SEISMIC HAZARD RESULTING FROM AFTERSHOCK ACTIVITY FOLLOWING A CASCADIA SUBDUCTION EARTHQUAKE

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ABSTRACT:

Great (M>8.0) subduction interface earthquakes, or megathrust earthquakes, are typically followed by hundreds or even thousands of aftershocks, several of which may have magnitudes exceeding M7.0. While the seismic hazard resulting from a Cascadia megathrust earthquake is well recognized and discussed, little attention has been given to quantifying the subsequent aftershock activity and its potential impact on communities in the region. The probability of the next Cascadia megathrust earthquake occurring within the next 100 years is estimated to be 17 percent. Based on an analysis of recorded aftershock sequences at Cascadia-like subduction zones, this paper offers preliminary estimates of ground shaking probabilities resulting from Cascadia megathrust earthquake aftershocks for 22 communities in southwestern British Columbia, Canada and the Pacific Northwest, USA. Calculations estimate the likelihood of an aftershock exceeding each of three intensity levels (MMI V - widely felt; MMI VI - threshold for non-structural damage; and, MMI VII - threshold of structural damage). Results presented in this paper are intended to enable community officials and the general public to better understand the Cascadia earthquake threat and to encourage a more comprehensive discussion of the next great Cascadia megathrust event.

KEYWORDS: Aftershocks, subduction earthquakes, ground shaking probabilities, Cascadia

1. INTRODUCTION

Subduction zones are known to create the largest recorded earthquakes (greater than M8.0) around the world. These ‘megathrust’ earthquakes, are typically characterized by prolonged shaking (longer than three minutes), by generation of tsunamis, and by triggering of hundreds, even thousands, of aftershocks. In many cases, some of these aftershocks can exceed M7 and, depending on proximity to communities, these aftershocks can be more damaging than the main event. Consequently, megathrust aftershock sequences can be a significant and underestimated source of environmental, life, property and economic loss.

The 2004 Sumatra subduction interface earthquake (M9.0), for example, was followed by over 18,000 aftershocks within three months of the mainshock (Mishra et al., 2007a; Lay et al., 2005). Twenty-eight of those aftershocks were greater than Mw6.0, four were greater than Mw6.5, and one was greater than Mw7.0. Two of the event’s aftershocks were Mw7.5 and the persistent seismic activity was found to not only exacerbated losses, but to lead to heightened states of anxiety and panic in the affected area (Mishra et al, 2007b).

Understanding the impact of megathrust event aftershock sequences on communities is therefore important for a number of reasons. First, compared with other types of earthquakes, megathrust earthquakes generate a far greater number of aftershocks owing to the larger plate displacements along the rupture plane and throughout the subduction zone. Second, megathrust aftershock sequences can continue for months or even years after the main event, which is in stark contrast to the shallow crustal earthquake aftershock sequences that typically continue for days or weeks. Third, while the megathrust mainshock typically takes place off-shore, at depth, and some distance from communities, the area in which aftershocks occur can extend beyond the rupture zone (Mishra et al., 2007a) and closer to coastal communities. Fourth, community structures affected by megathrust aftershocks may already be compromised by the prolonged shaking associated with the mainshock. And fifth, mainshock response and recovery activities are likely to be hampered by on-going episodic shaking (Mishra et al, 2007b; CREW, 2005).

The intent of this paper, therefore, is to begin to quantify and present the likely impacts of Cascadia megathrust aftershocks on North American communities. To this end, the paper analyzes nine historical circum-Pacific megathrust earthquakes and their aftershock sequences to develop two likely Cascadia aftershock scenarios. These scenarios are then used to estimate the likelihood of one of three levels of ground shaking occurring in each of 22 communities. Results present the likelihood that each community will experience a) widely-felt shaking, b) non-structurally-damaging shaking, or c) structurally-damaging shaking from aftershock activity following a Cascadia megathrust earthquake.

