based sedimentation rates.

TURBIDITE EVENT STRATIGRAPHY AND IMPLICATIONS FOR CASCADIA BASIN PALEOSEISMICITY

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Numerous Holocene turbidite events have been found in Cascadia Basin canyon mouth and downstream channels from Vancouver Island to Cape Mendocino. The consistent pattern of turbidite deposition from multiple canyon sources along 1000 km of the continental margin has several implications for the Basin paleoseismic record. Correlation of events is based on the first occurrence of Mazama Ash in turbidites (Nelson *et al* 1968) and on the approximate onset of Holocene sediment deposition as determined by a dominance of radiolarian fauna in hemipelagic sediment (Nelson 1976). The Holocene onset is estimated to be about 11,300 calendar yr BP (cal yr) near the base of the continental slope (Goldfinger *et al.* 1997). The first post-Mazama turbidite event occurred about 7500 cal yr ago or 100 yr after the Mt. Mazama eruption forming Crater Lake, Oregon. Twelve post-Mazama (MA) events are found in the Juan de Fuca Channel in north Cascadia Basin; 12 or 13 MA events occur at multiple locations in Cascadia Channel and Rogue Channel which is at the south end of Cascadia Basin. Astoria Canyon mouth and upper Astoria Channel contain 11-13 MA events; however, erosional cutouts and bed amalgamation make exact event determination difficult. In previously existing cores, only 3 MA events were found in middle and lower Astoria Channel, which appeared to contradict Adams (1990) hypothesis for 13 MA events. In new cores, we find a progressive loss of turbidites from 7 to 6 to 5 MA events at each successive downstream channel splay in upper Astoria Channel. This down-channel loss of MA events resulting in only 3 MA events in the mid-lower Astoria Channel explains the previous apparent contradiction. In sum, for 700 km along the Cascadia subduction zone, our interpretation, like Adams', is that 13 MA events occurred. Assuming event 12 took place 7500 cal yr and event 1 took place in AD 1700 (Satake *et al.* 1996), 12 turbidite events have occurred during 7200 years or on average every 600 years. Existing AMS ages show 700 yr between the first and second MA events; the same periodicity between most events in all cores also is suggested by the consistent thickness of hemipelagic sediment representing about 600 yr between turbidite beds.

Where Mazama Ash stratigraphy is not present south of the Rogue Canyon, the number of evenly-spaced Holocene turbidite events in channel systems progressively increases toward the Mendocino Triple Junction at the southern end of Cascadia Basin. In Trinidad Canyon 25 Holocene turbidite events or 1 per 452 yr occur, in Eel 50 or 1 per 226 yr, and in Mendocino 1 per 65 yr based on AMS ages found in a 1986 box core. The synchronicity of turbidite events in the northern two thirds of Cascadia Basin (1 per 600 yr) and the progressively increasing frequency of events toward the triple junction are best explained by seismic triggering. The increased frequency of Holocene turbidite events off the Northern California portion of the margin suggests either segmentation of the margin, with a shorter recurrence interval for the Northern California segment, or margin-wide synchronicity, with the additional Holocene events representing a mix of seismic sources. Because up to 7.2 magnitude earthquakes.have occurred in the Mendocino vicinity since 1986 and because there is no surface sand in a 1999 box core taken at the 1986 Mendocino Channel site or other southern Cascadia channel locations, it appears that southern Cascadia Basin turbidite events represent greater than 7.2 magnitude earthquakes. Most important, the Cascadia Basin evidence verifies that turbidite event stratigraphy can be an effective paleoseismic technique. This technique can be applied to other active margin settings worldwide, where an extensive fault traverses a continental margin with several active turbidite systems. One such example is the turbidite record preserved near the base of Noyo Canyon off the northern San Andreas margin. The turbidite event record of Noyo Canyon appears to (1) correlate with the present northern San Andreas paleoseismic record on land, (2) account for the additional number of Cascadia turbidite events adjacent to the Mendocino Triple Junction and (3) suggest margin-wide synchronicity of the 13 post-MA events for the entire Cascadia subduction zone.

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THERMAL AND PETROLOGIC PROCESSES IN THE CASCADIA SUBDUCTION ZONE

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The subduction of the Juan de Fuca plate beneath North America cools the Cascadia forearc. The low surface heat flux through the Cascadia forearc is a consequence of the downward advection of isotherms by the subducting lithosphere. The thermal structure of a subduction zone is determined primarily by the convergence rate and the thermal structure (age) of the incoming lithosphere (e.g., Peacock 1996). Compared to most subduction zones, the Cascadia subduction zone is relatively warm because of the slow convergence rate (~40 mm/yr), the young age (5-10 Ma) of the incoming Juan de Fuca plate, and the thick (3-3.5 km) blanket of insulating sediments which acts to increase temperatures in the underlying oceanic crust.

Hyndman and Wang (1995) constructed detailed, two-dimensional thermal models across the Cascadia forearc. Surface heat flow measurements were used to constrain the rate of shear heating along the subduction thrust. The best fit to the observed heat flow data requires no shear heating which is consistent with the apparent lack of shear heating in the warm Nankai subduction zone. Hyndman and Wang's (1995) thermal models predicts thrust temperatures of ~250°C at the deformation front increasing to ~525°C at 40 km depth. The downdip limit of the Cascadia seismogenic zone may be controlled by the temperature-induced transition (350-450°C) from stick-slip to stable sliding behavior (Hyndman and Wang 1995). Pressure-temperature paths calculated for the subducted Juan de Fuca oceanic crust intersect greenschist-facies metamorphic conditions in contrast to the lower temperature, higher pressure blueschist-facies conditions encountered in most subduction zones.

During subduction, substantial amounts of water will be expelled from sediments and altered oceanic crust due to porosity collapse (compaction) and water-releasing metamorphic reactions (e.g., Moore and Vrolijk 1994). Tectonic burial and deformation results in dramatic reduction of sediment porosity and expulsion of pore fluids within a few tens of kilometers of the deformation front. In contrast, pore waters in the fractured upper part of the subducted basaltic crust may not be expelled until ductile conditions are achieved much deeper in the subduction zone. Metamorphic dehydration reactions also release significant amounts of water beneath the Cascadia forearc. Important water releasing reactions in subducted sediments include the breakdown of clay minerals to form micas (e.g., smectite → illite) and the opal → quartz transformation. Hydrous minerals, such as zeolites, in altered oceanic basalt and gabbro will breakdown and release water during low-grade (sub-greenschist and greenschist-facies) metamorphism. At 40-50 km depth, subducted Juan de Fuca oceanic crust should transform to eclogite (a dense rock composed of garnet and pyroxene) which may explain the rapid increase in dip of the subducting Juan de Fuca plate.

Water released from subducted sediments and oceanic crust migrates upward primarily by focused (channelized) flow along faults and high-permeability sedimentary layers (Moore and Vrolijk 1994); in contrast, diffuse upward flow is likely to be limited by low-permeability stratigraphic horizons (Moore and Vrolijk 1994). Water expelled by compaction and low-temperature metamorphic reactions will act to elevate fluid pressures along the subduction thrust to values possibly approaching lithostatic. While most expelled water is expected to reach the seafloor or land surface, some water may be absorbed by hydration reactions in the upper plate. Water that enters the forearc mantle will react with olivine and pyroxene to form serpentinite, a relatively weak rock that may control the downdip limit of the seismogenic zone in cool subduction zones (Peacock and Hyndman 1999). At depths greater than ~40 km, water released by metamorphic reactions may trigger intraslab earthquakes due to dehydration embrittlement (Kirby *et al.* 1996). In the warm Cascadia subduction zone, intraslab earthquakes occur at relatively shallow depths (<100 km) and represent a significant hazard. Most water is expelled at depths < 50 km, but enough water is released from the subducted slab at depths of ~100 km to trigger partial melting of the overlying mantle and the observed arc volcanism.

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PROBABILITY DISTRIBUTIONS FOR RECURRENCE OF USGS HAZARD MAP CHARACTERISTIC EARTHQUAKE SOURCES IN THE PACIFIC NORTHWEST

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Likelihood functions for annual recurrence rate can be derived from the Poisson and Weibull probability distributions, given the number of events observed, N, over time T. From the fractiles of these likelihoods, the corresponding fractiles of the probability of recurrence in the next thirty years can be calculated for (1) the single paleoevent on the Seattle Fault and (2) the supposed subduction events observed indirectly at Willapa Bay.

For the Poisson model, the maximum likelihood annual recurrence rate is given by N/T, but the mean recurrence rate, which drives probabilistic hazard analyses, is given by (N+1)/T. Fractiles for the distribution of rate parameter can be determined by using the likelihood function in a spread sheet.

For the Seattle Fault, taking N=1 and T=6000, the mean rate is 1/3000. The rate at the 0.1 fractile (1/11,000) is 7 times smaller than the rate at the 0.9 fractile (1/1,500).

At Willapa Bay, Washington, Atwater and Hemphill-Haley have documented 7 disturbances occurring over the past 3500 years, interpreted as subduction earthquakes, greater than magnitude 8. These data yield a mean recurrence rate of 1/440, and the rate at the 0.1 fractile (1/760) is 2.5 times smaller than the rate at the 0.9 fractile (1/300). For the next 30 years the corresponding probabilities are 4 percent and 10 percent.

For the Weibull model, a likelihood function for recurrence rate parameter can be obtained from the Poisson likelihood function, replacing T by the sum of the intervals scaled by raising them to the power of the Weibull shape parameter. For this data set, the shape parameter is 1.87 (Poisson occurrences would give 1.00). This value narrows the distribution for rate parameter, such that ratio of the fractiles (0.1: 1/720 and 0.9: 1/430) is now a factor of 1.7. However, the recurrence probability results in the next 30 years are comparable to the Poisson results, because for an elapsed time of 300 years since the last event, the time-dependent model makes the probability of future occurrence relatively smaller than suggested by the parameter for the lower fractile rate and larger for the higher fractile rate.

For a Poisson model there is a far greater likelihood of short recurrence intervals than in the Weibull model. If the methods of identifying and dating events cannot discriminate one event from two events in a time interval of, say, 100 years, short-interval events may be missing from the record. In this case, a Weibull model could not be distinguished from a truncated Poisson model having an average recurrence rate as much as 30 percent higher than that given by the observed number of events.

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A DECADE OF QUANTIFYING EARTHQUAKE HAZARDS FROM COASTAL GEOLOGIC RECORDS: CENTRAL CASCADIA MARGIN, USA

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After several years (1986-1989) of reconnaissance work on Cascadia earthquake records in Oregon's coastal deposits we shifted our emphasis to focus on applied studies of related earthquake hazards. The chronology of hazard studies (1990-2000) includes event recurrence interval and minimum rupture area (Briggs 1994, Darienzo and Peterson 1995), coseismic liquefaction (Peterson and Madin 1997), tsunami inundation (Peterson and Priest 1995, Fiedorowicz and Peterson 1999), and post-subsidence effects of coastal flooding (Barnett 1997) and beach erosion (Doyle 1996, Meyers *et al.* 1996). In this paper we discuss the application of regional paleoseismic data to quantify great earthquake hazards. Four difficulties are addressed including sampling strategy restrictions, radiocarbon dating errors, geologic record discontinuity, and uncertainty of hazard prediction.

For hazard mapping purposes, sampling strategy needs to be dense, complete, and uniform within mapping (jurisdictional) boundaries. By comparison, paleoseismic records are typically preserved in isolated tidal wetlands, coastal ponds, and/or exposed outcrops. Broad extrapolation between data-rich localities limits site-specific hazard prediction. Although the strongest evidence for event correlation is based on stratigraphic signatures, both deterministic- and probabilistic-hazard analysis require absolute dating, typically by radiocarbon. Uncertainty in radiocarbon reservoirs, contamination, and counting statistics yield dating errors that yield poor age correlation, and thereby undermine confidence in hazard magnitude estimates. The geologic record in high-energy coastal environments is notoriously discontinuous. Incomplete time-series records minimize local event frequency. Taken together the uncertainties of local hazard prediction weaken arguments for mitigation, and provide justification for inaction at city, county and state jurisdictional levels.

Some of these geologic record limitations can be overcome by dedicated investigations that search for, and compile, specific data needed to evaluate hazard frequency and magnitude. Regional paleoseismic evaluations completed for the central Cascadia margin, i.e., northwest Oregon and southwest Washington, include (1) mean recurrence interval (400+/-200 years for the last 2500 years), (2) locked-zone rupture area (>2400 km^2, >M_w 8.5), (3) peak ground acceleration (>0.1-0.2 g at >100 km inland from the coast), (4) high-velocity tsunami inundation (0.5-1 km overland inundation of open-coast barrier plains), (5) post-subsidence coastal flooding (0-2 m), and (6) post-subsidence beach retreat (0-300 m). Some of the paleoseismic data sets are also used to verify and/or calibrate various numerical models of fault rupture-area probability (Geomatrix 1995), and tsunami excitation (Priest *et al.* 1997).

The results of these studies and many others, are reflected in recent upgrades of UBC seismic zonation in western Oregon (Zone 3) and along the southwest Oregon coast (Zone 4), and in ongoing tsunami hazard mapping in Oregon (DOGAMI, NOAA) and Washington (WDNR, NOAA). Future hazard analyses by agencies and consultants will need to focus on site-specific evaluations based on geophysical, geotechnical, and hydrodynamic modeling results. However, the paleoseismic geologic studies discussed here will provide the initial bounding conditions for these hazard-modeling efforts, and will add credibility to model based recommendations for hazard mitigation.

