Appendix L: Cascadia Subduction Zone

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Discussion

The geometry and recurrence times of large earthquakes associated with the Cascadia Subduction Zone (CSZ) were discussed and debated at a March 28-29, 2006 Pacific Northwest workshop for the USGS National Seismic Hazard Maps.

The CSZ is modeled from Cape Mendocino in California to Vancouver Island in British Columbia. We include the same geometry and weighting scheme as was used in the 2002 model (Frankel and others, 2002) based on thermal constraints (Fig. 1; Flück and others, 1997 and a reexamination by Wang et al., 2003, Fig. 11, eastern edge of intermediate shading). This scheme includes four possibilities for the lower (eastern) limit of seismic rupture: the base of elastic zone (weight 0.1), the base of transition zone (weight 0.2), the midpoint of the transition zone (weight 0.2), and a model with a long north-south segment at 123.8° W in the southern and central portions of the CSZ, with a dogleg to the northwest in the northern portion of the zone (weight 0.5). The latter model was derived from the approximate average longitude of the contour of the 30 km depth of the CSZ as modeled by Fluck et al. (1997). A global study of the maximum depth of thrust earthquakes on subduction zones by Tichelaar and Ruff (1993) indicated maximum depths of about 40 km for most of the subduction zones studied, although the Mexican subduction zone had a maximum depth of about 25 km (R. LaForge, pers. comm., 2006). The recent inversion of GPS data by McCaffrey et al. (2007) shows a significant amount of coupling (a coupling factor of 0.2-0.3) as far east as 123.8° West in some portions of the CSZ. Both of these lines of evidence lend support to the model with a north-south segment at 123.8° W.

The primary constraint on our Cascadia earthquake model is that great earthquakes occur on average once every 500 years beneath sites on the coast over the CSZ, based on paleoseismic studies of coastal subsidence and tsunami deposits (e.g., Atwater and Hemphill-Haley, 1997). We considered two sets of rupture scenarios for these events: 1) M 9.0 +/- 0.2 events that rupture the entire CSZ every 500 years on average and 2) M 8.0-8.7 events whose rupture zones fill up the entire zone over a period of about 500 years. The rupture zones in the latter set of scenarios are moved or floated along the strike of the CSZ. This represents the aleatory variability of the types of rupture along the CSZ.

Various lines of evidence are used to assess the relative likelihood of these two sets of rupture scenarios. The 1700 earthquake that caused a tsunami in Japan is thought to have ruptured the entire zone in an earthquake with M about M 9.0 (Satake and others 1996, 2003). Furthermore, recent sedimentation studies along the continental shelf also provide evidence that great earthquakes usually rupture most of the Cascadia subduction interface (Goldfinger et al., 2003). In contrast, Nelson and others (2006) and Kelsey and others (2002, 2005) reported tsunami deposits along northern California and southern Oregon that give evidence for additional M 8.0-8.6 earthquakes that are not apparent in studies along the Washington coast. We have applied the M 8.0 – 8.7 model for the entire CSZ lacking any evidence for different rupture behavior between the north and southern portions of the fault.

For the WGCEP and the NSHMP model we assign a probability of 0.67 to the M 8.8-9.2 scenario and a probability of 0.33 for the set of M 8.0-8.7 scenarios with floating rupture zones. In the 2002 maps, we used M9.0 and M8.3 scenarios with equal

probabilities. To be clear, when we say "probability of a scenario" this indicates that the effective rate of the scenario in the hazard calculation is the probability of that scenario multiplied by the recurrence rate calculated for that scenario as if it was the only scenario. The higher probability of the M 8.8-9.2 complete CSZ rupture scenario in the 2007 update compared to that in the 2002 maps reflects the consensus of people at the Pacific Northwest workshop that this was a more likely scenario for the great earthquakes than the set of floating M8 scenarios.

