Tsunami hazard assessment in Oregon

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Abstract. Tsunami hazard assessment in Oregon has proceeded by first completing a detailed inundation simulation of the Siletz Bay area where various model parameters were tested against estimates of inundation and run-up from prehistoric tsunami deposits. Reconnaissance-level inundation maps for the entire coastline were then produced to implement Senate Bill 379, which limits construction of critical and essential facilities in tsunami inundation zones. Detailed simulations based on three standardized Cascadia subduction zone earthquake sources have since been completed at Astoria, Warrenton, Gearhart, Seaside, Newport, Coos Bay, and Gold Beach. If funding is available, detailed inundation mapping will be accomplished for (in priority order, highest to lowest): (1) Alsea Bay (Waldport); (2) Rockaway Beach; (3) Siuslaw estuary (Florence); (4) Nestucca Bay (Pacific City); (5) Coquille estuary (Bandon); and (6) Umpqua estuary (Winchester Bay-Reedsport). Each mapping project is done in close collaboration with the affected local governments. Maps of worst-case inundation are being completed for production of evacuation brochures in most communities, whether detailed inundation maps are available or not. The design and degree of conservatism employed in these evacuation maps is, again, worked out in close collaboration with local governments.

1. Introduction

Scientific findings of the last 14 years have shown that the Oregon 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 tsunamis that will be very dangerous to populated areas of the Pacific Northwest coast. Starting in 1993, the State of Oregon Department of Geology and Mineral Industries (DOGAMI) responded to this threat by pursuing an applied research program to estimate the potential for tsunami inundation. A public education program was developed, staff training was initiated, and an aggressive program to produce tsunami hazard maps was begun.

2. Pilot Tsunami Inundation Map at Siletz Bay, Oregon

Once support was provided by a grant from the Oregon Department of Land Conservation and Development (DLCD), a pilot tsunami hazard mapping

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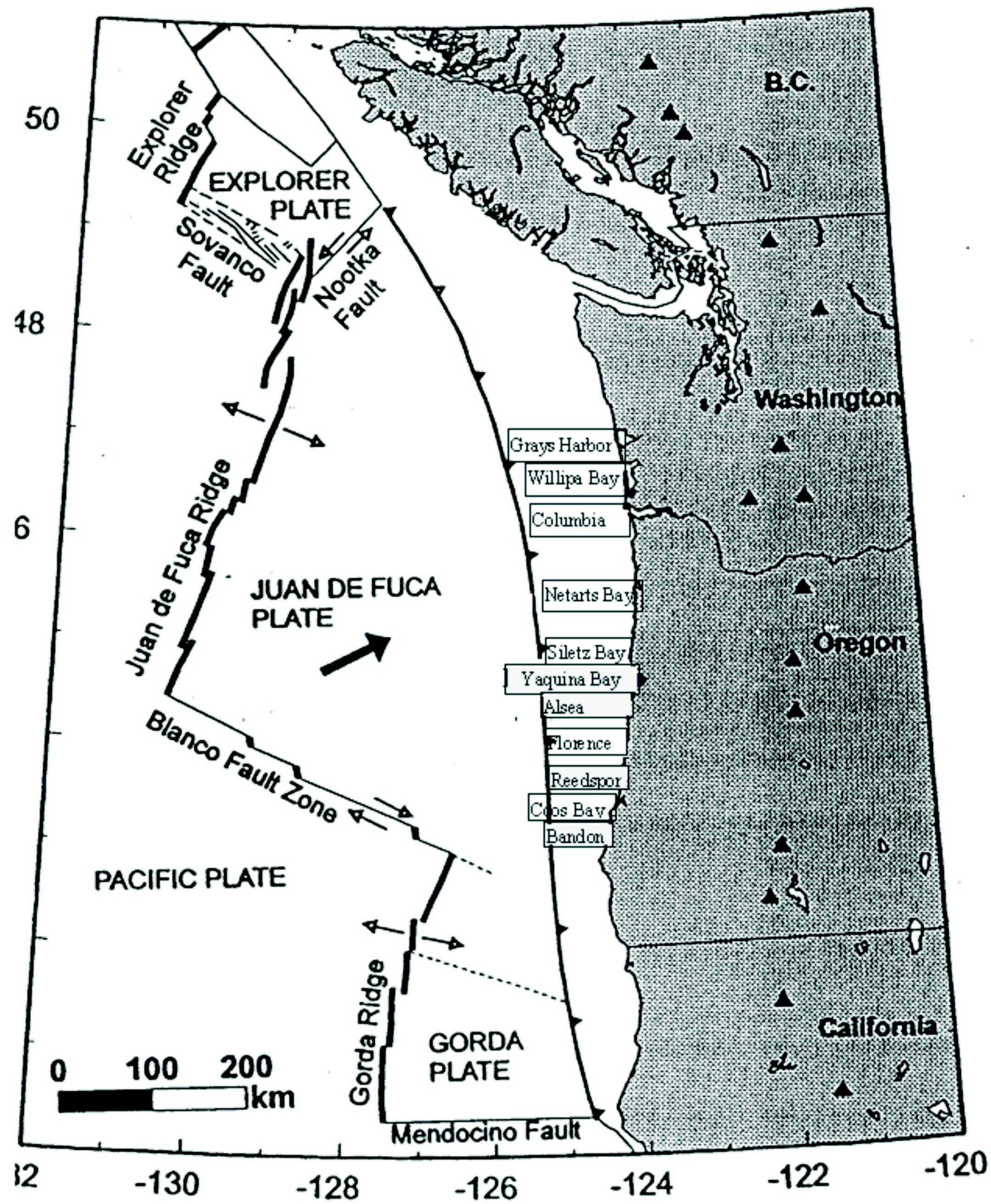