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SEISMOTECTONICS OF THE 1964 ALASKA EARTHQUAKE AS AN ANALOG FOR FUTURE TSUNAMIGENIC SOUTHERN CASCADIA SUBDUCTION EARTHQUAKES

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Striking similarities in large-scale structure of the eastern Aleutian and southern Cascadia subduction zones include: shallow megathrust dips (<10°); continental margin settings; wide forearc accretionary sequences of Mesozoic and Cenozoic age; active forearc fold-and-thrust belts that extend onshore; complex transitions to transform boundaries on their east and south ends, respectively; and long late Holocene paleoseismic records of subduction zone earthquakes. Both margins are characterized by nearly orthogonal plate convergence (~5 cm/yr in Alaska and ~3 cm/yr in Cascadia). The overall similarities suggest that the 1964 Alaska earthquake tectonic displacements and associated major tectonically-generated tsunami may be the best available analog for interpreting the Cascadia paleotsunami record and for forecasting vertical displacements and associated tectonic tsunamis that are likely to accompany future great Cascadia earthquakes.

During the great 1964 Alaskan earthquake (M_w 9.2), the eastern Aleutian subduction zone ruptured 800 km along strike and 125-250 km down dip (Plafker 1969). Coseismic dip slip of as much as 30 m occurred along the plate interface, which dips at an average angle of 9° NW in the northeastern end of the rupture zone. Out-of-sequence upper plate splay faults on Montague Island and seaward of Middleton Island accommodated at least 23 meters of slip, equal to more than 2/3 of the total slip in that part of the displacement field. Combined movement on the megathrust and splay faults resulted in uplift of 140,000 km^2 of the continental shelf and offshore islands of as much as 11.3 m and subsidence of as much as 2.3 m within a subparallel landward belt 125,000 km^2.

The 1964 earthquake is unique in that the relationship between vertical displacement and tsunami height in the near field could be determined over much of the displacement field. The general shape of the tsunami source on the continental shelf is roughly approximated by a broad, relatively low amplitude upwarp of less than 4 m having minimum dimensions of 640 km by120 km, superimposed upon which is a narrow belt of uplift to at least 11.3 m that is about 10 km wide and is inferred to extend some 550 km southwest from Montague Island. The broad uplift is caused primarily by coseismic slip on the Aleutian megathrust, whereas the narrow zone of large uplift corresponds with coseismic slip of at least 7.9 m along steeply-dipping (50°-85° NW) major intraplate thrust faults within the Patton Bay fault zone that splay off the megathrust (Plafker 1969).

Coseismic uplift of the continental margin generated a major tsunami that had near-source runup heights to a maximum height of 12.7 m above tide level, an amount only about 10% higher than the maximum measured tectonic uplift. At most outer coast localities, runup was significantly less than 12.7 m. Empirical and experimental data indicate that local shallow water bathymetry and shoreline configuration may result in amplification of wave runup by a factor of as much as 2 relative to vertical seafloor displacement in the tsunami source area (Costas Synalokis, personal communication, 2000).

The structure of the southern part of the Cascadia subduction zone includes a 70-100 km wide active fold and thrust belt that extends onshore in northern California and has been mapped for about 200 km offshore north of Humboldt Bay (Clarke 1992). North of Humboldt Bay, the fold and thrust belt is composed of two distinct thrust fault zones, the Mad River fault zone and the Little Salmon fault zone which together have taken up as much as half of the total convergence across this part of the Cascadia margin. Fault dips are as much as 60° in the subsurface but generally are considerably shallower where observed near the surface in the southern part of the belt. Structural studies of faults in the onshore part of this belt suggest that both the Little Salmon fault and the megathrust undergo coseismic slip during subduction zone earthquakes (Carver *et al.* 1999).

In southern Cascadia, recurrence intervals for large subduction zone events range from 200 to more than 700 years and average 375 years; corresponding wave run-up heights are interpreted to be 9-14 m (Carver *et al.* 1999). For this average recurrence time and an orthogonal convergence rate of 3 cm/yr, average dip slip per event is 11.25 m. For the extreme case where all the slip is confined on the shallow-dipping megathrust, maximum coseismic uplift offshore at the wave source would be no more than 2 meters and runup heights are likely to be less than 4 m, a height that is totally incompatible with the paleotsunami data. We conclude therefore, that the available data on recurrence and paleotsunami runup height can be accommodated only if most, or all, of the coseismic slip during great southern Cascadia megathrust events is partitioned onto steeply-dipping intraplate splays such as the Mad River and Little Salmon fault zones. Thus, if all coseismic slip is taken up on a splay fault having near-surface dips of 30°-60°, the uplift offshore at the tsunami source increases to 5.6-9.7 m, an amount that would be in the range of the interpreted 9-14 m wave runup heights, assuming a plausible shallow water height amplification factor on the order of 1.5. Implications of this model are that (1) the main tsunami source and largest coseismic deformation lie closer to shore than would be the case for slip mainly on the megathrust and (2) the part of the approximately 20-km wide accretionary prism between the offshore Little Salmon fault zone and the Cascadia megathrust is essentially decoupled from the underthrusting oceanic crust and is aseismic.

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ESTIMATING THE CASCADIA TSUNAMI THREAT: IMPORTANT ISSUES

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Cascadia subduction zone tsunamis could conceivably cause life loss much greater than losses from seismic shaking alone. Society must decide how to set priorities among mitigation options (hazard assessment, planning, engineering, education, etc.). Depiction of tsunami destructiveness and probability drives these decisions. Hydrodynamic simulations depicting destructive potential of Cascadia tsunamis have been hindered chiefly by uncertainties in the earthquake source, rupture simulation methods, and lack of verification. Uncertainties in the hydrodynamic simulation methods and oceanographic factors are also of concern, but coseismic sea floor deformation is a much greater source of error (Priest *et al.* 1997, Myers *et al.* 1999).

Paleoseismic and other data tends to support Cascadia earthquakes with moment magnitudes of ~9, rupture lengths of ~1000 km, and recurrence of ~500 years (see summary by Clague 1997), but there is much active debate about rupture width, total slip, distribution of slip, and the possibility of submarine landslides. Geological and geophysical data on rupture width have been interpreted to support narrowing of the rupture south of the Columbia River (Hyndman and Wang 1995), but paleo-subsidence data in northern and central Oregon can be interpreted to support widths twice as wide as those of Hyndman and Wang (e.g. Priest *et al.* 1997). Analysis of the Alaska 1964 subduction zone earthquake demonstrated that partitioning of slip onto splay faults and asperities can dramatically affect sea floor deformation (e.g. Holdahl and Sauber 1994). Table 1 summarizes the effects of source uncertainties.

Table 1. Effect on tsunami hazard of source parameters, all other parameters constant

Tsunami Source Parameter	Effect on Tsunami Hazard
Larger rupture length	Larger affected coastline length
Larger total thrust slip	Larger run-up and inundation
Larger slip on left lateral faults (from oblique convergence)	Smaller run-up and inundation (from decreased thrust slip)
Larger rupture width	Smaller run-up; slightly smaller inundation
Larger slip in asperity or splay fault	Larger run-up and inundation (local)
Larger submarine landslides	Larger run-up and inundation (local)

Refinement of our knowledge of asperities, splay faults, total fault slip, and rupture simulation algorithms will produce the greatest benefit for the entire Cascadia margin. Better defining landslide hazard and rupture width will be of most benefit to Oregon and northern California. Submarine landslides are probably more likely on the southern Oregon and northern California coast, since the continental slope is generally steeper there. Oblique convergence causes a potential reduction in thrust slip of 13 percent in southern half of the margin (McCaffrey and Goldfinger 1995). Likewise, most workers agree that the potential Cascadia rupture is wide (≥100 km) north of the Columbia River; but If the rupture narrows drastically south of the Columbia River, as inferred by Hyndman and Wang (1995), a leading depression wave (trough) is generated which can amplify run-up by 40-50 percent (Tadepalli and Synolakis 1994, Priest *et al.* 1997, Myers *et al.* 1999). Uncertainties in total fault slip and partitioning of slip to splay faults or asperities are an issue for the entire margin; both factors can cause large variations in run-up (Geist and Yoshioka 1996) and inundation (Priest *et al.* 1997). Compounding these problems are inaccuracies in fault rupture simulation, which is still in an early stage of development (see problems encountered by Priest *et al.* 1997).

Even the best theoretical work must have verification from field data. Since there is essentially no historic field data, prehistoric (paleo-tsunami and paleo-deformation) data and modern geodetic measurements of crustal strain must be used. Extending and refining the database on paleo-deformation by study of buried and uplifted soils should be a top priority. Identifying paleo-tsunami deposits and then extracting from them estimates of current velocity and water depth is equally important. The feedback between this information and tsunami simulations can only occur if paleo-topography and paleo-bathymetry can be estimated. This information is dependent on availability of detailed modern bathymetry and topography together with a thorough understanding of coastal geomorphic evolution over at least the last 300 years. Even with high uncertainty in pale-topographic conditions, sensitivity analysis may place important constraints on maximum and minimum size of paleo-tsunamis. Field verification sites should be located where paleoseismic data are abundant and paleogeographic uncertainties are low.

Accurate depiction of the Cascadia tsunami hazard will require interdisciplinary teams focused on a few strategic sites. The interstate and international scope of the problem makes it important for a federal agency to take a leadership role in coordinating the work. Since the primary problems are geologic, the logical agency for the United States is the U.S. Geological Survey in close coordination with the leader in tsunami mapping and simulation, the National Oceanic and Atmospheric Administration.

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ROCK SLIDE - DEBRIS AVALANCHES AS RECORDS OF PREHISTORIC EARTHQUAKES IN WESTERN WASHINGTON STATE

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In the Cascade Range and Olympic Mountains of western Washington, rock slide - debris avalanches, many greater than 2 x 10^6 m^3 in volume, record the timing of ancient earthquakes. The ages of more than 25 of these landslides have been estimated by radiocarbon dating of associated subfossil wood. However, only about 25 percent of these estimates allow constraint of the calendric age of landslide-induced tree mortality; the outer rings from subfossil trees provide the best age constraints. Therefore, additional studies are needed in order to provide ages for yet undated landslides and to refine and extend the record of prehistoric earthquakes.

Landslides may be classified according to the type and nature of their movement and material (Cruden and Varnes 1996), which in turn can offer clues about their triggering mechanisms. A rock slide-debris avalanche begins as a mass of rock that first fails along slip or shear surfaces or within a narrow zone, for example, along a bedding and/or joint plane or other discontinuity, and then transforms into an avalanche of debris. The initiation of such a landslide is commonly dominated by inertial forces instead of quasi-static forces such as the increased pore-water pressure that can reduce shear strength and cause debris flows or earthflows (Pierson and Costa 1987). The western Washington rockslides, therefore, were likely to have been triggered by strong shaking during earthquakes. Schuster *et al.* (1992) in their study of rock avalanches in the eastern Olympic Mountains cited other empirical evidence to support this inference:

- The rocks that slid or avalanched have not failed at such scales historically during storms
- Worldwide, 29 of 71 rock avalanches that are included in an inventory of landslide dams (Costa and Schuster 1991) were triggered by earthquakes having magnitudes of 6.0 or greater (Keefer 1984)
- In New Zealand, the distribution of lakes dammed by landslides approximates the locations of shallow earthquakes of magnitude 6.5 or greater (Perrin and Hancox 1992)

Some of the largest rockslide-debris avalanches occurred about 6900, 3800?, 2600?, 2300, <1600?, 1000, <900?, 600, and 400-to-300 radiocarbon years ago (Logan *et al.* 1998, Pringle *et al.* 1998). Additionally, volcanic hazards studies, mostly by the U.S. Geological Survey, have identified large "sector collapses" from Cascade Range volcanoes that have been recorded at about 5500, 5000, 2600, 2500?, 2300, 1500, 1000, and 600 radiocarbon years ago, and these may be associated with seismic activity (and eruptions?) at or near volcanoes (U.S. Geological Survey reports).

Tree-ring studies have improved the quality and accuracy of radiocarbon ages for rockslides. For example, when combined with radiocarbon analysis, our studies of tree rings of the buried and submerged trees from the southeast Olympic Mountains suggest a correlation among geographically distinct landslides, a nearby fault-dammed lake, and the Canyon River fault (Pringle *et al.* 1999). These correlations have allowed averaging of radiocarbon ages from the different sites, and a reduced error range that apparently discriminates a strong seismic event within about one century after the Seattle fault rupture of AD 900-930.

Tree-ring studies have also allowed more precise determination of calendric ages for rockslides. Using two different tree-ring methods, for example, we have estimated the age of a rock slide-debris avalanche from Mount Wow, west of Mount Rainier, to within a calendar year of AD 1821—coincident with an ethnographic account of an earthquake near there. Further studies of the subfossil forests will provide more accurate estimates of the size and frequency of ancient earthquakes, better characterize the activity along fault zones, reveal evidence for previously undocumented or poorly-studied fault zones, and allow development of better and more extensive tree-ring chronologies—all of which will allow better forecasts on the nature of future earthquakes.

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COMMUNICATING THE EARTHQUAKE THREAT TO THE GENERAL PUBLIC

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As more and more geologic evidence comes to light on the potential for great (M_w 8-9) earthquakes from a Cascadia subduction zone megathrust event along the Pacific Northwest coast, scientific organizations and government agencies face the challenge of keeping the general pubic informed. Traditional media (newspapers, radio and television stations), given its limitations in communicating to a passive audience, has been most people's only source of information on earthquake risks (Oregon Department of Geology and Mineral Industries Public Opinion Survey, in press).