Here we describe the scenarios in more detail. In the first model, we consider rupture of the entire length of the CSZ with great earthquakes having a magnitude of M8.8 (weight 0.2), M9.0 (0.6), and M9.2 (0.2). The average recurrence time for such an event was taken to be 500 years, based on the palesoeismic evidence. In the second model we consider a set of floating ruptures between M 8.0 and 8.7. The key constraint of the second model is that the annual rate of having a rupture zone beneath any given site along the coast is 1/500, to be consistent with the paleoseismic observations. This procedure is similar to the model applied in Geomatrix (1995), where rupture zones for each magnitude were assumed to fill the CSZ every 500 years. We calculate the overall rate of earthquakes for the CSZ for a given magnitude so that the rate of having a rupture zone occurring beneath any given site on the coast is 1/500, on average. When rupture zones are floated along the CSZ using equal distance increments, sites near the middle of the CSZ will have a higher rate of ruptures beneath them compared to sites near the northern and southern ends of the CSZ. We used the magnitude-length relation for subduction-zone earthquakes determined by Geomatrix (1995). The rupture zones were floated using 5 km increments. The average rate of rupture zones under a site was calculated for a set of sites along the coast separated by 0.1 degrees in latitude and extending the entire length of the CSZ. Probabilities were assigned to scenarios with magnitudes at one-tenth magnitude unit intervals from 8.0 to 8.7. The recurrence parameters for each magnitude interval are shown in Table 1; probabilities in the last column of Table 1 sum to 0.33 which is the weight of this model. The implied recurrence intervals for M 8.0 to 8.2 earthquakes are between 78 and 107 years, shorter than the observed seismic history that does not contain any of these events. To account for this lack of historic earthquakes between M 8-8.2, we have weighted the probability of these rupture scenarios by one-half, compared to the intervals between M 8.3 and 8.7, to make the rates more compatible with the earthquake record.

The effective recurrence rate of each scenario in the hazard calculation is the recurrence rate multiplied by the probability of that scenario. In the final model, considering all of the M9 and floating M8 rupture scenarios and their probabilities, the effective recurrence time (reciprocal of the mean rate) for earthquakes with M≥8.0 is 270 yr. The reason for this relatively short recurrence time is that we are treating the M 8 earthquakes as independent events whereas they were likely clustered in time in order to explain the similar timing of coastal subsidence events found along the CSZ.

Table 1: Recurrence parameters for M 8.0-8.7 events

Magnitude	Recurrence (yr) for rupture under any site along coast, on average	Recurrence (yr) along entire CSZ	Probability of scenario
8.0	500	78	0.026
8.1	500	91	0.026
8.2	500	107	0.026
8.3	500	129	0.051
8.4	500	151	0.051
8.5	500	178	0.051
8.6	500	209	0.051
8.7	500	245	0.051

       A complete time-dependent model for the Cascadia subduction zone, including M 8.8-9.2 scenarios that rupture the entire CSZ as well as M8.0-8.7 scenarios that partially rupture the CSZ, is problematic and will require extensive future work. We adopt the following strategy. We first calculate the time-dependent probability only for the M 8.8-9.2 scenario, given the elapsed time since the last M9 earthquake in 1700 and a 500 year average recurrence time. Time-dependent probabilities were calculated for the M 8.8-9.2 scenario using a Brownian Passage Time recurrence distribution with an aperiodicity of 0.5 based on the published work of Petersen et al. (2004). This aperiodicity was determined by Petersen et al. (2004) directly from the dates of coastal subsidence events at Willapa Bay reported by Atwater and Hemphill-Haley (1997). The last large M 9.0 earthquake is thought to have occurred in January, 1700, or 307 years ago (Satake and others, 1996). A time-dependent probability of 14% for the next 50 years was calculated, somewhat higher than the 10% Poisson (time-independent) probability. We apply this 40% increase in the probability, relative to that of the time-independent model, to the M8.8-9.2 portion of the aleatory model of rupture variability. We use the time-independent probabilities for the M8.0-8.7 scenarios.

