Priority directions for research on tsunami hazard estimation: Cascadia Subduction Zone, Pacific Northwest coast of North America

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Abstract. Cascadia subduction zone tsunamis could conceivably cause the loss of tens of thousands of lives on the Pacific Northwest coast of North America. Paleoseismic and other data support Cascadia earthquakes with moment magnitudes of ∼9, rupture lengths of ∼1000 km, and recurrence of 400–600 years; the last event was 301 years ago, so the conditional probability of another occurring in the next 100 years is high. Hydrodynamic simulations depicting destructive potential of Cascadia tsunamis have been hindered chiefly by uncertainties in the earthquake source, rupture simulation methods, and lack of independent verification. Uncertainties in the hydrodynamic simulation methods and in oceanographic factors (e.g., non-linear tidal effects) are also of concern; however, coseismic seafloor deformation is a much greater source of error. Research priorities should therefore be directed toward refinement of our knowledge of asperities, splay faults, total fault slip, and rupture simulation algorithms. Tsunami and fault dislocation simulations should be checked against coseismic deformation, inundation, water depth, and current velocities estimated independently from investigations of paleotsunami deposits and buried salt marsh soils. An organized interdisciplinary team effort operating within the framework of a comprehensive science plan is clearly needed. Leadership at the federal level in both Canada and the United States is the key to further progress.

1. Why Is the Cascadia Tsunami Hazard of Foremost Importance?

Scientific findings of the last 14 years have shown that the Pacific Northwest coast is vulnerable to great (M 8–9) earthquakes that can occur on the offshore Cascadia subduction zone fault system (Fig. 1; see Atwater *et al.*, 1995, and Nelson *et al.*, 1995, for summaries). Such earthquakes can generate catastrophic tsunamis that will likely devastate populated areas of the Pacific Northwest coast. For example, if a Cascadia tsunami of 10–15 m elevation (e.g., Priest *et al.*, 1997a) struck the City of Seaside, Oregon during a peak visitation day, on the order of 35,000 people could be trapped at elevations below 10 m (Alfred Aya, 2001, personal communication). If some large percentage of the lives in just this one town were lost, it would far exceed projected losses from earthquake shaking for a Cascadia event (e.g., Wang, 1998; Wang and Clark, 1999). When the totality of the exposed transient and permanent populations in Canada and the United States is considered, the life risk from Cascadia tsunamis dwarfs most other natural or man-made disasters that might affect the region. Furthermore, economic losses are likely to be substantial, but there is no published information that quantifies the extent of these losses from the tsunami.

It might be argued that a Cascadia subduction zone tsunami is a rare

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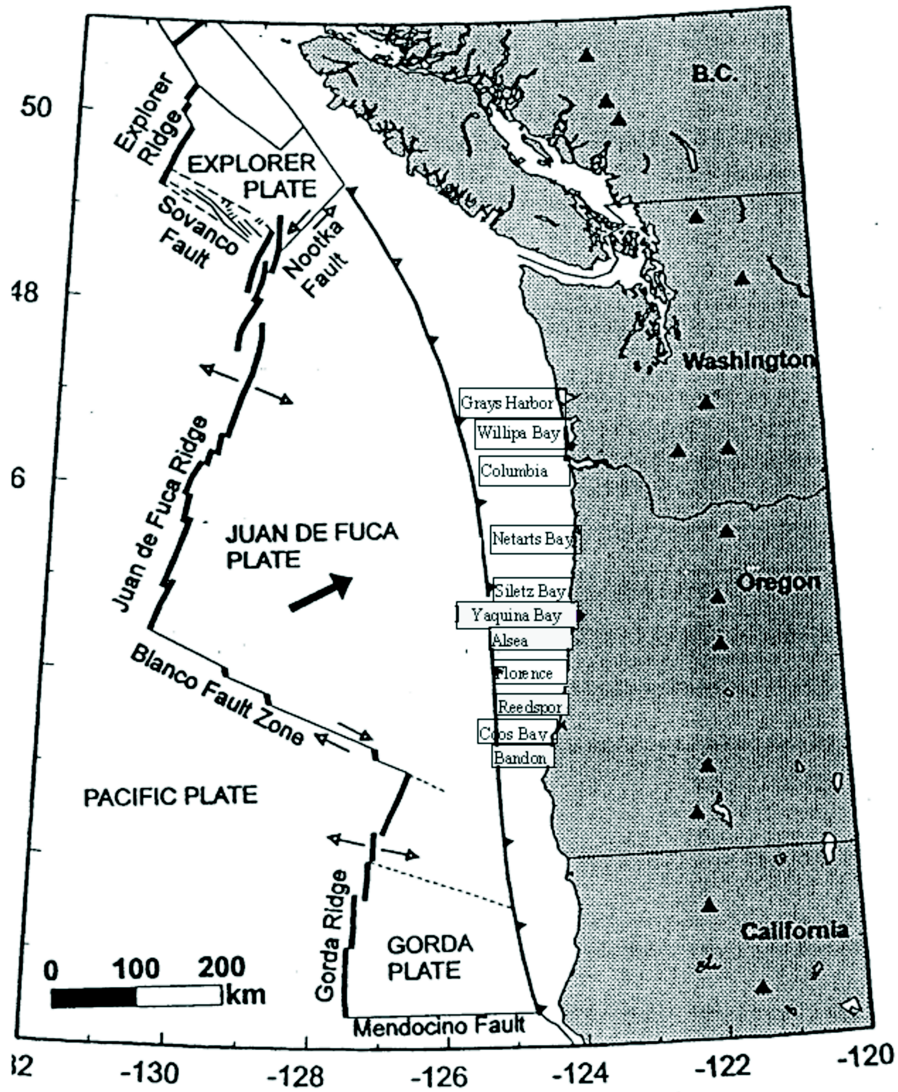