Too often, especially in presentations made to business and civic groups, Oregon Department of Geology and Mineral Industries (DOGAMI) staff members find people misinformed about the earthquake hazard and unclear or unwilling to take any steps that would reduce their risk. Our 1999 public opinion survey reinforces these observations, finding 40% of respondents in Oregon thinking a major earthquake will occur in the next 10 years. 81% said they had experienced an earthquake in the past, but only 24% knew to "drop, cover and hold" if an earthquake occurred and over 70% had done nothing to prepare for it. These statistics should concern everyone involved in earthquake education and help focus the effort in leading people to action. The fact is most people have never experienced a damaging earthquake and therefore may be in denial. Inconsistent messages on the part of agencies responsible for disseminating information also plays a role in the public's inaction (Lopes 1998) and inaccurate information from the media can lend confusion to an already confusing message.

It is obvious that non-traditional approaches to communicating the earthquake threat are needed. No longer is it enough for an agency like DOGAMI to produce a relative earthquake hazard map for a community and hope the media attends the press conference. While efforts in recent years have concentrated on qualifying the earthquake threat in selected Oregon communities, as we've seen in recent surveys, the information isn't getting through. New and different studies, publications and outreach strategies are now being used to lead people to action.

The release of Special Paper 29, "Earthquake damage in Oregon: preliminary estimates of future earthquake losses" (Wang and Clark 1999) marked the first time a state of the art computer model (HAZUS 97) had been used to estimate statewide earthquake damages and economic losses from a Cascadia subduction zone earthquake model and a 500 year recurrence interval model. The study also summarized individual county losses, estimating displaced households, damage to schools, fire stations and bridges, which helped people relate the earthquake threat to something they could understand.

The release of earthquake scenario ground shaking maps for the Portland metro area (Wong *et al.* 2000) on January 24, 2000 was another important effort to inform the public about the earthquake threat. The release coincided with a DOGAMI Governing Board meeting, the visit of the Japanese researcher who helped uncover the evidence of an AD 1700 Cascadia tsunami (Satake *et al.* 1996) and the 300th anniversary of the last great Cascadia subduction zone earthquake (January 26, 1700). The maps themselves modeled two different scenarios: a M6.8 earthquake on the fault that runs under downtown Portland and a M9.0 Cascadia subduction zone event. To personalize the effects of these scenarios, the Modified Mercalli Intensity Scale was used in color coding the peak horizontal acceleration values. Pre- and post-release briefings were also held for city officials, utility representatives and regional planners and the media was afforded complete access to all involved in the creation of the maps.

The establishment of an Information Center in partnership with the USDA Forest Service is another way DOGAMI is using non-traditional efforts to reach the public. Earthquake hazard maps, posters and free risk reduction literature is prominently displayed through the store next to hiking guides and coffee table picture books. The development of school curricula, regional workshops, and a one day conference to instruct lodging managers and owners on tsunami risk reduction strategies are also new ways DOGAMI is trying reach out with a proactive earthquake hazard mitigation message.

While these efforts are a good start and we continue to look for strategic partnerships to help us communicate more effectively, more organizations and agencies need to be involved. National partnership models like the National Disaster Education Coalition (American Red Cross, FEMA, the National Weather Service, U.S. Geological Survey, the U.S. Fire Administration and the National Fire Protection Association) need to be pursued on a regional level. Relationships with local media and private-public partnerships are also needed. Most important, a consistent, believable message that personalizes the risks needs to encourage people to take action.

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WHAT PRESENT DAY EARTHQUAKES CAN TELL US ABOUT STRAIN ACCUMULATION AND THE NEXT GREAT CASCADIA EARTHQUAKE

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Earthquake actively in the Cascadia subduction zone region in the past century appears not to have involved activity on the Cascadia subduction fault. Approximately 30 years of modern instrumental observations (e.g. Ludwin *et al.* 1991, Rogers 1998) have shown that earthquakes occur within the oceanic plates and within the continental North American plate, but not on the boundary fault between them. This ongoing earthquake activity represents a considerable earthquake hazard, and in many regions of Cascadia, it represent a much greater hazard than that posed by great subduction earthquakes. By studying these ongoing earthquakes, we not only learn more about the hazard that they present, but much can also be learned about constraints on great subduction earthquakes. Studying these earthquakes can provide both unique information and independent observations that can corroborate inferences about great subduction earthquakes made using other geoscientific techniques.

One of the most compelling observations that the subduction fault represents a seismic hazard is the lack of earthquakes on the fault surface, which suggests a currently locked fault. When this lack of seismic of activity is coupled with the abundance of earthquakes on offshore fracture zones that indicate the Juan de Fuca plate is moving towards the North American plate (e.g. Hyndman and Weichert 1983), the conclusion is that strain must be accumulating. Relative plate movement over geological time is recorded by magnetic anomalies on the sea floor and in deformation of sediments beneath the continental shelf, but the contemporary offshore earthquake activity lets us know that plate motion is going on now. The resultant accumulating strain in the coastal region has been measured by a number of geodetic techniques.

The earthquakes within the subducting plate define its position beneath the coastal region (e.g. Tabor and Smith 1985). The earthquake locations, together with active seismic techniques, allow the dip of the subduction fault to be determined along much of its length. The depth distribution of earthquakes in the overlying plate define its brittle thickness and thus the down-dip length of the seismogenic portion of the subduction fault, where this brittle thickness is in contact with the subducting plate. The down-dip extent of the currently locked portion of the fault also has also been deduced independently from the analysis of both geothermal and geodetic data. The dip and the down-dip extent of the potential fault rupture are very critical in deducing seismic hazard from subduction earthquakes because they constrain how close the seismogenic region of the fault is to urban areas.

Analysis of small earthquakes reveals that the stress regimes in the downgoing and overlying plates are distinctly different and thus the plates are decoupled from one another except along the subduction fault. Earthquakes in the North American plate reveal that the principal stress is parallel to the coast (almost perpendicular to the strain that is building up), and that the two remaining stress axes are of the same order of magnitude. This means that the present shear stress on the subduction fault must be low and that the fault is probably a very weak fault (e.g. Wang *et al.* 1995), implying that repeated rupture on the same fault surface is likely.

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GREAT EARTHQUAKES IN SUBDUCTION ZONES

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Most of the world's great earthquakes are underthrusting events in subduction zones. For this paper, I shall apply the term "great earthquakes" to those events with M_w8. In the 20th century, there have been three earthquakes with M_w9; all three events were subduction underthrusting events and they occurred in Chile, Alaska, and Kamchatka. Most of the events with M_w8.5 in the 20th century are subduction earthquakes (e.g., Pacheco and Sykes 1992), but several other tectonic environments are represented as we consider events with M_w from 8 to 8.5. For example, the largest oceanic and continental strike-slip events fall in this range, as do some of the continental dip-slip earthquakes. In addition, intra-plate events within the subducting lithosphere can be as large as 8.5 (see review by Ruff 1996). While it is easy to determine that outer-rise and deep slab events are not plate boundary events, some of the intermediate-depth slab events with thrust focal mechanism are difficult to discriminate from plate boundary thrust events. Those subduction zones that have produced the greatest underthrusting earthquakes tend not to have great earthquakes in the subducting slab – the Kuriles arc is the notable exception to this rule. The background seismicity on the plate interface varies from very quiet (e.g., Alaska and Cascadia) to quite active at the magnitude 7 level (e.g., some parts of Chile and the Kuriles).

Plate boundary earthquakes occur within the seismogenic zone. In subduction zones, the seismogenic zone down-dip edge is at a depth of about 40 km, with global variability from 20 to 50 km. Given the shallow slab dip angle of 15° or so, the maximum down-dip width of the seismogenic zone is about 150 km – though it is usually smaller since the seismogenic up-dip edge does not extend all the way to the trench axis in most arcs. Underthrusting earthquakes with M_w of 8 rupture the full width of the seismogenic zone with an along-strike rupture length on the order of 100 km. Since all great subduction earthquakes have about the same static stress drop, earthquake size can grow only by increasing the along-strike fault length. The greatest events have fault lengths of hundreds of kilometers. In this sense, the total potential fault length provides the upper bound on earthquake size for a particular subduction zone. Since there are many sources of plate segmentation, the key to generating great earthquakes is a relatively smooth and homogeneous plate interface over hundreds of kilometers.

All the great underthrusting earthquakes pose significant tsunami hazards. Indeed, observations of the far-field tsunami from the 1700 Cascadia earthquake gave us valuable constraints on the origin time and size of this great event (Satake *et al.* 1996). There has been a recent focus and awareness that landslide-generated tsunamis present a localized yet terrible tsunami threat. These examples unfortunately complicate the evaluation of tsunami deposits and inferences for overall tsunami wave height. In the future, marine surveys can search for near-shore submarine landslides that might be sources of large localized tsunami waves.

Great earthquake recurrence displays great variability from the regular recurrence of similar-sized events to changes in segment rupture pattern and large variability in recurrence intervals. Even where average recurrence intervals can be determined, there can still be a factor of two variability for individual recurrence times. Irregular recurrence can be caused by many different mechanisms. Even the simplest models of plate boundary segment interaction can produce earthquake sequences with sufficient variability in size and recurrence times (see review in Ruff 1996). In this context, the easiest way to reduce variability in earthquake size and recurrence time is to have just one large coherent segment for the entire subduction zone. This segmentation style may be applicable to southern Chile, Alaska, and possibly Cascadia. If the Cascadia subduction zone is divided into smaller segments, then seismicity, geologic, geodetic, and modeling studies may illuminate the location of the asperities that define these segments (see other Penrose conference papers).

While the tectonic environment of Cascadia made it a candidate for great earthquake occurrence (Heaton and Kanamori 1984), it has been the careful work of paleo-seismologists and tsunami hunters that has "proven" that Cascadia should join the Chile, Alaska, and Kamchatka subduction zones as generators of magnitude 9 earthquakes (see other Penrose conference papers). In terms of geologic and geophysical characteristics, the Cascadia subduction zone is an extreme end-member within the global spectrum. Some of these aspects may be important as we enter the next phase of Cascadia studies that try to better forecast the recurrence interval for the *next* great Cascadia event.

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GEODETIC MONITORING OF CRUSTAL STRAIN ASSOCIATED WITH PLATE SUBDUCTION IN JAPAN

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Japan is located on a complex plate boundary region. Strain accumulation due to relative motion of tectonic plates is a principal source of disastrous earthquakes in and around Japan. Among these plate boundaries, subduction zones of the Pacific and the Philippine Sea plates are source of large megathrust earthquakes. Especially, the Nankai Trough, where the Philippine Sea plate is being subducted beneath the Japanese islands, has some similarities with the Cascadia subduction zone.

In order to mitigate seismic hazard, the Japanese government has been trying an earthquake prediction experiment in the Tokai area, at the northeastern end of the Nankai Trough. In this area, large earthquakes have not occurred for nearly 150 years since the 1854 Ansei earthquake (M8.4) while rest of the Nankai Trough ruptured in the 1944 Tonankai (M8.1) and the 1946 Nankaido (M8.3) earthquakes. Since the average earthquake repeat time along the Nankai Trough is about 120 years, a large earthquake is supposed to occur in the near future. Intensive monitoring of seismicity and crustal deformation has been continued for more than 20 years. Somehow the expected 'Tokai earthquake' has not occurred although there have been other damaging earthquakes in other regions such as Kobe.

Monitoring of crustal strain is an important part of earthquake studies. Since large earthquakes are nothing but an instantaneous release of elastic strain energy accumulated in the earth's crust, geodetic monitoring of interseismic strain accumulation is to investigate a preparation process of future earthquakes. In Japan, geodetic survey networks for triangulation and leveling were established in the late 19th century. These networks have been resurveyed from time to time, revealing coseismic as well as interseismic crustal deformation of the Japanese islands. Along the Nankai Trough, crustal deformations have been observed before, at the time of, and after the 1944 and the 1946 earthquakes (Thatcher 1984, Sagiya and Thatcher 1999). We now have knowledge of crustal deformation during last 100 years, that is, almost a complete recurrence cycle of great earthquakes at the Nankai Trough. Such a complete set of geodetic observation data is quite rare. The Nankai Trough provides such an important data for the study of subduction earthquakes.

Recently, in 1990's, a dense array of permanent GPS (Global Positioning System) stations have been established in Japan for precise monitoring of crustal deformation. About 1000 stations are continuously operated, realizing quasi-real time monitoring with millimeter accuracy. Preset-day deformation pattern of the Japanese islands have been revealed based on observation data for a few years (e.g., Sagiya *et al.* 2000). Large strain accumulation associated with the subduction of the Pacific and the Philippine Sea plates beneath the Japanese islands are identified, and such deformation data can be utilized to infer physical process of the plate boundary. Sagiya (1999) analyzed continuous GPS data to infer plate interaction in the Tokai area, and obtained laterally heterogeneous distribution of a subduction effect along the plate boundary. On the other hand, by continuous monitoring with GPS, we could observe significant postseismic deformation of the 1994 Sanriku earthquake (M7.5)(Heki *et al.* 1997). Such a postseismic process has important implications for an earthquake recurrence cycle.

Monitoring of crustal deformation with the GPS array will be continued in the 21st century, and we will learn more about deformations associated with subduction earthquakes from these data. Along with various observational and modeling efforts, we will be able to understand the nature of subduction zones more, which would lead us to reduce possible seismic hazard.