2. CASCADIA SUBDUCTION ZONE

The Cascadia Subduction Zone (CSZ) is located along the western margin of the North America plate and extends some 1100 km from southwestern British Columbia, Canada to northern California, United States of America (Figure 1). This relatively young (less than 10Ma), warm subduction zone ranges between 40 and 150 km wide and is characterized by the oceanic Juan de Fuca plate moving eastward underneath the continental North America plate at a rate of approximately 40mm/year (Figure 1).

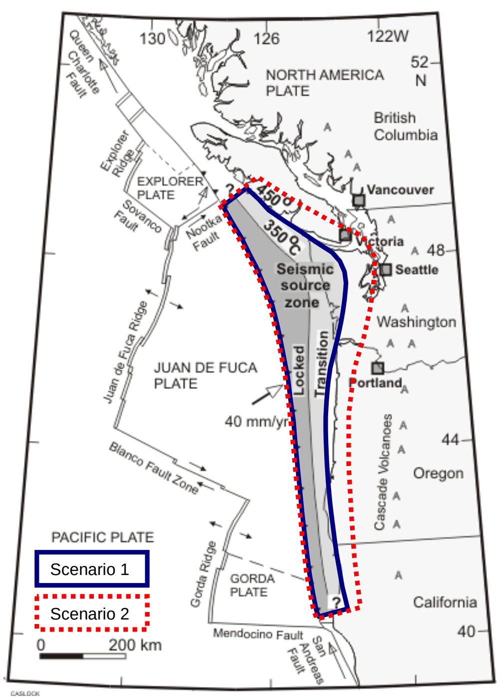

Figure 1. Tectonic setting of the Cascadia Subduction Zone (adapted from Flück et al, 1997) with two aftershock source zones indicated

The last Cascadia megathrust earthquake occurred on January 26, 1700. The event is estimated to be an Mw9 event and the entire length of the subduction fault is thought to have ruptured generating a tsunami that caused damage along the coast of Japan (Satake et al. 1996). Various lines of evidence indicate that these great Cascadia earthquakes occur repeatedly (Clague, 1997; Atwater et al., 1995) with an estimated return period of between 500-600 years (590 ± 105 - Adams and Weichert, 1994; 520 ± 330 years - Atwater and Hemphill-Haley, 1997). Onur and Seemann (2004) estimate of the probability of a Cascadia megathrust earthquake occurring within the next 10, 50, and 100 years to be 7.5%, 11%, and 17%, respectively.

3. METHODOLOGY

To estimate the activity rate of aftershocks following the next Cascadia megathrust event, a review of recorded megathrust events from relatively young, warm subduction zones was undertaken. Thirteen circum-pacific megathrust events with magnitudes equal or greater than Mw8.0 were identified and their aftershock sequences for a one-year period were collected for analysis (Table 1). In the case of the Sumatra events, aftershocks were separated into those associated with the December 2004 event and those associated with the March 2005 event, based on the rupture zones of the respective mainshocks.

Table 1. List of subduction interface earthquakes compiled in this study (G-R: Gutenberg-Richter).

Event Year	Event Name	Mainshock Magnitude (Mw)	Number of Aftershocks (Source)	Rupture Zone Area (km^2)	Completeness Magnitude (Mw)	G-R a-values	G-R b-values
1957	Andreanof	8.4	32 (NEIC)	210,000	--	--	--
1960	Chile	9.5	47 (NEIC)	322,000	--	--	--
1964	Alaska	9.2	962 (AEIC/NEIC)	225,000	5.0	7.7	1.1
1985	Mexico	8.1	31 (NEIC)	8,500	--	--	--
1985	Chile	8.0	259 (NEIC)	18,700	5.2	6.1	0.9
1986	Aleutians	8.0	442 (NEIC)	24,700	4.6	6.9	1.0
1995	Chile	8.0	196 (NEIC)	12,000	5.3	5.8	0.9
1995	Mexico	8.0	56 (NEIC)	12,000	--	--	--
2001	Peru	8.4	348 (NEIC)	32,000	4.7	6.4	0.9
2003	Hokkaido	8.3	293 (NEIC)	24,000	4.9	6.1	0.9
2004	Sumatra	9.0	3267 (NEIC)	385,000	5.2	8.0	1.1
2005	Sumatra	8.6	1841 (NEIC)	68,000	4.3	7.2	1.0
2007	Peru	8.0	156 (NEIC)	20,000	4.3	5.9	0.9
Cascadia Scenario 1		9.0	--	97,000	--	7.0	1.0
Cascadia Scenario 2		9.0	--	150,000	--	7.2	1.0