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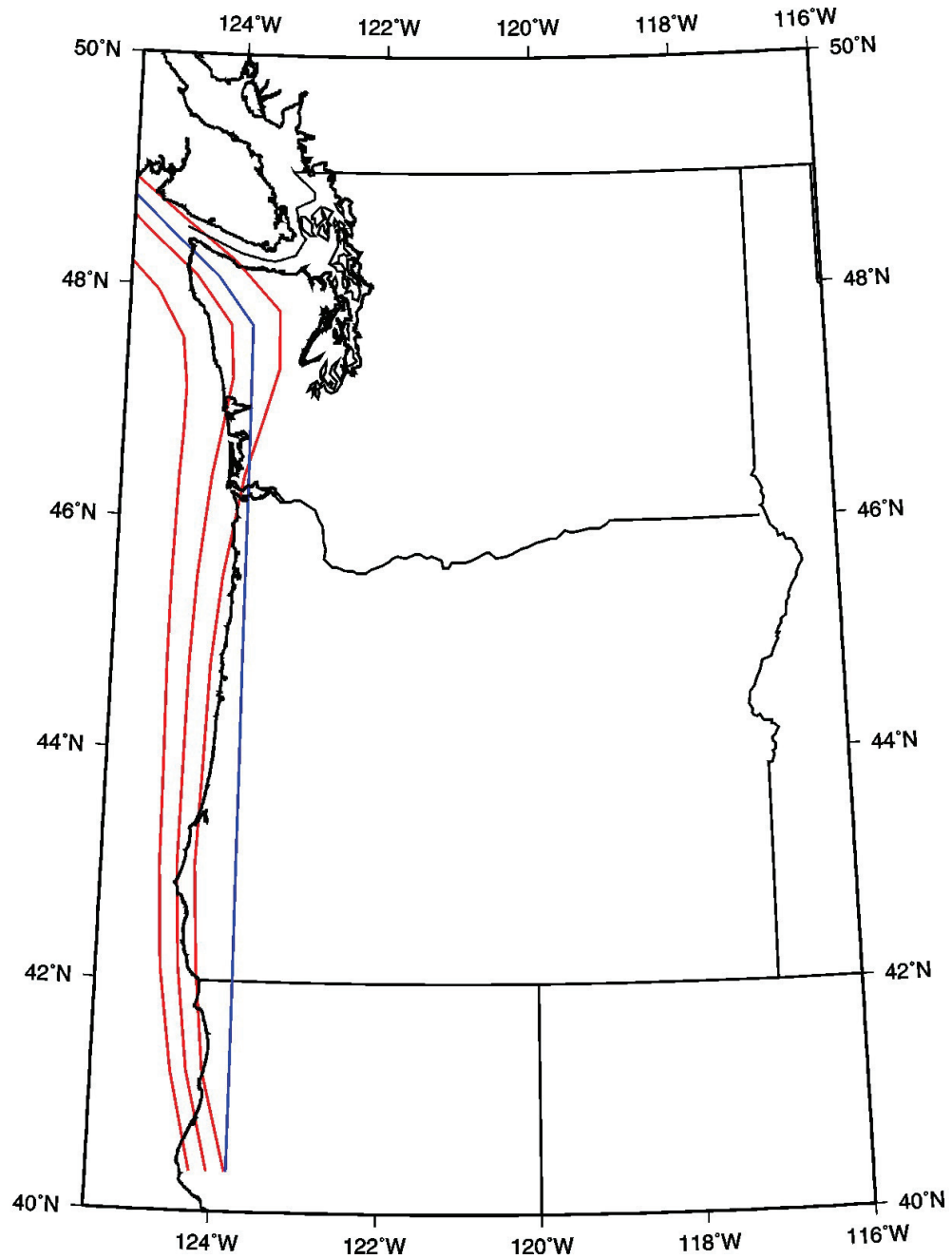
Figure 1. Location of the eastern edge of earthquake rupture zones on the Cascadia subduction zone for the various models used in this study. The red and blue lines show the base of the rupture sources. The red lines indicate (from the west) the base of the elastic zone, the midpoint of the transition zone, and the base of the transition zones. The blue line shows the base of the model that assumes ruptures extend down to about 30 km depth.