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COSEISMIC FAULT SLIP AND SEISMIC MOMENT OF THE 1700 CASCADIA EARTHQUAKE ESTIMATED FROM JAPANESE TSUNAMI OBSERVATIONS

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We estimate the fault parameters and seismic moment of the January 1700 earthquake in the Cascadia subduction zone, by comparing the computed tsunami heights with those observed in Japan. The moment magnitude M_w is estimated to be about 9, which is insensitive to the assumed rupture length along strike. The slip on the fault and amount of coseismic subsidence, on the other hand, depend on the assumed fault length, but are insensitive to the updip and downdip widths of the rupture zone. If the 1700 event ruptured the entire Cascadia megathrust (about 1000 km), then the average slip is estimated to be at most 15 m.

We first compute coseismic ocean bottom deformation using a 3-D elastic dislocation model that numerically integrates point source solutions over the curved subduction thrust fault (Flück *et al.* 1997). In this dislocation model, the downdip widths of the full rupture zone and a landward transition zone over which slip decreases linearly with depth were constrained mainly by thermal data (Hyndman and Wang 1995) and interseismic uplift observations. Using the calculated vertical seafloor displacements as initial conditions, we carry out numerical computation of tsunami propagation across the Pacific. Linear long-wave equations are numerically solved on actual bathymetry (given by 5' of the arc) for the northern Pacific Ocean. A very fine grid (12" of the arc) system is used for the Japanese coasts where we compare the computed and observed tsunami heights. Numerical tests indicate that the computed tsunami heights on the 12" grid system are about twice as large as those on a coarser (1') grid. Tsunami heights obtained using the coarser grid are thus under-estimated by a factor of two, but our results obtained using the fine grid can be directly compared with the observed run-up heights. For the observed tsunami heights, we have examined Japanese historical documents to estimate the run-up heights and applied corrections for sea-level changes due to crustal deformation in the past 300 years (Satake *et al.* 1996, Tsuji *et al.* 1998).

By comparing with the observations, we conclude that the average coseismic slip is at most 15 m for a 1000-km long rupture. The estimated slip is insensitive to the width of the landward transition zone, because the transition zone makes very little contribution to seafloor deformation. However, the width of the transition zone does affect the earthquake magnitude estimate. The seismic moment is $4 - 7 \times 10^{22}$ Nm (corresponding to $M_w = 9.0$-9.2), depending on the width of the transition zone. We also tested models with shorter rupture, such as including only the northern California segment (corresponding to the Gorda "plate") or having a fault extending only along the Oregon coast. To explain the tsunami run-up heights observed in Japan using these shorter faults, coseismic fault slips of more than 30 m are required, but the resultant seismic moments are similar to that of the longer fault. Therefore, $M_w \sim 9$ is a robust magnitude estimate for the 1700 earthquake.

For a 15-m slip along a 1000-km long fault, the coseismic subsidence along the Oregon and Washington coasts is calculated to be less than 2 m, which is similar to the paleoseismological estimates. Because the relative convergence rate at Cascadia subduction zone is about 4 cm/year, an average coseismic slip of 15 m for megathrust events would require an average recurrence interval of less than 400 years, if the plate convergence takes place only in the form of subduction earthquakes. The apparently longer recurrence intervals estimated from paleoseismological studies imply that a part of plate convergence may take place aseismically.

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EMERGENCE EVENTS DURING THE PAST 3000 YEARS ALONG THE SOUTHERN KURILE TRENCH AT AN ESTUARY IN NORTHEASTERN JAPAN

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Estuarine deposits from the past 3000 years near Akkeshi, Hokkaido (43°N, 145°E), record four sudden emergence events but little net change in relative sea level. The emergence events are shown by interbedding of peat and mud, and by diatom assemblages in these interbedded deposits. The events produced abrupt contacts where brackish-water mud is overlain by freshwater peat. These contacts have been dated--by radiocarbon methods and tephra correlation--to ca. 2000, 1200, 600, and 300 cal yr BP. Despite this evidence for repeated emergence, the net change in relative sea level is about 1.5 m of submergence in the past 3000 years. This net change, however, was inferred from deposits that may be subject to settlement from compaction.

The emergence events are probably related to subduction along the southern Kurile Trench. At this plate boundary, Cretaceous oceanic crust subducts beneath a continental plate at nearly 10 cm/yr. Along the nearby Hokkaido coast, tide gages operating since the 1940s have recorded chronic submergence close to 1 cm/yr. If this modern submergence is due to strain accumulation and if the ancient emergence events represent strain release, the relative sea-level fluctuations near Akkeshi may provide geologic records of great thrust earthquakes.

DOWN TO EARTH TSUNAMI HAZARD MITIGATION: PROGRESS TOWARD ELUCIDATING PREHISTORIC TSUNAMI DYNAMICS FROM THE GEOLOGIC RECORD AT OPEN COASTAL SITES ALONG THE CENTRAL CASCADIA MARGIN

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The Holocene stratigraphic records of freshwater settings located in beach plains have been investigated for evidence of prehistoric tsunami inundation. Vibra- and gouge-cores were extracted from bogs, marshes and lakes at Grayland and Long Beach, Washington and Rockaway and Neskowin, Oregon. The field sites were selected to test for expansive, barrier dune-ridge overtopping, and overland inundation of potential Cascadia tsunami.

At least one, and sometimes up to three target sand layers have been traced 1.0-1.5 km landward of the present shoreline at Grayland, Long Beach, and Neskowin. Current beach dune elevations at these sites range from 6 to 10 meters. For hazard mitigation purposes, the most useful results come from two field sites at Long Beach where paleoshorelines have been constrained by earthquake-induced retreat scarps and radiocarbon-dated beach ridges (Meyers *et al.* 1996). Based on the landward extent of inferred tsunami-deposited sand and terrestrial detritus layers, these data indicate a minimum inundation distance of 0.8 km and 1.3 km +/- .2 km for a sand layer with radiocarbon dates of 820 +/- 50 ^{14}C yr BP and 860 +/- 50 ^{14}C yr BP, respectively. Scanning selected cores for microfossils (marine diatoms) and geochemical tracers (bromine) has verified a marine source for these sand layers. Tsunamigenic sand layers that correspond to the well-studied AD 1700 great Cascadia earthquake are poorly represented in the strata at all of the study sites, and are notably lacking at Long Beach.

The results of these tsunami mapping efforts warrant further study to 1) verify the regional extent and source of the ~800 year old sand layers, which might correlate with an unrecognized Cascadia segment rupture (Clague and Bobrowsky 1994), 2) confront the discrepancy between the weak coastal tsunami records produced from the inferred large-magnitude AD 1700 rupture (Atwater and Hemphill-Haley 1997), and 3) validate the use of marine geochemical tracer techniques to measure the maximum inundation distances of low velocity paleo-tsunami flooding. The open-coastal paleotsunami records demonstrate actual inundation hazards to exposed communities in low-lying barrier settings. Future sediment transport investigations of these deposits will yield critical information on paleotsunami hydrodynamics including surge velocities, water column elevations, and maximum inundation distances.

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COSEISMIC VS. NON-SEISMIC RELATIVE LAND / SEA-LEVEL CHANGE INFERRED FROM STRATIGRAPHIC EVIDENCE

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Analysis of Holocene data from estuaries and coastal lowlands around the world reveals different relative land / sea-level changes, from now on referred to as relative sea-level change, owing primarily to the spatially variable consequences of processes that range from global to local in origin. For each site the change in relative sea level, ($\Delta\xi_{rsl}$) at time τ, and location φ can be expressed schematically as:

$$\Delta\xi_{rsl}(\tau,\varphi) = \Delta\xi_{eus}(\tau) + \Delta\xi_{iso}(\tau,\varphi) + \Delta\xi_{tect}(\tau,\varphi) + \Delta\xi_{local}(\tau,\varphi) \qquad (1)$$

where $\Delta\xi_{eus}(\tau)$ is the time-dependent eustatic function, $\Delta\xi_{iso}(\tau,\varphi)$ is the total isostatic effect of the glacial rebound process including both the ice (glacio isostatic) and water (hydro isostatic) load contributions, $\Delta\xi_{tect}(\tau,\varphi)$ is the total effect of tectonic or seismic processes, and $\Delta\xi_{local}(\tau,\varphi)$ is the total effect of local processes within the estuary. In order to use observations from the sedimentary record to reconstruct sea-level change the local factors can be expressed schematically:

$$\Delta\xi_{local}(\tau,\varphi) = \Delta\xi_{tide}(\tau,\varphi) + \Delta\xi_{sed}(\tau,\varphi) \qquad (2)$$

where $\Delta\xi_{tide}(\tau,\varphi)$ is the total effect of tidal regime changes and the elevation of the sediment with reference to tide levels at the time of deposition, and $\Delta\xi_{sed}(\tau,\varphi)$ is the total effect of sediment consolidation since the time of deposition.

Sediments from estuaries and coastal lowlands contain litho- and biostratigraphic evidence that potentially record these different factors. $\Delta\xi_{eus}(\tau)$ and $\Delta\xi_{iso}(\tau,\varphi)$ occur over timescales that produce 'gradual' changes, while $\Delta\xi_{tect}(\tau,\varphi) + \Delta\xi_{local}(\tau,\varphi)$ can produce both 'gradual' and 'rapid' changes. The working definition of 'gradual' follows the general law of stratigraphy that sediments that lie one above the other in the stratigraphic column *without an hiatus* must represent environments that can occur spatially adjacent. This horizontal – vertical association provides a further consideration, for $\Delta\xi_{local}(\tau,\varphi)$ factors may cause horizontal changes, such as marsh expansion over tidal flat sediments, without any vertical change in RSL.

Since the mid 1980's studies of sediments from estuaries and tidal marshes in Cascadia provides much of the evidence for late Holocene seismic activity. The sedimentary processes in these tidal-wetland environments are directly comparable to those in aseismic locations, especially the east coast of North America and Northwest Europe. Techniques and methodological approaches developed from numerous studies in these areas successfully provide a framework for identifying coseismic subsidence (Long and Shennan 1994). Identification of sea-level tendencies (where positive indicates an increase in marine influence, negative a decrease) from biostratigraphic evidence (especially plant macrofossils, pollen, diatoms or foraminifera) forms a critical stage in testing competing working hypotheses involving seismic and non-seismic factors. Nelson *et al.* (1996) proposed five kinds of criteria that must be evaluated when inferring regional coastal subsidence due to great plate boundary earthquakes : the suddenness and amount of submergence, the lateral extent of submerged tidal-wetland soils (commonly called peats), the coincidence of submergence with tsunami deposits, and the degree of synchroneity of submergence events at widely spaced sites.

Development, by a number of research groups, of numerical techniques provides a sounder foundation for identifying the suddenness and amount of submergence. Thus for Johns River, Washington, Shennan *et al.* (1996) identified 8 episodes of rapid tidal marsh submergence in the last 5000 yr, with one event of greater than 1.5 m submergence, 4 events 1±0.5 m submergence, and 3 events of 0.5m or less submergence. For Netarts Bay, Oregon, Shennan *et al.* (1998) identified 7 peat-mud couplets covering the last 3500 yr. Three record gradual sedimentation within an infilling body of water. The other four record rapid submergence, burial of tidal marshes and their replacement by low marsh environments. In three the submergence was small, 0-0.5m. The most recent, around AD 1700, was 0.4±0.3 m. At Johns River, submergence for the most recent event, almost certainly of the same age, was 1±0.5 m.

Analysis of the Netarts Bay data illustrates the current limitations on quantitative estimates of submergence using microfossils because of the absence of comprehensive datasets for contemporary microfossil assemblages. These are necessary in order to develop robust quantitative transfer function approaches.

Further analysis of the data from Washington and Oregon (Long and Shennan 1998) and Alaska (Shennan *et al.* 1999) identify glacio-isostatic effects and variations in the rate of relative sea-level change at different stages within the earthquake deformation cycle. We now favor the following four stage cycle of $\Delta\xi_{tect}(\tau,\varphi)$ for sites in similar positions to those of the Washington and Oregon coasts and the Cook Inlet relative to the plate boundary: post-seismic RSL fall, interseismic RSL fall, pre-seismic RSL rise, co-seismic rapid RSL rise. Pollen and diatom data from Alaska, Netarts Bay and Johns River, including sampling sediment layers at 1mm intervals, illustrate the case for pre-seismic RSL rise, and how it can be differentiated from local factors such as sediment mixing. Preliminary ^{137}Cs measurements from Alaska provide a timescale for one case. There remains much to investigate about the nature of pre-seismic RSL rise and whether it represents any kind of precursor of large earthquakes.

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QUANTITATIVE RECONSTRUCTIONS OF PAST ENVIRONMENTAL CHANGES USING FOSSIL DIATOM ASSEMBLAGES FROM COASTAL MARSH DEPOSITS IN THE PACIFIC NORTHWEST

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Paleoecological reconstructions based on fossil diatoms from coastal deposits provide a powerful basis for inferring significant but often subtle ecological changes associated with past shifts in relative sea level (RSL). Rapid ecological changes are commonly associated with abrupt RSL displacement caused by coseismic uplift and subsidence, as documented following the 1992 Cape Mendocino and 1964 Alaska earthquakes (Ovenshine *at al.* 1976, Carver *et al.* 1994). Diatoms are uniquely suited for RSL studies because they are common in coastal environments, preserve well in sediments, and are sensitive to changes in salinity, tidal inundation, and elevation.

I describe a method for reconstructing quantitatively past changes in salinity and elevation using modern and fossil diatom assemblages from coastal marshes. The method utilizes a two-step weighted averaging regression and calibration technique that uses diatom assemblages to generate transfer functions for inferring past changes in elevation and salinity (WACALIB version 3.3, Line and Birks 1990). In modern marshes around Puget Sound, Washington, distribution of diatom assemblages is primarily controlled by salinity, and secondarily by elevation, as shown by correspondence analysis (Sherrod 1999). A tidal inundation index calculated for the Puget Sound area shows that diatoms are also distributed along a tidal inundation gradient that is closely correlated to elevation.