Figure 1: Plate tectonic map of the Cascadia subduction zone fault system illustrating the location of the surface trace of the fault at the deformation front (line with triangles). The subduction zone dips 8–12° eastward under the continental shelf.

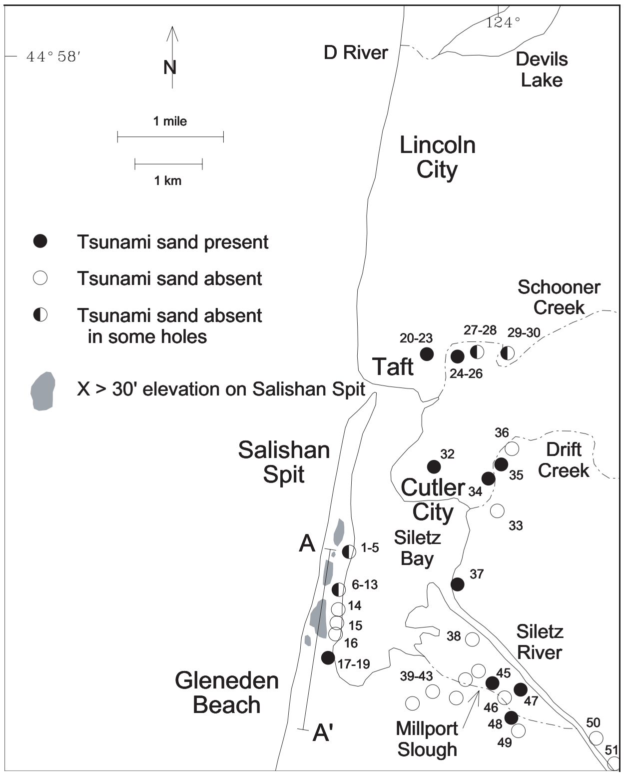

Figure 2: Map of Siletz Bay showing the location of coring sites where marsh soils buried after coseismic subsidence were found. These coseismic subsidence events occurred during one or more of seven earthquakes that struck during the last 2,800 years (see Peterson *et al.*, 1995). As indicated, some core sites have prehistoric tsunami sands on one or more of the buried soils. A–A′ is the location of the cross section of Fig. 3. As explained in Fig. 3, a barrier west of sites 14, 15, and 16 (stippled area) prevented deposition of tsunami sand at those sites when earthquakes struck about 300 and 800 years ago (older records were destroyed by estuarine erosion). Sites 17, 18, and 19 have thick tsunami sands derived from dunes and beach sand to the west, so dunes west of these sites were overtopped by tsunamis 300 and 800 years ago. Figure taken from Priest *et al.* (1995).