Figure 1: Plate tectonic map of the Cascadia subduction zone fault system illustrating the location of the surface trace of the fault at the deformation front (line with triangles). The subduction zone dips 8–12° eastward under the continental shelf.

event, so why should significant efforts be made to investigate it? The answer is that such events are not that rare. The last event was 301 years ago, and while intervals as long a 1000 years can separate events, reported recurrence is on the order of 400 to 600 years (Atwater *et al.*, 1995). With the *known condition* that 301 years of strain has already accumulated on the subduction zone, the conditional probability of a recurrence in the next 100 years is much higher than a random event with a 400–600 year recurrence. How high that probability might be is a matter of debate, but surely it is somewhere between the probabilities for random 100- and 500-year river or ocean floods that the United States uses for flood insurance zoning. The difference is that it is fairly difficult to kill tens of thousands of people with storm-driven floods, since these floods come with significant warning, whereas Cascadia tsunamis arrive within minutes of a local subduction zone earthquake.

2. What Needs to be Done That is Not Being Done?

Federal Emergency Management Agency (FEMA) National Flood Insurance Rate Maps (FIRM) for the Pacific Northwest coast do not currently utilize a tsunami flooding scenario. If the conditional probability for Cascadia tsunamis falls somewhere in between the 100- and 500-year flood for open coastal and estuary sites, FIRM restudies of these sites should use a Cascadia scenario for at least the 500-year flood zone. There is now more than enough scientific information to justify a vigorous effort within the FEMA flood program to define a standardized Cascadia scenario for FIRM restudies.

Although tens of millions of dollars have been expended by FEMA to produce financial and life loss estimates for earthquakes (i.e., the Hazards in the U.S. program or HAZUS), no similar effort has been expended on tsunamis. It is true that earthquakes can affect many more areas of the United States than tsunamis, but only a few scenario earthquakes in very highly populated areas could put as many lives at risk as a locally generated tsunami on even a modestly populated coast. A HAZUS module for tsunami damage and loss would be fully justified at this point in our scientific understanding of the Cascadia subduction zone hazard.

Why has 10 years of sustained effort by government and academia still not resolved many fundamental questions about the most important issue for estimation of tsunami hazard, the *tsunamigenic sea floor deformation from a Cascadia subduction zone earthquake*? To date there is still no coordinated effort to address the subduction fault rupture process in order to construct accurate initial conditions for tsunami simulations. The uncertainty from this factor is so large that current tsunami hazard maps produced in Oregon have three scenario inundation boundaries that differ from one another by factors of two (e.g., Priest *et al.*, 1997b; Priest *et al.*, 2001). The primary uncertainties between these scenarios are in rupture length, rupture width, slip magnitude, and amount of slip concentrated in asperities. For example, in Seaside, Oregon the minimum Cascadia tsunami inundation differs little from a large teletsunami (Priest *et al.*, 1997a) and would probably inflict little loss of life or property. In contrast, the worst case Cascadia scenario would overwhelm the entire town and probably cause very large losses of life and property (Priest *et al.*, 1997a). The reality is probably somewhere in the middle, which, if it could be specified with confidence, would give local government urgently needed evacuation options that they do not now have. Their only choice at present is to try to evacuate thousands of people across several old bridges or hope that there will someday be enough seismically resistant high-rise buildings to accommodate vertical evacuation.