Salinity and elevation reconstructions from several sites at Puget Sound show abrupt ecological changes attributed to past earthquakes on one or more faults. Fossil diatoms from a marsh near the Seattle fault record several abrupt changes in salinity and elevation during the past 7500 years. A large earthquake on that fault dated to AD 900-930 produced seven meters of uplift at Restoration Point and caused an abrupt shift from obligate marine diatom taxa to freshwater taxa (Bucknam *et al.* 1992, Atwater 1999). Two earlier changes are noted: one possibly caused by 1.5–3.5 m of subsidence between 1500-1900 years ago, and the other possibly caused by about 1.5 meters of uplift between 6400-7200 years ago. An equally plausible alternative explanation for environmental changes at Restoration Point prior to 1100 years ago is opening and closing of a coastal bar or spit.

Buried forest and high marsh soils indicate abrupt submergence about 1100 years ago at four localities in southern Puget Sound. Forest soils and *in-situ* Douglas-fir stumps are buried by salt marsh peat at Little Skookum Inlet and Red Salmon Creek. At localities along McAllister Creek and Nisqually River, laminated tideflat mud buries high marsh soils. High-precision radiocarbon ages show that submergence occurred between AD 800-970 and fossil diatoms indicate abrupt environmental changes at the time of submergence. At Little Skookum Inlet and Red Salmon Creek, salt marsh peat a few centimeters above a buried forest horizon contain diatoms indicative of low marsh and tideflat environments. At McAllister Creek and Nisqually River, laminated mud directly over high marsh peat contains low marsh and tideflat diatoms. Estimates of submergence based on weighted-averaging of diatom assemblages and paleoecological inferences show that the largest amount of submergence was at Little Skookum Inlet and Red Salmon Creek ($\geq$3.4 m and $\geq$1.2 m, respectively). Submergence was less at McAllister Creek and Nisqually River (~1 m). Several alternatives exist for inferring which fault caused the subsidence. A low angle fault continuous with the Seattle fault is among the possibilities because radiocarbon ages show that timing of the subsidence includes the AD 900-930 age range, the probable time for a large earthquake on the Seattle fault (Atwater 1999). Alternative explanations invoke other possible faults in southern Puget Sound located near previously identified high-amplitude geophysical anomalies (Gower *et al.* 1985). Submergence in southern Puget Sound also falls within the age range for a Cascadia subduction zone earthquake about 1100 years ago, causing speculation that faulting within North America possibly accompanied or closely coincided with this subduction zone earthquake (Atwater and Hemphill-Haley 1997).

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TSUNAMI DISASTERS AND MITIGATION

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TSUNAMI DISASTERS collected from documents in the past are as follows:

Human Lives [Drowned. Injured by debris etc. Diseases caused by swallowing alien substances during drifting]

Houses [Washed away. Destroyed. Flooded]

Coastal Structures [Toe erosion, displacement and overturning of sea walls, sea dikes, breakwaters and quay walls]

Traffic: *Railway* [Erosion of embankments. Displacement of rails and bridges. Rails buried by sands or by debris], *Highway* [Displacement and falling down of bridges. Overturning of bridge abutments or piers by erosion. Erosion of embankment. Closure of traffic by debris on roads], *Harbor* [Change in water depth. Closure of port area due to transported debris and cars. Collision of ships in harbors]

Lifelines: *Water Supply* [Destruction of hydrants by collision of debris], *Electricity* [Overturning and washed-away of electric poles. Submersion of power plants], *Telephone* [damage to telephone lines and poles. Cut-off of underground telephone line at the junction to the aerial lines. Submergence of telephone receivers]

Fishery [Damage to fishing boats. Destruction and loss of rafts, fishes and shells in aquaculture. Loss of fishing gears. Closure of harbor entrance by fishing gears]

Commerce and Industry [Depreciation of goods by submergence]

Agriculture [Physiological damage to crops due to submergence. Farms buried by sands. Closure of irrigation channels by sands and debris]

Forest [Physical damage (breaking and overturning of trees, soil erosion). Physiological damage by sea water and sands]

Oil Spill [Environmental pollution. Spread of fires]

Fire (Causes) [Kitchen fire. Heating. Engine room of fishing boats. Submerged batteries of fishing boats. Collision to gasoline tank. Electricity leakage]

PHENOMENA OF NEAR-FIELD TSUNAMIS AND THE DEGREE OF DAMAGE (Shuto 1993, 1997) are roughly expressed in terms of tsunami height H (=crest height above MSL in the sea or crest height above ground on land). A near-field tsunami may have a dominant wave period shorter than 10 minutes.

At H=1 m, in case of a steep bottom slope, a tsunami is like a tide without breaking. In case of a gentle bottom slope, it swells rapidly near the shoreline although it is not recognized in the offing. Some of wooden houses are partially damaged.

At H=2m, in case of a steep bottom slope, a tsunami is like a tide which sometimes has breaking short waves on its front. In case of a very gentle bottom slope, it can be recognized like a wall in the offing. Sometimes the crest of the wall-like tsunami shows the spilling breaker. The second, third and later waves can easily show the plunging breaker when they meet the receding current of the preceding waves.

Most of wooden houses are demolished. Stone, brick and concrete block houses can withstand. Damage to fishing boats and loss of lives begin. Tsunami control forests can stop floating materials. If under-growth is thick, tsunami energy is reduced.

At H=2.5m, a tsunami, becomes to have the spilling breaker at its front in the long, shallow sea, and generates continuous noise like a sea roar, a storm, a locomotive or large trucks.

At H=4m, tsunami profiles are similar to the case of H=2m, with the increasing percentage of appearance of the breaking front.

Some of stone houses are demolished. Reinforced concrete buildings can withstand. Half the fishing boats are damaged. Tsunami control forests are damaged, but some of them are still effective to stop floating materials.

At H=5m, when a tsunami front hits the coastal cliff, it generates a loud sound that can be heard at distant places, expressed as a distant thunder or an explosion.

At H=8m, no tsunami shows tide-like rise of water level. The first wave becomes plunging breaker.

Stone houses are demolished. Reinforced concrete buildings may withstand although no examples that experienced such deep inundation are available in the past. All the fishing boats are damaged. Most of tsunami control forests are ineffective.

TSUNAMI DEFENSE WORKS consists of three parts; defense structures, city planning and defense systems. Their major items are as follows:

Defense Structures [Sea walls. Tsunami breakwaters. Tsunami gates. Tsunami control forest] Coastal embankments without solid covers such as stone and concrete are easily scoured by overflow deeper than 20 cm. Tsunami breakwaters at the entrance of a bay limit the discharge into the bay, thus effectively reducing the tsunami height inside. Tsunami gates are constructed at the river mouth, in place of heightening river embankments for a long length.

City Planning [Relocation of residence. Tsunami resistant building zone] Residences, town halls, hospitals, fire stations, police stations, schools, kinder gardens and others should be located at the high ground outside the tsunami risk area. Reinforced concrete buildings are resistant to impact forces of tsunamis and floating materials, even though their windows and doors are often broken. Rows of reinforced concrete buildings along the shore will stop floating materials and thus protect weak wooden houses behind.

Defense Systems [Forecasting. Evacuation. Drills. Continuation of disaster culture. Rescue operation] The best and last method to save human lives is an early evacuation according to forecasting and warning. Shaking caused by an earthquake is a natural tsunami warning with 10% exception, i.e. tsunami earthquake. In 90's, 11 major tsunamis occurred in the Pacific. Three of them were tsunami earthquakes. Public education is indispensable to make forgettable human beings to continue the precious former experiences and to prepare for the next tsunami.

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SHORELINE STRATIGRAPHY OF LAKE WASHINGTON; IMPLICATIONS FOR HOLOCENE CRUSTAL STRAIN AND EARTHQUAKE RECURRENCE IN THE CASCADIA FOREARC

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The frequency of great earthquakes on the outer coast of the Cascadia subduction zone has been established using turbidites and marsh stratigraphy (Atwater and Hemphill-Haley 1997). Theoretically, the same techniques can be applied to the benthic sediments and shorelines of Lake Washington, which extends 26 km across all strands of the Seattle Fault and the Seattle Basin within the continental forearc crust of the Puget Lowland. Karlin and Abella (1996; and more recent abstracts) have carefully documented and dated as many as 42 distinct "silt bands" within the benthic stratigraphy; they interpret them as seismic turbidites suggesting an earthquake recurrence interval of 300-500 years. There is no question that one of the prominent late Holocene "seismites" in Lake Washington was associated with the 1100 yr BP crustal earthquake associated with abrupt vertical motions along the Seattle Fault, tsunami deposits, rockfall avalanches, and subaqueous landslides. This association, however, appears to be an indirect one, at least in the vicinity of Juanita Bay, where the benthic silt band represents the basin-ward advection of silt during a brief, but intense, phase of shoreline erosion. This erosion, which produced a new spit at Nelson Point, was initiated by an abrupt, 1-2 meter rise in lake level caused by some combination of coseismic submergence within Seattle Basin and coseismic uplift of its southern outlet. Mechanistically, this basin-side silt band suggests the primary linkage...displacement → submergence→erosion→advection→benthic sedimentation ...rather than the linkage...displacement→strong ground motion→landslides→turbidites→ benthic sedimentation.

Prior episodes of submergence are indicated by repeated reversals from woody to gyttja-rich peat horizons in freshwater marshes removed from landslide sites. For example, in Mercer Slough, there are 21 abrupt transitions within the interval 6100 ± 160 to 1030 ± 100 ^{14}C yr BP, with an average submergence depth of 0.52 meters, yielding a recurrence interval of 270 years, comparable to the recurrence interval for benthic silt bands of Core TT147-1. At Yarrow Bay, there are nine such submergences prior to a prominent concentration of silicate mud dated to the 1100-year submergence event. The submergence history, although driven primarily by the sea level rise and progradation of the Duwamish delta between 9 and 3 ka, was punctuated by avulsion events (Smith *et al.* 1989) at the lake outlet, which complicate paleoseismic interpretations. Some silt bands are coseismic; some may even be turbidites. However, a non-seismic origin for silt bands prior to 3 ka is consistent with the lack of evidence for movement on the Toe-Jam strand of the Seattle Fault (Nelson *et al.* 2000) during the early to mid-Holocene time, as well as with the evidence for limited (< 3 m) tectonic warping of the Lake Washington shoreline since deposition of the Mazama tephra ca. 6.9 ka.

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NHEMATIS: PROGRESS ON A CANADIAN NATURAL HAZARD RISK ASSESSMENT MODEL

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Emergency Preparedness Canada, in cooperation with public and private sector partners, has been conducting extensive research on risk assessment and vulnerability to natural hazards in Canada. Its major research effort is the National Hazards Electronic Map and Assessment Tools Information System (NHEMATIS), comprising an electronic natural hazards map of Canada and a series of risk assessment/search and query tools. By combining the power of expert system technology with the spatial analysis capabilities of a geographic information system (GIS), NHEMATIS provides a repository of information on historical and potential future hazards, an inventory of information on facilities and people at risk to natural hazards, and tools and algorithms for estimating the damage that could be caused by various natural hazard events.

NHEMATIS currently contains national geographic databases as well as data for five local study areas for demonstration purposes. Hazard impact assessment modelling capabilities in NHEMATIS are currently available for earthquakes, floods, tornadoes, and landslides.

New directions have been identified to enhance the functionality, profile and implementation of NHEMATIS. The suitability of NHEMATIS as an educational tool is being evaluated by designing and delivering two laboratory assignments in an upper-year undergraduate geography course. Student user feedback will lead towards the development of a NHEMATIS "quasi curriculum" for educational purposes. A World Wide Web application to deliver key components of NHEMATIS functionality is being developed to advance public awareness of risk and vulnerability concepts.

Finally, in order to strengthen the core of NHEMATIS, the different equations available and commonly used for earthquake attenuation are being reexamined. Historical maps of estimated MMI (Modified Mercalli Index) will be obtained for a range of events in eastern and western Canada and used to evaluate which equations are best suited for use within NHEMATIS. Improved sets of equations and parameters will be built into the NHEMATIS software.

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UNCERTAINTIES RELATED TO ESTIMATING THE TIMING, SOURCE AREAS, AND MAGNITUDES OF PALEOEARTHQUAKES FROM LIQUEFACTION FEATURES

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Earthquake-induced liquefaction features are proving useful in paleoseismology, especially in regions where active faults can not be studied directly (e.g., Munson *et al.* 1997, Tuttle *et al.* 1998, 2000, Talwani *et al.* 1999). Greater care needs to be taken, however, to fully state uncertainties related to current methodologies. Age estimates of liquefaction features are used to determine the timing of paleoearthquakes and to develop regional earthquake chronologies. Inferences about source areas and magnitudes of paleoearthquakes are drawn from areal and size distributions of similar-age liquefaction features. Only with a good understanding of timing, source areas, and magnitudes of paleoearthquakes can accurate estimates of repeat times of large earthquakes be made.