project was started in order to learn how best to map inundation from Cascadia subduction zone earthquakes. Siletz Bay was chosen as the first project, because geologic evidence for past tsunamis was still preserved and the landscape was only modestly modified from prehistoric conditions. Possible subduction zone earthquake sources and derived tsunami simulations were tested against paleotsunami evidence to establish some ground truth for the simulations (Priest *et al.*, 1995). Figure 2 illustrates how distribution of paleotsunami deposits at Salishan Spit appears to be controlled by topography. This information gives clues to potential tsunami water elevations. In this case it appears that parts of the spit now exceeding about 9–10 m of elevation were effective barriers to Cascadia tsunamis. Additional work is needed to prove that similar topographic highs were in fact present when the tsunami sands were deposited. Additional work is also needed to

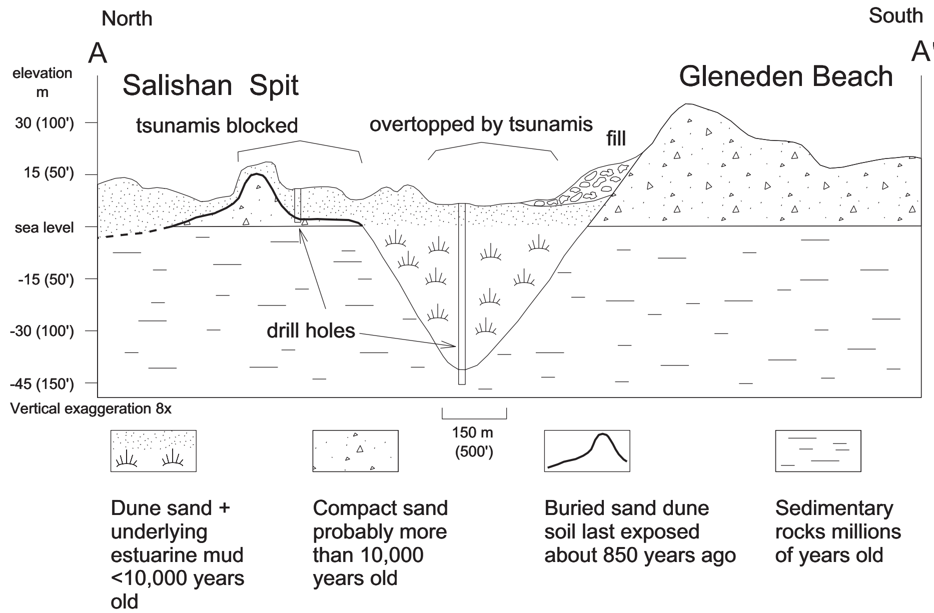

Figure 3: Vertical cross section along line A–A′ of Fig. 2. Topography is the maximum elevation of the spit and bluff projected into the cross section. The soil carbon 14 dated at 850 ± 60 radiocarbon years is located within a dune barrier that apparently blocked prehistoric tsunamis. The dunes are probably as high now as they have ever been in the geologic past, because introduction of European dune grass has generally caused dune growth and stabilization throughout the Oregon coast. The highest parts of the spit are underlain by a thick sequence of semi-consolidated Pleistocene marine terrace sands. Persistence of these semi-consolidated sand deposits shows that this portion of the spit has been in a stable position for thousands of years. Figure taken from Priest *et al.* (1995).

prove that the thinning and disappearance of tsunami sands from buried soil horizons behind dune barriers is from lack of deposition versus later or contemporaneous erosion.

Even with these uncertainties, it was reassuring to see that the scenario tsunami simulations conformed well with interpretations of the paleotsunami data. The highest run-up case reached open coastal elevations of about 15–17 m and was blocked by the highest parts of the dunes. The middle case (9–11 m) was just blocked by the current 9–10 m highs that correspond to areas that apparently blocked tsunamis that struck about 800 and 300 years ago. The lowest case had run-up elevations (6–8 m) that were somewhat higher than the lowest possible elevation of the blocking dunes. The lowest paleodune elevation is marked by a paleosol with an age of 850 ± 60 radiocarbon years before present (Priest *et al.*, 1995; Fig. 3). The paleosol was probably about 5 m above sea level at the time of the 800 year event (Priest *et al.*, 1995).