Of the 13 subduction events captured, four were excluded from the analysis due to limited aftershock records – 1957 Andreanof, 1960 Chile, 1985 Mexico, and 1995 Mexico. The remaining nine datasets were standardized by converting all aftershock magnitudes to moment magnitude (Utsu, 2002; Sipkin, 2003). As potential shallow aftershock activity in Cascadia is of most interest, the aftershock databases were further refined by considering only aftershocks above 40 km depth. No effort was made to identify and remove ambient steady-state seismicity from the aftershock dataset. Completeness analysis was conducted by creating magnitude-recurrence charts to determine at which magnitude rates began to drop off.

Given the minimum aftershock magnitudes in the cleaned datasets, Gutenberg-Richter (G-R) b-values were calculated for each aftershock sequence (Table 1) and found to range between 0.9 and 1.1. Our b-value observations agree with Shcherbakov et al. (2004), who note that aftershock sequences demonstrate good agreement with the G-R equation and have b-values that are not statistically different from the values for mainshocks. The mean b-value we use for Cascadia scenarios is 1.0.

The aftershock activity rates were standardized with respect to the rupture zone areas by calculating the activity rate per square kilometre for each subduction zone, and then multiplying the average activity rate/km^2 by the estimated Cascadia source areas (scenarios 1 and 2). Based on these magnitude-recurrence calculations, mean a-values of 7.0 (scenario 1) and 7.2 (scenario 2) (Table 1) were used as a proxy for estimating the activity rate of aftershocks following a future Cascadia megathrust earthquake. Figure 2 presents a sample magnitude-recurrence plot for one of the megathrust events studied, as well as a comparison plot for all megathrust events. In Figure 2a, the dark blue curve represents a maximum-likelihood fit to the data, while the orange curve represents a least-squares fit. Maximum-likelihood curves were used to obtain a- and b-values throughout the study. For illustration purposes, the magnitude-recurrence relations in Figure 2b are plotted for magnitudes between Mw4 and Mw7.