Differentiation of earthquake-induced liquefaction features from other soft-sediment deformation structures must be addressed in any paleoliquefaction study. Dewatering due to rapid sedimentation and compaction is one of the more common causes of syn-depositional non-seismic liquefaction features. Also, artesian pressure, piping, rapid post-flooding pore-water release, mass movements, and diversion of runoff can lead to the formation of post-depositional structures that resemble earthquake-induced liquefaction features. Earthquake-related deformation structures are most clearly differentiated from non-seismic structures through a combination of field evidence (e.g., distribution pattern, conduit morphology, sedimentary and stratigraphic characteristics of deposits, and material source) and laboratory x-ray radiography that often reveals the internal flow of liquefied sediment (e.g., Sims 1973, 1975, 1978a, b; Li *et al.* 1996; Obermeier 1996). Prehistoric sand blows and related sand dikes are considered by most researchers to be primary evidence of strong ground shaking and to provide the best opportunities for dating paleoearthquakes. However, the current methodology of bracketing the age of liquefaction features by dating material in bounding horizons adds uncertainties to age estimates. In order to employ liquefaction features to their full advantage, the most datable features should be identified and studied in detail and their ages constrained as narrowly as possible. Narrow age estimates, preferably 200 years or less, are necessary to correlate features with confidence across a region and to establish the area affected by a particular earthquake or earthquake sequence. Factors that influence distribution of liquefaction features include site conditions and earthquake characteristics. Given that these factors are unknown for prehistoric events, there are large uncertainties in deducing source areas of paleoearthquakes from the distribution of liquefaction features even under the best of circumstances. Magnitude estimates of paleoearthquakes are commonly based on distances of liquefaction features to inferred epicenters. Therefore, uncertainties related to the ages of liquefaction features and the source areas of their causative earthquakes need to be quantified and reflected in magnitude estimates of paleoearthquakes.

In the Pacific Northwest, paleoliquefaction features have been used to define the area and magnitude of strong ground shaking during the circa AD 1700 earthquake and to identify other areas affected by late Holocene earthquakes (e.g., Atwater *et al.* 1995, Dickenson and Obermeier 1998). Much can still be learned about Cascadia paleoearthquakes by broadening the search for liquefaction features, studying in detail the most promising sites for dating liquefaction features, and by comparing liquefaction generated by Cascadia events with that induced by modern earthquakes in geologic and tectonic settings similar to the Pacific Northwest. For example, the 1964 Alaska (M~9), 1942 Hispaniola (M~8), and 1992 Cape Mendocino (M 7.1) earthquakes may serve as useful calibration events.

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TSUNAMI HAZARD MAP OF THE SOUTHERN WASHINGTON COAST: MODELED TSUNAMI INUNDATION FROM A CASCADIA SUBDUCTION ZONE EARTHQUAKE

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Recent research confirming the potential for a great earthquake off the Washington, Oregon, and northern California coastlines has led to concerns about the effect of a local tsunami generated there. Since locally generated tsunami waves would reach nearby communities within minutes of the earthquake, there would be little or no time to issue formal warnings and evacuation areas and routes will need to be planned well in advance. This map was prepared as part of the National Tsunami Hazard Mitigation Program (NTHMP) to aid local government in designing evacuation plans for areas at risk from potentially damaging tsunamis. The map shows three sets of data pertaining to tsunamis: 1) model data; 2) paleoseismic data; and 3) historic data from the 1964 Alaskan tsunami.

1) The landward limit of tsunami inundation shown on this map is based on a computer model of waves generated by two different scenario earthquakes on the Cascadia subduction zone. Baptista and Myers modified the finite element model ADCIRC for modeling earthquake deformation and resulting tsunami. The model calculates a wave elevation and velocity for each point of the grid at specified time intervals for a period of eight hours from the time of the earthquake. The scenario modeled is a magnitude (M_w) 9.1 Cascadia subduction zone (CSZ) event, with a rupture length of 1050 km. and a rupture width of 70 km. An asperity west of the Olympic Peninsula is used in the second model to generate locally higher uplift and simulate a worst case tsunami. The land surface along the coast is modeled to subside during ground shaking by about 5 feet, which is consistent with some paleoseismologic investigations (see Priest *et al.* 1997, for a complete discussion). The model is smoothed to account for resolution limitations and, in some instances, to place the inundation limit at nearby logical topographic boundaries. The model does not include the influence of tides but use a tide height of four feet. The tide stage and tidal currents can affect the impact of a tsunami on a specific community. The arrival time and duration of flooding are key factors to be considered for evacuation strategies. We show time histories of the modeled waves at twelve localities immediately offshore from key communities. These time histories show the change in water surface elevation with time for eight hours of modeling. Negative elevations are wave troughs, i.e., times when water is flowing out to sea. Positive elevations represent wave crests. Note that for locations on the outer coast the first wave crest is generally predicted to arrive at between 30 and 60 minutes after the earthquake, whereas within Willapa Bay and Grays Harbor, the first crest is not expected to arrive for more than an hour. However, because a CSZ earthquake is expected to lower the ground surface along the coast, flooding of areas less than about 5feet above tide stages is expected immediately.

2) Geologic evidence of the last (AD 1700) earthquake and tsunami are also shown on the map. Mary Ann Reinhart (written communication, 1999) has identified marsh surfaces that she infers to have subsided coseismically during the AD 1700 event. We show where these marsh

deposits are overlain by an inferred tsunami sand and also where an inferred tsunami sand does not cap a subsided marsh surface. Peterson and Schlichting (1998) cored peat deposits from freshwater lakes on the Grayland Plains and the Long Beach Peninsula. We show where they found evidence of tsunami inundation in AD 1700. The data are preliminary as of this writing, but they infer an older tsunami (not shown on map) that was more extensive. Also on the map are three archaeological localities that show evidence of abandonment attributed to the AD 1700 earthquake (Atwater and Hemphill-Haley 1997). We show both where there is an inferred tsunami sand and where sand is lacking. The paleoseismic data are shown because they illustrate the minimum extent of the AD 1700 tsunami. However, they do not show the maximum extent but only lack of deposition or preservation of sand.

3) The tsunami following the March 27, 1964, Alaskan earthquake was the largest and best recorded historic tsunami on the southern Washington coast. Newspaper reports and unpublished observations and photos by Hogan *et al.* (1964) are shown.

Sources of model error are discussed in detail in Priest *et al.* (1997). Because the tsunami depends on the initial deformation of the earthquake, which is poorly understood, the largest source of uncertainty is the input earthquake. The scenarios used reasonably honor the paleoseismic constraints, but the next CSZ earthquake may be substantially different from these. Also, the model was run with modern topography and bathymetry reflecting engineering structures (dams and jetties) that influenced erosion and deposition; road building and excavation of the dunes protecting the coastline; and the introduction of European beach grass that traps sand and enlarges the dunes. The bathymetry and topography at AD 1700 can only be inferred; the difference between that tsunami and the ones modeled here are unknown. Thus while the modeling can be useful for evacuation planning, it is not of sufficient resolution for land use planning.

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MITIGATION AND SESSION OVERVIEW

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The focus of this session is on mitigation of earthquake and tsunami hazards and has been designed to build on Mr. Ivan Wong's preceding hazards session.

Mitigation is risk reduction, which can involve addressing the hazard, the exposure, the vulnerability, or any combination of these. Mitigation methods include both "soft" (such as public awareness) and "hard" (such as engineered retrofits) solutions. Without mitigation, however, even the most impressive studies with the most significant findings are lacking. Unless action is taken, actions ranging from increasing public awareness to improvements in design, codes, structural hardening, emergency plans, legislation, and so on, these important findings do not increase public safety and the benefit is minimal.

Are we prepared for a great Cascadia earthquake? What would happen if the big one hit right now? How would we, a most informed group of Cascadia earthquake experts, fair? How many of us would die? How would the rest of the Pacific Northwest fair? The answers to these questions indicate that much more mitigation is needed.

Remarkable information and improvements have been made since the mid-1980s. Still, this region is not yet prepared. When the big one hits, there will be casualties from damaged buildings and coastal tsunamis, emergency response will be limited, communities will be isolated from downed bridges and roads, water lines will break- causing fires to rampage and water shortages, waste water lines will break- contaminating the environment and tempting diseases, electricity, natural gas, and communication systems will have severe outages. Individual and family readiness for over 72 hours is recommended.

The Cascadia fault combined with inherited old infrastructure is the reason for the high risk in this region. One thing that is clear is that emergency response is not enough. Proactive steps include conducting studies to better understand the problems, for example, ranging from determining the ground shaking characteristics, to strengthening vulnerabilities of the vital lifelines. Moneys are required to harden these systems, which requires the transfer of knowledge and commanding the public to make these demands. More progressive programs, like the Federal program to identify all seismically vulnerable federal buildings, are needed.

Two Oregon examples are provided: the first by the Oregon Department of Geology and Mineral Industries (DOGAMI) and the second by the State Earthquake Commission. DOGAMI is working with the other state agencies to establish a similar program on the state level. The Oregon State Government is trying to develop plans to evaluate the earthquake risk for selected state-owned buildings, provide a ranking system for future prioritized mitigation, and develop long term funding for implementation. This program would include hundreds of buildings valued over $1 million each, including hospitals, large office buildings, corrective facilities and state colleges. DOGAMI would help develop regional and local information on the site soil response, liquefaction and co-seismic landslide susceptibilities, building damage, losses associated with damaged buildings, loss of lives, and loss of operations to state functions. In addition, cost-effective strategies to improve life safety and benefit-cost evaluations will be developed for high-risk structures with high rankings. This risk information will help prepare the government and state's population through increased earthquake awareness, future risk reduction action (e.g., strengthening facilities) often linked to routine maintenance actions, improved policies, effective emergency response plans, accurate levels of state insurance coverage and serve as a example to communities to promote local mitigation. DOGAMI plans to help implement this study and substantially lower risk over the next 10 plus years, with luck before the big one strikes.

The second example involves improving the seismic safety of fire stations, hospitals, and schools. The State Earthquake Commission has proposed legislation to do so. Mr. Bill Elliott, our last speaker this afternoon and Past Chair of the Earthquake Commission, will discuss public policies and describe this legislation.

The remainder of the session focuses on what it takes to be prepared for the big one and what kinds of research and efforts could be conducted. The speakers are:

Mike Hagerty, Chief Structural Engineer at City of Portland, Building Codes
Chris Thompson, Degenkolb, Principal, Seismic Design
Linda Noson, AGRA, Senior Research Scientist, Transportation and Utilities
Nobuo Shuto, Faculty of Policy Studies, Iwate Prefectural University, Tsunami Mitigation
Jim Ament, State Farm Insurance, VP Operations, Financial Perspective
Bill Elliott, Elliott Consultants LCC, Manager, Public Policy

Each speaker was asked to address four points relating to their topic, including their own expert opinion as well as the perspectives of others in their field. These points are:

1) What are the main issues?
2) What is the state of practice?
3) What improvements are needed?
4) How can we achieve these improvements?

The six invited speakers will address mitigation involving building codes, seismic design, transportation, utilities, tsunami mitigation, financial perspective, and public policy. These presentations will be followed by a group discussion.

PREDICTED CASCADIA LOSSES

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Recent worldwide earthquakes have resulted in staggering losses. The Northridge, California. Kobe, Japan, Loma Prieta, California, Izmit, Turkey, and Chi-Chi, Taiwan earthquakes, which range from magnitudes 6.7 to 7.7, have all occurred near populated areas. These earthquakes have resulted in estimated losses between $3 and $300 billion with tens to tens of thousands of fatalities (Eguchi *et al.* 1998; U.S. Geological Survey website, miscellaneous references). The Federal Emergency Management Agency (FEMA) estimates national earthquake losses to be $4.3 billion per year (Nishenko and Drury 1999).

Subduction zones are capable of producing the largest earthquakes. The 1939 M7.8 Chilean, the 1960 M9.5 Chilean, the 1964 M9.2 Alaskan, the 1970 M7.8 Peruvian, and the 1985 M7.9 Mexico City earthquakes are examples of damaging subduction zone quakes located near populated areas (U.S. Geological Survey website). The Cascadia fault zone poses a tremendous hazard in the Pacific Northwest because of the ground shaking and tsunami inundation hazards coupled with the population exposure. Not surprisingly, highest (probabilistic) losses for the nation are forecast to be in California, Washington, and Oregon, respectively. Highest (probabilistic) losses with respect to building value (loss ratios), are forecast to be in California, Alaska, Oregon, and Washington (Nishenko and Drury 1999).

To address the potential impact of Cascadia, the Oregon Department of Geology and Mineral Industries (DOGAMI) conducted a preliminary statewide damage and loss study in 1998. The Oregon study incorporated the influence of near surface soil effects and default building, social and economic data available in FEMA's HAZUS97 software. HAZUS is rapidly becoming the state-of-practice standardized damage and loss assessment tool. Direct financial and social losses due to damaged buildings were estimated for a magnitude-8.5 Cascadia subduction zone earthquake located off the coast of Oregon.

Direct financial losses are projected at $12 billion or higher (Wang and Clark 1999). Casualties are estimated at about 13,000. Over 5000 of the casualties are assumed to result in fatalities from hazards relating to tsunamis and unreinforced masonry buildings (Wang 1999). Losses to Washington, Northern California and British Columbia have not been estimated but are assumed to be significant. The Cascadia Region Earthquake Workgroup is currently estimating losses from a magnitude-9.1 Cascadia quake.

The estimated socioeconomic losses determined in this damage and loss study provide important information that the public can easily relate to, namely, dollars and casualties. These results received widespread attention from the media and elected officials. Result from damage and loss studies have allowed for a communication bridge between geoscientists and the public policy and decision makers and are a remarkably powerful tool to promote risk-based mitigation decisions. Sound geologic input data are important to better the accuracy of these studies. In turn, with more accurate loss estimates, reasonable public policies to minimize disasters and increased financial and personal safety can be developed and implemented.