Table 1: Summary of fault and tsunami scenarios currently used for detailed tsunami inundation mapping for Oregon and Washington. Rupture widths, slip, run-up, and current velocities are at the latitude of Yaquina Bay, except Model 2CN, which does not reach Yaquina Bay. The width, slip, run-up, and velocity for Model 2CN are at the latitude of Siletz Bay, 30 km north of Yaquina Bay. Model 1A Asperity slip is only an estimate, since no fault rupture model was run to generate this Gaussian asperity. Open coastal run-up elevations are corrected for a tide at mean higher high water (1.3 m above geodetic mean sea level) and for coseismic subsidence. Coseismic subsidence is derived from the fault rupture models. Data is from Priest *et al.* (1997).

Scenario (model number)	Rupture length (km)	Rupture width (km)	Slip (m)	M_w	Run-up (m)	Maximum current velocity in m/sec (knots)
Worst Case (1A + Asperity)	1050	70	~35 at asperity (or higher fault dip than assumed in model)	9.1	10.7	8.3 (16)
Middle Case (1A)	1050	70	17.5	9.1	8.1	6.5 (13)
Lowest Case (2CN)	450	65	7	8.7	3.4	2.5 (5)
Lowest Case (2CS)	450	90	7	8.6	4.8	3.8 (7)

3. Oregon Senate Bill 379 Tsunami Inundation Mapping

As DOGAMI finished the Siletz Bay project in 1995, the Oregon Legislature passed Senate Bill 379, which limits construction of critical and essential facilities in the tsunami inundation zone. This bill required immediate mapping of a statewide inundation zone. Using a ~M 9 subduction zone earthquake with slip distribution and shape hypothesized by Hyndman and Wang (1995), DOGAMI, in partnership with Oregon Graduate Institute of Science and Technology (OGI), produced 56 tsunami inundation maps covering the entire Oregon coastline (Priest, 1995). The resulting tsunami run-up elevations were similar to the ~9–11 m (middle case) at Siletz Bay.

4. Development of Standardized Mapping Techniques at Yaquina Bay, Oregon

Additional funding was received in 1996 from the U.S. Geological Survey's National Earthquake Hazard Reduction Program to produce a detailed inundation map for Yaquina Bay (Newport, Oregon). This support allowed further refinement of earthquake source models and tsunami simulation methods (Priest *et al.*, 1997; Myers *et al.*, 1999; Priest *et al.*, 2000).

An important departure from the earlier work at Siletz Bay was joint development by DOGAMI, OGI, and the National Oceanic and Atmospheric Administration (NOAA) of a worst-case earthquake source based roughly on the largest asperity in the Alaska 1964 earthquake and observations of asper-

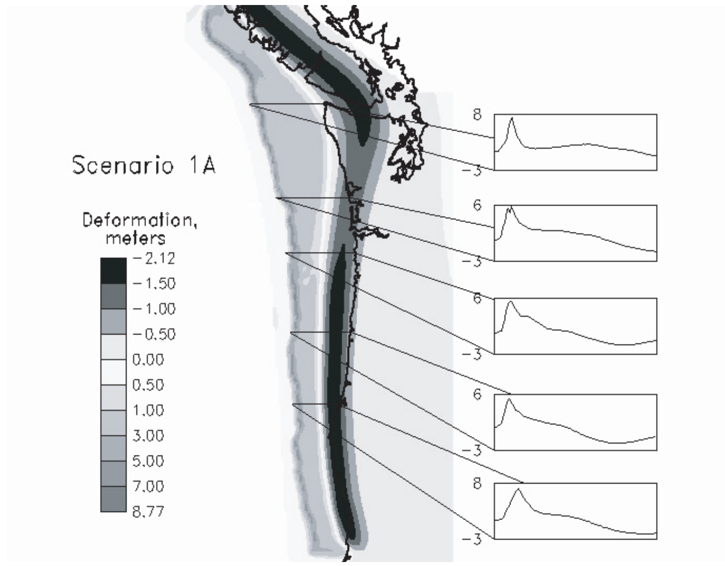

Figure 4: Surface deformation from the middle case fault rupture, Scenario 1A. Figure taken from Myers *et al.* (1999).