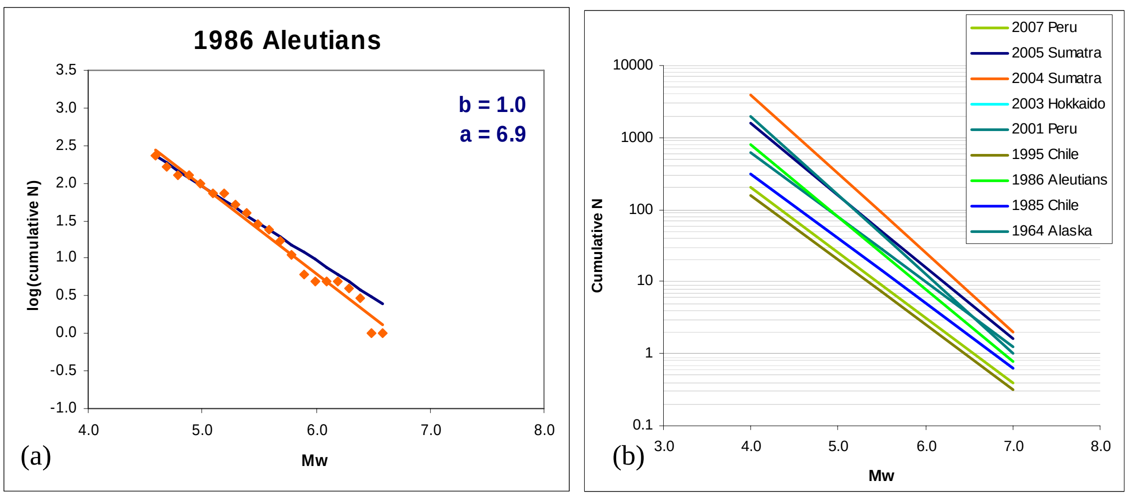

Figure 2. (a) Sample G-R magnitude recurrence plot; (b) Magnitude recurrence plots for study megathrust events.

In developing a G-R relationship for Cascadia, this study assumes that future Cascadia subduction events will reflect the characteristics of the last great event in 1700 (Satake et al., 1996). Accordingly, the entire length of the Cascadia subduction zone is anticipated to rupture with Mw9.0. We adopt a minimum aftershock magnitude of Mw4.0 for the hazard analysis since magnitudes lower than 4.0 are not likely to be significant in terms of generating widely-felt earthquake shaking. And we assume that the aftershocks will have a magnitude of less than Mw8.0, which is one magnitude unit less than the main shock. Hence we use a maximum aftershock magnitude of Mw7.9 in the hazard calculations.

With the mean subduction recurrence information calculated (as described above) and given the expected Cascadia event parameters, seismic hazard was calculated using conventional Probabilistic Seismic Hazard Analysis (PSHA) procedures. Aftershock occurrence was thus modeled as a Poissonian process over a one-year time-frame (i.e. the probability of one earthquake is independent of the time of previous events). While the Poisson distribution does not address decay in aftershock activity within the one-year period, it captures the average activity rate uniformly over a one-year period.

Two source zones were used to calculate probable Cascadia megathrust aftershock sequences. Both are based on Wang et al.'s (2003) revised Cascadia dislocation model. Cascadia Scenario 1 uses the estimated area of coseismic slip area, while Cascadia Scenario 2 uses the larger estimated effective transition area (Figure 1).

The ground motion attenuation relationships adopted are those currently used by the Geological Survey of Canada for shallow crustal earthquakes (Adams and Halchuk, 2003). These calculations assume homogeneous "firm ground" conditions as defined by an average shear wave velocity of 360 m/s to 750 m/s within the upper 30 m.

Annual rates of exceedance are calculated using EZ-Frisk (Risk Engineering, 1997) for the PGA values that correspond to MMI V, VI and VII (PGA of 0.067g, 0.13g, and 0.24g, respectively) in twenty-two selected communities (Table 2). The conversion between MMI and PGA is based on Wald et al. (1999) equation, and communities were selected based on population size, proximity to the subduction zone, and spatial distribution.

4. RESULTS AND DISCUSSION

Probabilities are presented in Table 2 for the likelihood of MMI V, MMI VI and MMI VII being exceeded in selected Canadian and American communities as a result of aftershocks occurring in the 12-months following a Cascadia megathrust earthquake. Two scenarios are offered to reflect two probable Cascadia megathrust aftershock source zone sizes. Results from both scenarios are presented in Figure 3 to illustrate the geographic distribution of the aftershock hazard along the western North American coast.

Given uncertainties in the calculations, including 1) spatial extent of aftershock activity, 2) a- and b-value estimations, 3) ground motion attenuation relations, and 4) PGA-MMI relationships, the relative rankings of the communities within each scenario are more important than small differences in the values between communities.