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PALEOLIQUEFACTION TO HELP CHARACTERIZE SHAKING FROM THE 1700 CASCADIA EARTHQUAKE

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The geographic extent of liquefaction features has been used to estimate the magnitude of prehistoric earthquakes. In addition, the analysis of paleoliquefaction features has been used to estimate the strength of shaking resulting from prehistoric earthquakes (Obermeier and Pond 1999). Limited studies in the Pacific Northwest indicate that the size and abundance of liquefaction features is not as great as those resulting from other large historic earthquakes (Obermeier 1989). In addition, the studies indicate that peak ground accelerations (PGA) resulting from the 1700 Cascadia event were relatively low, 0.1 to ~0.3 g (Obermeier 1995, Obermeier and Dickenson 1997). These later findings were based on features observed on islands in the lower reaches of the Columbia River and the reconnaissance studies conducted in Western Oregon and Washington.

A 1995 study (Walsh *et al.* 1995) of liquefaction features resulting from the 1964 Alaska earthquake found that while liquefaction was widely reported throughout the meizoseismal area, liquefaction features were preserved only in limited areas, i.e. those areas with coseismic subsidence. In areas of coseismic uplift, no evidence of liquefaction remains, even though liquefaction-induced lateral spreading and sand extrusion were reported as common immediately after the event. In the Pacific Northwest, particularly in Oregon, streams tend to be relatively high energy until near the coast and therefore are not well suited to the preservation of liquefaction features. In near coastal areas that are suited for the preservation of features, the tidal range is much lower than in Cook Inlet, Alaska, so it is difficult to observe liquefaction features stratigraphically beneath the 1700 surface. The features observed on islands in the Columbia River are relatively widespread but not particularly abundant. This may be the result of the ephemeral nature of these islands in a very large, energetic river system. For these reasons, it is difficult to study paleoliquefaction in the Pacific Northwest.

Estimates of bedrock acceleration resulting from the geotechnical back-calculations of the paleoliquefaction features for the 1700 Cascadia earthquake can serve as guidelines for shaking but may be compromised due to the depositional environments. The calculations are also dependent on the location of the earthquake source zone, stress drop and attenuation during the event. In order to utilize paleoliquefaction features to constrain the magnitude and levels of ground shaking associated with the 1700 Cascadia event, further studies are required in the Pacific Northwest. Potentially promising areas in Oregon for the paleoliquefaction features from Cascadia earthquakes are along the coasts, particularly along central and southern Oregon coast, where the 1700 surface is exposed.

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EARTHQUAKE RISK ASSESSMENT IN TILLAMOOK COUNTY, OREGON

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Cascadia subduction poses a great earthquake hazard to the coastal communities in the Pacific Northwest. It has been 300 years since the last great Cascadia earthquake in 1700 (Atwater 1987, Yamaguchi *et al.* 1997). It is not a question of whether the next great earthquake will occur but when it will occur. It is beyond human capability at present to predict when such great event will occur. However, the potential hazards and risks posed by the future great subduction earthquake can be assessed.

Tillamook County is located on the northwestern coast of Oregon. Due to its location and the local geologic conditions, the county faces high potential seismic hazards and risks posed by the Cascadia subduction zone. Tillamook County has been chosen by the Federal Emergency Management Agency (FEMA) as the first county in Oregon for Project Impact, to mitigate natural hazards. As a part of Project Impact, the seismic hazards in Tillamook County posed by the future Cascadia earthquakes were first evaluated. The building inventory in the county was also investigated. Then, seismic risk in Tillamook County was assessed using HAZUS99, a seismic risk assessment software (FEMA 1999).

The three seismic hazards, ground motion amplification, liquefaction, and earthquake-induced landslides, all dependent on the local geologic conditions were evaluated from surface geologic maps (Beaulieu 1973, Wells *et al.* 1994), water well data, seismic investigations, geotechnical data, and digital elevation models (DEMs). The areas with high ground motion amplification hazard as well as the areas with high liquefaction potential are concentrated in the bays (Nehalem, Tillamook, Netarts, and Nestucca) and along the coast where the young and soft estuary, fluvial, and dune deposits are thick and abundant. The areas with high earthquake-induced landslide potential are widely spread in the county, due to weak soils and rocks and high relief of landforms.

About 21,600 people (1990 Census data) live in Tillamook County. A county total of 18,300 buildings was estimated with a total replacement value of about $1.7 billion. The database includes 2 hospitals, 31 schools, 11 police stations, and 10 fire stations. It also includes 65 bridges and 19 major highway segments. All these inventory data and the seismic hazards were used to model the damages and losses from subduction-type scenario earthquakes. Two scenarios, the hazard from a M 8.5 subduction event 20 km offshore and the probabilistic ground-shaking hazard with a 2500-year recurrence interval (Frankel *et al.* 1996) were simulated.

The M 8.5 scenario earthquake would cause at least slight damage to about 13,000 buildings, with losses of about $200 million and 100 persons injured or dead. All hospitals, schools, and police and fire stations would be affected with at least moderate damage. 31 bridges would be damaged, 14 of them would be completely destroyed. The 2500-year probabilistic hazard scenario would cause at least slight damage to all the buildings, with losses of about $800 million and 400 persons injured or dead. All hospitals, schools, and police and fire stations would be affected with at least moderate damage. 40 bridges would be damaged, 18 of them would be completely destroyed.

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TECTONICS OF THE CASCADIA SUBDUCTION ZONE, NORTHWEST U. S. AND ADJACENT CANADA

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In the Cascadia forearc, contemporary deformation appears to result from a combination of tectonic processes that includes forearc migration and terrane accretion in addition to subduction. Defining the relative contribution to the deformation field of each of these processes may help us to better understand the distribution of earthquake hazard along the margin.

Neogene deformation and clockwise paleomagnetic rotations indicate that the Cascadia fore arc is migrating northward along the coast and breaking up into large rotating blocks. Deformation occurs mostly around the margins of a large, relatively aseismic Oregon coastal block composed of thick, accreted seamount crust. This 400 km-long block is moving clockwise with respect to North America about a rotation pole in the backarc near the Columbia River, and thus it rotates over the trench at Cape Blanco and creates an extensional volcanic arc on its trailing edge. Northward movement of the block breaks western Washington into smaller, seismically active blocks and compresses them against the Canadian Coast Mountains restraining bend. Arc-parallel transport of fore-arc blocks is calculated to be up to 8 mm/yr. The predicted long-term block motions compare favorably with GPS velocities observed in the Oregon forearc when elastic deformation due to subduction is taken into account (Kahzaradze *et al.* 1999, McCaffrey *et al.* 2000, Savage *et al.* 2000), and together they indicate that damaging upper plate earthquakes are likely in a broad deformation zone along block margins. The GPS velocity field in the forearc may largely be explained as the sum of two existing deformation models for Cascadia, each based on geologic and geophysical data independent of GPS: 1) an elastic deformation model of the locked Cascadia subduction zone constrained by heat flow, seismic profiling, and vertical deformation (Hyndman and Wang 1995, Flück *et al.* 1997); and 2) paleomagnetically and geologically constrained long term clockwise rotation of an Oregon forearc microplate about a nearby pole in the backarc, in response to oblique subduction, Basin-Range extension, and Pacific-North America dextral shear (Wells *et al.* 1998).

In addition to forming the core of the rotating forearc block, the thick mafic forearc crust of Siletzia may exert control on the distribution of contemporary vertical deformation in the forearc and the inferred zone of coupling with the subducting oceanic plate (Wells *et al.* 1998). The mafic core of the rotating block has the lowest uplift rate along the coast (Mitchell *et al.* 1994, Hyndman and Wang 1995), and the inferred narrow locked zone is entirely offshore, apparently following the western limit of Siletzia. Outboard of Siletzia, sediments of the Eocene to Quaternary accretionary wedge and marginal basin complex correlate with the geodetically and thermally defined locked zone. The accretionary-marginal basin complex appears on gravity maps to be organized into a series of five large sub-basins (A-E), with the largest off Washington and northern Oregon (at least 250 km long) and decreasing in size southward. They look very much like the string of offshore basins along the Nankai forearc (A-E; e.g., Sugiyama 1994), where the basins have been correlated with historic seismic segmentation of the subduction zone. The basins are inferred to be related to the seismogenic rupture process and appear to correlate with slip distribution along the subduction zone during the 1944 and 1946 events (Sagiya and Thatcher 1999). We suggest that the Cascadia subduction zone may be likewise segmented into very large sausage-shaped rupture patches, decreasing in size to the south, that correlate with offshore basins outlined by gravity lows. McNeill *et al.* (1998) have described a variety of oblique, upper plate folds and faults that may in part be related to such large-scale seismic segmentation of the subduction zone. Although segmentation does not preclude great earthquakes, it does suggest that the subduction zone earthquake history south of Cape Blanco (and possibly Yachats) should be different as one goes back in time.

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NEPTUNE: A FIBER-OPTIC SEAFLOOR OBSERVATORY ON THE JUAN DE FUCA PLATE

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The NEPTUNE project (http://www.neptune.washington.edu) is an ambitious plan to deploy a submarine fiber-optic network on the Juan de Fuca Plate off the coast of the Pacific Northwest (Delaney and Chave 2000, Delaney *et al.* 2000, NEPTUNE Phase 1 Partners 2000). The network will host scientific instrumentation to study a wide variety of geological, oceanographic, and ecological processes. A conceptual design and feasibility study (NEPTUNE Phase 1 Partners, 2000) demonstrates that there are no insurmountable technical obstacles. It is envisioned that the backbone would comprise 3000 km of cable connecting about 30 evenly distributed primary nodes. Secondary branch cables could extend to any location on the plate. At each node a junction box would provide standard power and communication interfaces for scientific instruments. The complete network could carry 10 GB/s of data and deliver up to 100 kW of power and would have an operational life span of at least 25 years. The network design includes a branch that runs near the base of the continental shelf, extending the length of the subduction zone from the Mendocino transform fault to the Explorer plate.

As part of the feasibility study a number of ad-hoc working groups met to explore the research possibilities that will be created by NEPTUNE's capabilities. A seismology and geodynamics working group met in Seattle in June 1999 and their report is available online (NEPTUNE Seismology and Geodynamics Working Group 2000). Long-term seafloor seismic and geodetic instrumentation along the Cascadia margin will contribute greatly to our understanding of subduction zone processes, improve assessments of seismic hazard, and may form part of an early warning system. Seafloor seismometers will detect and locate the small but tectonically important earthquakes currently missed by onshore networks, and will provide better constraints on the depths and focal mechanisms of larger events. Geodetic observations will provide critical information on the nature and extent of offshore deformation. When combined with data from land networks, these observations will lead to improved constraints on the great earthquake cycle and the width of the locked zone and its variations along the margin. NEPTUNE will also facilitate multidisciplinary experiments at the Nootka Fault and Mendocino Triple Junction to study the relationships between large earthquakes, fluid flow in the accretionary prism, and catastrophic sediment transport events.

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PACIFIC NORTHWEST EQ RISK: SENSITIVITY TO CASCADIA RUPTURE BEHAVIOR

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Damaging earthquakes may not be an everyday occurrence in the Pacific Northwest, but nonetheless represent a significant catastrophic risk. We present preliminary assessments of losses from Pacific Northwest earthquakes and explore the sensitivity of these losses to the rupture behavior of the Cascadia subduction zone.

The analysis was conducted on a portfolio of locations covering Washington, Oregon, and California north of 40°N, spaced on a 0.1° grid. Insured residential and commercial value for each grid cell was modeled from client data, Dun and Bradstreet square footage, U.S. census population, GDP, means construction costs, and other statistical factors. Site conditions for each cell represented an areal average, derived from geologic maps digitized and assigned NEHRP site classes on the basis of inferred shear wave velocity. Yumei Wang provided data for the state of Oregon (Wang and Weldon 1998).

The hazard model used for the analysis included four source types: crustal faults, crustal background, intraslab, and interface. Parameters for the first three were derived from a U.S. Geological Survey 1996 project (Frankel *et al.* 1996), except that a M7.25 maximum was assumed for deep Puget Sound events. Interface events are described separately. The attenuation of Boore *et al.* (1997) was assumed for crustal earthquakes, those of Youngs *et al.* (1997) for intraslab and Cascadia subduction zone events. Attenuation and rate uncertainty were not included in this analysis, only mean values. Ground motion was converted to loss on the basis of state-specific residential and commercial vulnerability curves defined for the inventory of predominant structure types.

The Cascadia interface was modeled using the results of Flück *et al.* (1999), with downdip rupture extending to the halfway point of the transition zone. A recurrence of 475 years for complete rupture of the interface was assumed, based on Darienzo *et al.* (1994). Reported intervals range from 150 to 1500 years; see discussion of rates and probabilities in McCann (1999). Three rupture scenarios were modeled: a complete rupture of the CSZ in a single M_w9.0 earthquake (#1), piecewise rupture in six M_w8.5s (#3) and an equally weighted combination of these two end members (#2). The number of events in scenario #3 is simply based on moment ratios between 9.0 and 8.5, and represents a conservative estimate than the more likely three to four events described in Geomatrix (1995).

Two principal risk metrics were examined, average annual loss (AAL) and loss exceedance probability curves. The AAL is an expected value of loss, usually normalized to ‰ ($ loss per $1000 coverage). The loss cost for any given location in the exposed states can be significantly affected by the rupture model assumed. Scenarios #1 and #3 caused the contribution of Cascadia subduction zone events to vary 20-40% from the "median" scenario #2. With the exception of coastal locations, however, this variability is similar to that contributed by uncertainty in other source types.