ities in other subduction zones worldwide (Priest *et al.*, 1997). This worst case scenario utilized a regional source very similar to the ∼M 9 earthquake used for the Senate Bill 379 maps, but with a maximum of 6 m of uplift in a 100 × 150 km Gaussian "mound" 71 km offshore (Fig. 4). The asperity was placed at the slope break near the top of the continental slope (∼1000 m water depth). The slope break is the location of a major landward-dipping thrust fault (Goldfinger *et al.*, 1992) that may be capable of partitioning significant slip from Cascadia megathrust. Uplift in this mound was roughly twice that in the middle case scenario. The lowest hazard scenario (Model 2CS) had an uplift of about half the middle case and was simulated by a segment break that ruptured about half of the subduction zone. This lowest case source approximated a most probable Cascadia earthquake source estimated from an engineering analysis commissioned by the Oregon Department of Transportation (Geomatrix Consultants, 1995). A further departure from the Siletz Bay project was use of the point source fault rupture simulation software and a refined regional subduction zone rupture developed by the Geological Survey of Canada (Flück *et al.*, 1997). The resulting scenario tsunamis approximated the ones used earlier at the Siletz Bay and for Senate Bill 379 mapping but had a more realistic geologic basis. The three standardized sources (initial conditions) used for Yaquina Bay and subsequent maps are illustrated in Figs. 4–6.