Hydrodynamic models of tsunami propagation and dry land inundation are in need of further research, but the differences between the competing models are relatively small compared to the uncertainties in the fault sources. The same is true of variations in inundation from oceanographic factors like non-linear interactions between tsunamis and tides. These are very important but run-up and inundation seldom differ by factors of two.

Stochastic analyses of Cascadia fault ruptures (Geist and Yoshioka, 1996) and investigations of viscoelastic fault dislocation models (Wang, 1995; Wang and others, 1993) are promising new lines of research that may yield entirely new approaches to understanding the subduction zone fault rupture process. These theoretical investigations need to be tested with geodetic investigations of the Cascadia margin, investigations of fault geometry, and paleoseismic studies of fault slip, coseismic subsidence, and uplift. Of particular importance is identifying splay faults that may be partitioning large amounts of slip from the megathrust. There are numerous small paleo-seismological studies of paleo-tsunami deposits and paleo-deformation features in salt marshes by various workers, but there is little coordination of these efforts; nor is there any coordination between these studies and geodetic investigations. Few studies of Cascadia tsunami deposits have yielded quantitative estimates of tsunami water depth or current velocities that might test computer simulations. In most cases the paleo-seismological work has been so poorly funded that critical age dates could not be obtained, needed detailed sedimentologic analyses could not be performed, and paleo-geographic reconstructions of the topography has been impossible. As a result, many important lines of research have been stifled, the researchers focusing their efforts on other, better supported science. The message here is that theory is insufficient without field verification, particularly where lives are at stake; yet verification through paleo-seismology frequently takes a back seat to theory when research proposals are funded.

Another source of uncertainty in the sea floor deformation is submarine landslides. How vulnerable is the Cascadia margin to tsunamis from submarine slope failures? Again, theoretical slope stability analyses of the continental slope backed up by direct geological observations are the key to estimating the likelihood of landslides augmenting tsunamis during a Cascadia earthquake.

Tsunami simulations frequently suffer from lack of detailed bathymetric and topographic data. Large-scale bathymetric surveys are carried out to investigate interesting phenomena all over the world, but shallow water bathymetry and coastal topographic surveys that are so critical for detailed simulation of tsunami inundation are often overlooked. Again, this is a symptom of a scientific and tsunami hazard mitigation community that has not made its case when priorities are set for research funding.

Perhaps most shocking of all is the absence of an overall science plan to direct, coordinate, and set priorities for Cascadia investigations. Absence of a consensus science plan is probably at least part of the reason that there is no listed program in the National Science Foundation for funding Cascadia investigations aimed at the tsunami problem.

3. Recommendations

Federal governmental organizations in British Columbia and the United States need to develop a consensus science plan that places its highest priority on better defining tsunamigenic processes on the Cascadia subduction zone, particularly the fault rupture process. The objective is production of accurate tsunami simulations for tsunami hazard assessment. The U.S. Geological Survey and Canadian Geological Survey have the infrastructure and needed scientific expertise to provide the leadership. Academia in concert with National Science Foundation should be a strong partner in this effort. The National Oceanic and Atmospheric Administration (NOAA) has established a National Tsunami Hazard Mitigation Program (NTHMP) that can facilitate this process. The NTHMP can provide a valuable link to the hydrodynamic tsunami modeling community.

The chief stakeholders are the emergency response communities in Canada and the United States. These communities should be involved as stakeholder advisors and, where possible, as direct financial supporters of the effort. In the United States FEMA could justify being a funding partner, since, in addition to their leadership role in tsunami evacuation planning, they are responsible for the production of FIRM maps, the basis for the National Flood Insurance Program. Local and state government need to be strong partners as well, since all hazard mitigation is ultimately done at the local level. The NTHMP can, again, provide a valuable link to all of these groups.

Finally, FEMA can now justify making a serious effort to produce a statistically accurate tsunami module for HAZUS. Decision makers responsible for deciding how much of their limited resources should be spent on tsunami hazard mitigation need sound data on potential damage and loss.

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