On a regional level, the impact of correlation between locations increases the significance of rupture behavior. The loss associated with a M9.0 earthquake rupturing the entire subduction zone is about twice that of the largest single M8.5 loss. On a probabilistic basis, however, the overall costs to society are higher if the interface ruptures in a piecewise fashion. This is particularly true for the 250-year loss (0.004 probability), a level many insurance companies use to determine reinsurance purchasing. Washington and northern California are moderately affected, as not all M8.5 events will cause damage in the state. Oregon shows dramatic differences. Its location in the central part of the Cascadia subduction zone and significant exposure on the alluvium of the Willamette Valley conspire to cause losses to virtually any of the M8.5 events. Scenario #3 losses for Oregon at the 250-year level are approximately 8x that of scenario #1 and 1.5x of #2. The combined Pacific Northwest portfolio shows an increase of approximately 3x at the 250-year level for the multi-rupture case relative to the single M9.0.

A crucial question in this analysis is the assumption that the smaller events are independent, or at least sufficiently separated that the exposed value has time to recover to a similar level. If the Cascadia subduction zone ruptured in M8.5s spaced minutes or hours apart, the overall ground motions would be less than a single M9.0 (D. Perkins, communication at Penrose Conference). This also brings up issues of double-counting losses and how buildings damaged by the first event might be more likely to take damage in the second, but the overall losses would clearly be less than those assuming the value is completely reset between events. This analysis thus would represent an extreme estimate of the contribution of rupture behavior to loss variability.

These results show the impact of improved information on loss estimates. Insurers rely on loss estimation tools to manage their portfolio risk and to determine rates. It is in the best interests of the insurers, the public and the regulatory community that these estimates accurately reflect the level of risk.

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STRATIGRAPHIC EVIDENCE FOR TWELVE CASCADIA EARTHQUAKES IN THE LAST 6600 YEARS FROM THE COQUILLE RIVER ESTUARY, OREGON

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Twelve buried tidal marsh soils preserved beneath three tributary valleys of the Coquille River estuary provide a ~6600 year stratigraphic record of estuary response to the earthquake deformation cycle of the south-central Cascadia subduction zone in southern Oregon.

Each abruptly buried soil contains fossil diatoms from mid-to-high marsh environments. Multiple, fining upward sandy-mud beds overlying some buried soils contain diatom fragments from sand flat environments lower in the estuary suggesting rapid deposition from an oceanward source. In all cases, thick (0.5-2.0 m) packages of estuarine mud abruptly overlie the soils and associated sand beds and contain bivalve shells and diatoms common to mud flat environments. Abrupt mud-over-peat contacts record instances of rapid relative-sea level rise and corresponding estuary expansion that persisted for decades based on thick overlying tidal flat deposits. Gradual upward transitions from estuarine mud to marsh soil indicate gradual contraction of the estuary as relative-sea level fell.

The evidence for abrupt and gradual fluctuations in relative-sea level records the response of the Coquille estuary to coseismic subsidence during great (M>8) Cascadia earthquakes and gradual uplift during interseismic periods. Evidence for widespread deposition of sand sheets suggests that some of the earthquakes triggered tsunamis that inundated the lower 10 km of the estuary. Assuming a complete stratigraphic record of coseismic subsidence events at the Coquille River estuary, time intervals between prehistoric Cascadia earthquakes vary between about 300 years to >1000 years. Average earthquake-recurrence intervals for the south-central Cascadia subduction zone range from 570 to 590 years.

Relative sea-level curves developed from biostratigraphic and ^{14}C data at two sites on either side of the Coquille fault allow up to 1.3 m of differential relative sea-level change over the last ~6300 years. If rates of late Holocene sea-level change differ across the Coquille fault, then recent tectonic uplift on the fault provides the best explanation. The late Holocene uplift rate on the Coquille fault (0.2 m/ka), as determined by the potential discrepancy between relative sea-level curves, compares well with long term uplift rates derived from late Pleistocene marine terrace data.

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PREDICTING GREAT EARTHQUAKE GROUND SHAKING IN THE PACIFIC NORTHWEST FROM THE CASCADIA SUBDUCTION ZONE

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As in many scientific endeavors, the past is the key to the future. Unfortunately, the prediction of strong ground shaking in the Pacific Northwest from a great earthquake rupturing the megathrust within the Cascadia subduction zone is hampered by the absence of empirical data. The only significant strong motion data are recordings of the 54-km deep 1949 surface wave magnitude (M_S) 7.1 Olympia and the 60-km deep 1965 M_S6.5 Seattle-Tacoma intraplate earthquakes and the 1992 moment magnitude (M_w) 7.2 Cape Mendocino, California earthquake at the south end of the subduction zone.

Thus, empirical attenuation relationships, which have been traditionally used to estimate both deterministic and probabilistic ground motion hazard in the Pacific Northwest, have by necessity been derived from strong motion recordings from other subduction zones (e.g., Japan, Chile, and Mexico). Furthermore, the largest earthquake in these data is only a M_w8.2 (Crouse 1991). Whether these relationships are appropriate for the Pacific Northwest in terms of earthquake stress drops, crustal attenuation (Q) and velocity structure, and other source and path parameters is uncertain. The validity of extrapolating these relationships up to M_w9 is also a significant issue. The most commonly used attenuation relationships are those of Youngs *et al.* (1997) which are appropriate for rock or deep soil site conditions. These relationships were the only subduction zone relationships used in the 1996 U.S. Geological Survey probabilistic national hazard maps. Unlike other relationships, they distinguish between intraplate and interplate earthquakes. Relationships by Crouse (1991), which are appropriate for soil conditions, have also been used in practice.

Numerical modeling techniques, which have been developed in the past decade, have increasingly been used in the Pacific Northwest due to the lack of region-specific empirical data. For example, numerical simulations have been used to develop attenuation relationships appropriate for the Cascadia subduction zone (Silva *et al.* 2000) and to model Cascadia megathrust scenario events from M_w8.0 to 9.0 (Cohee *et al.* 1991, Silva *et al.* 1998, Wong and Silva 1998, Wong *et al.* 2000). Atkinson (1997) and Atkinson and Boore (1997) have developed attenuation relationships for the Cascadia region but they do not distinguish between crustal and subduction zone (intraplate and megathrust) events. The Atkinson (1997) relationships are empirically derived while those of Atkinson and Boore (1997) are based on numerical modeling.

A critical factor in estimating ground shaking, whether using empirical or numerical modeling approaches, is the distance to the megathrust rupture. The most widely accepted model of Hyndman and Wang (1995) places the rupture generally offshore depending on the assumption of the amount of the coseismic rupture into the transition zone. At present, debate regarding this issue is considerable due in large part to conflicting models. In western Washington, the eastern edge of the megathrust rupture may be located beneath or near the coastline or may extend as far east as the Olympia Mountains. Along the northern Oregon coast, the megathrust rupture may be offshore by several tens of kilometers or some distance inland (Wong *et al.* 2000). Along the southern Oregon coast, the megathrust rupture probably extends onshore as the subduction zone swings inland toward northern California.

Two studies have been recently performed which have potentially controversial implications to Cascadia subduction zone ground motions. Studies of paleoliquefaction features of the most recent 1700 event by Dickinson and Obermeier (1998) are consistent with a model where (1) the megathrust rupture zone is several tens of kilometers offshore if the 1700 earthquake was M_w8.5 to 9 in size, (2) very close to the coast if it is an M_w8 in size, and (3) the event had a low stress drop. They conclude that strong ground shaking (peak horizontal accelerations greater than 0.25

g) did not extend much onshore in the past few thousand years and that ground motions were quite low in light of current estimates of the size of the 1700 earthquake. Atkinson and Boore (1997) suggest that because of the lower stress drops of Cascadia earthquakes and higher rate of regional attenuation, ground motions for larger events (M_w>7.5) may be overpredicted compared to other subduction zones. Their suggestion that stress drops are lower for megathrust events, however, is based on an analysis of crustal and intraslab earthquakes. One issue that has received little study is the level of magnitude saturation for large subduction zone earthquakes either for Cascadia or other subduction zones. This lack of understanding is due to the lack of strong motion data for events larger than M_w8.

Despite the issues raised by the above studies, current studies indicate that M_w9 megathrust events along the Cascadia subduction zone will generate strong to very strong ground shaking in the Pacific Northwest. Depending on the calculational approach, surficial peak horizontal accelerations could exceed 0.5 g along coastal areas, and up to 0.2 g and possibly much higher at inland locations such as Seattle or Portland. Long-period (>1.0 sec) ground motions could also be large. Because of the large rupture areas involved in these megathrust earthquakes, much of the Pacific Northwest will be strongly shaken with long durations of up to several minutes.

Adding to the hazard of the Pacific Northwest's major urban areas is the fact that the Willamette Valley and Puget Sound are located in alluvial basins and valleys where there can be dramatic amplification of Cascadia subduction zone–generated ground shaking. Intensity observations in 1949 and 1965 indicate that these local geologic site effects can be significant. Thus the need for incorporating site response and possible basin effects into ground motion estimates appears to be particularly important in the Pacific Northwest.

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HECETA BANK: A TECTONIC WINDOW INTO THE CENTRAL OREGON CONTINENTAL MARGIN

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Heceta Bank is a broad north-northeast-trending ridge with its southern boundary marked by a change in shelf width from 70 km southward to 40 km. The ridge has been studied by multichannel seismic lines, several petroleum-exploratory wells, swath bathymetry, and sidescan sonar at several scales, piston cores, and submersible observations. The west boundary of Siletzia trends north across the bank, separating Siletzia on the east from a Paleogene and possibly older accretionary prism on the west. This boundary, the Fulmar fault of others, is marked by a sharp magnetic gradient and a change in seismic stratigraphy in addition to well data, which suggest that the boundary is pre-late Eocene. The Siletzia boundary appears to truncate a northeast-trending magnetic grain within Siletzia. Overlying strata of late Eocene to Miocene age are fine-grained equivalents of onshore Coast Range strata. Plio-Pleistocene fine-grained deposits resemble the Eel River section of northern California and are part of the Newport basin extending north to the Washington offshore. These strata were folded and were erosionally truncated during Pleistocene glacial lowstands. The Coast Range sequence, including these Plio-Pleistocene strata, is in tectonic contact with accretionary-prism sediments of largely Plio-Pleistocene age along a terrane boundary that crops out on Heceta Bank and is truncated by Pleistocene sea-level lowstands. West-northwest-striking left-lateral faults appear to be restricted to the accretionary prism. This terrane boundary may have been an outer-arc high that ponded the Newport basin sediments. Breaching of the outer-arc high by headward erosion of submarine canyons off Washington may have caused sediments to bypass the continental shelf and accumulate on the abyssal plain as the Astoria submarine fan. Folds on Heceta Bank trend north-northwest and are truncated by the north-northeast-trending shelf break, which curves northeastward to Newport and north-northwest to Nehalem Bank, a mirror image of Heceta Bank west of Astoria. On Heceta Bank, the shelf break is cut by a lowstand shoreline, presumably of late Wisconsin age, in which the shoreline angle deepens southward. Where the shelf is narrow between Yaquina Bay and Tillamook, geodetic uplift rates based on leveling data are lowest. Heceta Bank provides evidence that a complete understanding of the Cascadia subduction zone must include an analysis of the diverse active structures of the overlying North America plate edge.

IMPORTANT ISSUES IN CHARACTERIZING GROUND SHAKING HAZARDS ALONG THE CASCADIA SUBDUCTION ZONE

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Seismic hazard along the Cascadia subduction zone results from three sources of earthquakes, faulting within the North America plate, faulting within the subducting Juan de Fuca plate, and rupture of the interface between the two plates. The Cascadia interface seismic source dominates the seismic hazard along the coast and is the major contributor to low frequency ground shaking hazard in the major population centers (Vancouver, Puget Sound, the Portland Basin, and Willamette Valley. The principal factors affecting the shaking hazard posed by the Cascadia interface are: the down-dip location of the seismogenic portion of the interface, the frequency of occurrence of major interface ruptures, the maximum size of interface ruptures (the size of "characteristic" ruptures), and the level of shaking caused by interface earthquakes. These factors are all uncertain, resulting in uncertainty in the level of seismic hazards. We have conducted numerous probabilistic seismic hazard analyses in the region [including mapping the state of Oregon (Geomatrix 1995)] that explicitly incorporated detailed modeling of the uncertainties in characterizing the earthquake sources and the ground motions they produce. We will present examples of these studies illustrating the relative contributions of various to the total uncertainty in assessing ground motion hazard in the region.

Along the coast, the major sources of uncertainty in the hazard are the frequency of major interface ruptures, the down-dip location of the seismogenic rupture, and the level of ground shaking in the near field of large subduction zone interface ruptures. Uncertainty in the expected maximum magnitude (or magnitude of the characteristic event) does not have a major contribution to the overall uncertainty because the assumption of smaller ruptures requires more earthquakes in order to represent the paleoseismic evidence for interface ruptures along the length of the margin.

In the major population centers, the maximum magnitude (the size of characteristic earthquakes) for the Cascadia interface becomes an important issue because these earthquakes are the primary source of low frequency ground shaking hazard (spectral frequencies >0.5 Hz) and the estimates of low frequency ground motions are more sensitive to earthquake magnitude than those for high frequency ground motions. Uncertainty in the frequency of ruptures and the down-dip extent of seismogenic rupture remain important factors. Because these sites lie at distances from the interface comparable to those where most empirical data have been recorded, the uncertainty in characterizing ground motions becomes less of a factor that along the coast.

However, the projected size of the largest Cascadia earthquakes is one magnitude unit higher the largest earthquakes for which empirical strong ground motion data has been collected. Thus, uncertainty remains in extrapolating the empirical data to these earthquake magnitudes.

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