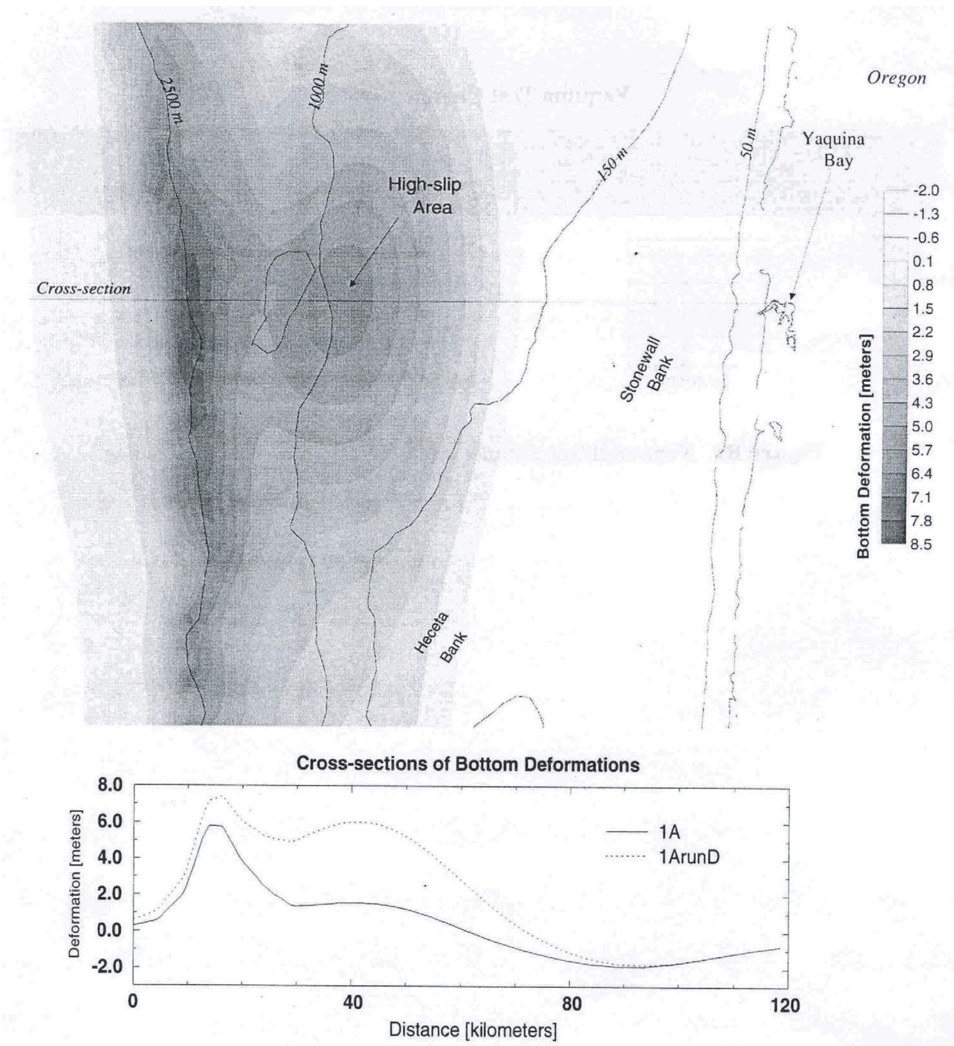

Figure 5: Surface deformation from the worst case fault rupture, Scenario 1A + Asperity (listed in the figure as 1ArunD). Note that this is the same regional deformation as Scenario 1A, but with a local Gaussian "mound" of uplift that roughly doubles the 1A uplift immediately offshore of a study area. The middle case (Model 1A) deformation profile is shown on the cross section for comparison. Figure taken from Myers *et al.* (1999).

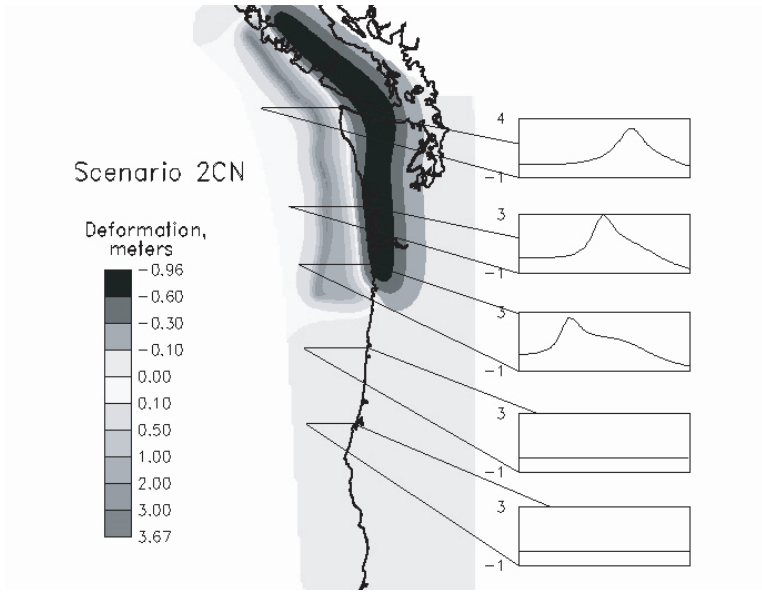

Figure 6: Surface deformation from the least case fault rupture, Scenario 2CN. This rupture is based on half the slip of the Scenario 1A but a maximum rupture width. The wider rupture was chosen because, other things being equal, wider ruptures produce smaller tsunamis than narrow ruptures in this geologic setting; hence, both slip and width favor smaller tsunamis. The maximum width was based on observations of paleo-coseismic subsidence (Priest *et al.*, 1997).

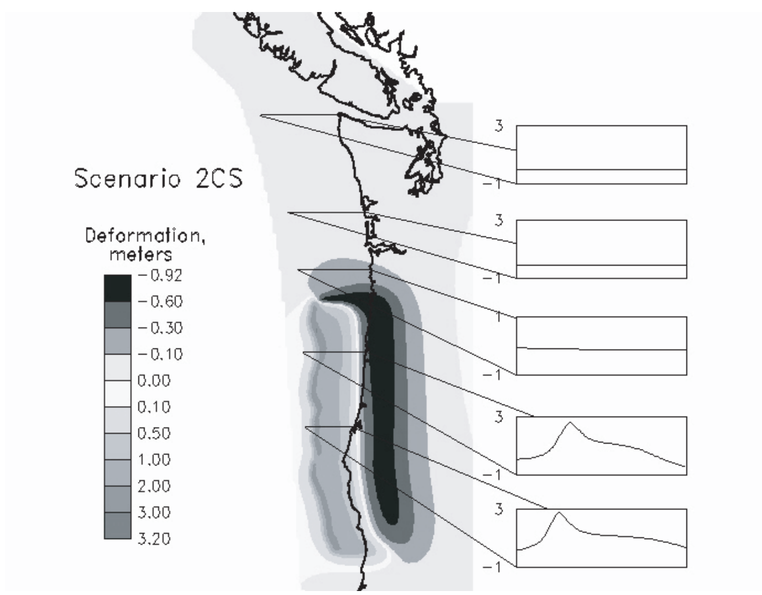

Figure 7: Surface deformation from the least case fault rupture, Scenario 2CS. This rupture is essentially the same as the 2CN case but for a southern segment break on the subduction zone. Figure taken from Myers *et al.* (1999).

5. Tsunami Hazard Mapping, 1998 and in the Future

DOGAMI, in partnership with OGI and the National Tsunami Hazard Mitigation Program of NOAA, has proceeded to do detailed inundation maps for Seaside, Warrenton, Astoria, Gold Beach, and Coos Bay, utilizing the three generalized earthquake sources developed in the Yaquina Bay project (Priest *et al.*, 1997). The only difference in each case was location of the worst-case asperity, which was moved immediately offshore of each study area. The lowest run-up scenario was produced by whichever segment break was appropriate (Figs. 6 and 7).

DOGAMI will continue to produce detailed inundation maps of selected populated areas in priority order based on estimated risk to life and property. From highest to lowest priority, these areas are: (1) Alsea Bay (Waldport); (2) Rockaway Beach; (3) Siuslaw estuary (Florence); (4) Nestucca Bay (Pacific City); (5) Coquille estuary (Bandon); (6) Umpqua Estuary (Winchester Bay-Reedsport).

6. Evacuation Planning

DOGAMI and Oregon Emergency Management are working with the DLCD and local government to produce evacuation brochures for use by local government. These brochures show an evacuation zone as well as evacuation routes. In general the evacuation zone encompasses the worst-case inundation mapped in available detailed studies but may be even more conservative, if local government officials so choose. DOGAMI works directly with local officials to draw an evacuation zone that meets local policy decisions on safety while still remaining scientifically reasonable. DLCD is incorporating the evacuation routes and zones into a coastal geographic information system that will be web accessible.

Installation of standardized evacuation and warning signs is proceeding in tandem with production of evacuation maps. In the coming year warning signs will be installed wherever the coastal highway system passes into and out of a potential tsunami inundation zone.

7. Discussion

Unless quantum advances are made in the understanding of Cascadia subduction zone rupture processes, future maps will, for the sake of consistency, use standardized earthquake sources similar to those developed for Yaquina Bay.

In spite of a decade of sustained effort the largest uncertainty in these tsunami hazard maps is still the Cascadia earthquake source. There is no agreement among scientific professionals on the likelihood of segmented ruptures, location and size of asperities, width of ruptures, amount of prompt slip relevant to tsunami generation, and slip distribution. Particularly vexing is uncertainty about slip that may be partitioned into splay thrust faults.

The high dip of many thrust faults in the near surface can cause extreme uplift, if significant slip is partitioned to them. DOGAMI has chosen to err on the side of caution in specifying source parameters, but there is clearly a need to decrease these uncertainties so the public is not faced with three scenario tsunamis that differ from one another by factors of two or more in inundation and run-up elevation.

Local government, when apprised of the uncertainties in the simulations, especially uncertainties with respect to local splay faults and submarine landslides, generally opts for adding an additional safety factor to the mapped inundation, when advising their citizens about evacuation. DOGAMI helps local government to add this additional safety factor in a scientifically reasonable fashion. In the future it would be useful to do a systematic investigation of these additional tsunami amplification factors to determine their importance.

8. Conclusions

State and local government in Oregon will continue to work in partnership with the National Tsunami Hazard Mitigation Program to refine our understanding of the tsunami risk to Oregon. The efforts so far have been extraordinarily successful in producing tsunami inundation maps for the highest priority population areas. The next step is to complete the mapping and make sure that the information results in meaningful mitigation. The existing close partnership between Oregon state and local government will assure that this objective is attained.

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