In both scenarios, coastal communities located closer to the rupture zone, such as Tofino, Port Renfrew, Long Beach, Newport, and Crescent City have the highest aftershock shaking probabilities. Each of these communities are certain to experience widely-felt aftershock-related ground shaking within one year of a Cascadia megathrust earthquake and are the most likely to experience non-structurally-damaging and structurally-damaging shaking. The Scenario 2 source zone, representing the effective Cascadia subduction transition zone significantly increases the probabilities of non-structural and/or structural damaging shaking occurring in several urban areas along eastern Vancouver Island, Puget Sound and the I5 corridor (e.g. Victoria, Seattle and Olympia).

It is important to note that the "probabilities of exceedance" provided here are not, and should not be mistaken for, probabilities of earthquake occurrence. Study results present probabilities of exceeding each of three specific levels of ground shaking at a given location within a one year period, assuming firm ground conditions. These probabilities therefore do not preclude a given location experiencing a given level of ground shaking more than once. Similarly, communities and structures built on soft, unconsolidated sediments (particularly beach, dune or deltaic sands) should expect their hazard probabilities to be higher the presented, while communities built on bedrock should expect their probabilities to be somewhat lower. The degree to which the probabilities vary with ground conditions will be the focus of future investigations.

Depending on the duration and strength of shaking resulting from the Cascadia megathrust mainshock, structures may be predisposed to failing at lower thresholds during aftershocks. Accordingly, shaking probabilities are likely to be higher than presented in areas that experience structural fatigue and damage from the initial mainshock.

Table 2. Probabilities of exceeding MMI V, VI, and VII in select communities over 12 months (assuming firm ground conditions). Values are rounded to the nearest whole number, and values less than 0.5% are represented by dashes.

Community	P[MMI ≥ V] (%)		P[MMI ≥ VI] (%)		P[MMI ≥ VII] (%)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Campbell River, BC	24	59	1	4	---	---
Nanaimo, BC	37	99	2	34	---	3
Tofino, BC	100	100	60	85	7	14
Port Renfrew, BC	99	100	37	87	3	16
Vancouver, BC	17	70	1	6	---	---
Victoria, BC	56	100	4	87	---	16
Abbotsford, BC	10	45	---	3	---	---
Forks, WA	100	100	87	89	17	18
Seattle, WA	24	93	1	16	---	1
Olympia,WA	53	100	3	72	---	11
Longview,WA	44	96	3	21	---	1
Oceanshores, WA	100	100	89	91	19	20
Long Beach, WA	100	100	80	92	15	22
Rockaway Beach,	99	100	38	92	3	24
Portland, OR	27	66	1	5	---	---
Salem, OR	37	81	2	9	---	---
Eugene, OR	33	68	2	6	---	---
Coos Bay, OR	100	100	44	90	4	19
Newport, OR	99	100	37	92	3	23
Medford, OR	20	39	1	2	---	---
Crescent City, CA	100	100	45	85	4	15
Eureka, CA	100	100	63	83	8	13

Source zone geometry and location are central to the estimation of shaking probabilities in this study. While we cannot attest to the likelihood of one scenario occurring over the other, we note that both scenarios adopt source zones that fall well within the current area of recorded strain and crustal deformation in the North America plate (Wang et al., 2003). Accordingly, Scenario 2 provides the more conservative results for planning preparedness activities intended to minimize life, property and economic losses in their respective jurisdictions.

5. CONCLUSIONS

The Cascadia subduction zone presents a significant seismic hazard to those living in southwestern British Columbia, western Washington and Oregon, and northwestern California; not only due to the pending Cascadia megathrust earthquake and ensuing tsunami, but also due to the hundreds of earthquakes certain to follow the mainshock.

This paper offers a first attempt to quantify and present the likely impacts of the next Cascadia aftershock sequence on communities in western North America. These aftershock shaking probabilities are large enough at each location to demand earthquake preparedness, response and recovery planning by the community members and local governments. Given, however, the magnitude, the duration and the geographic extent of these aftershocks and the long-term impacts they are likely to have on regional, national and international economies, these results appear significant enough to also demand comprehensive and coordinated disaster management at provincial/state, federal, and international levels.

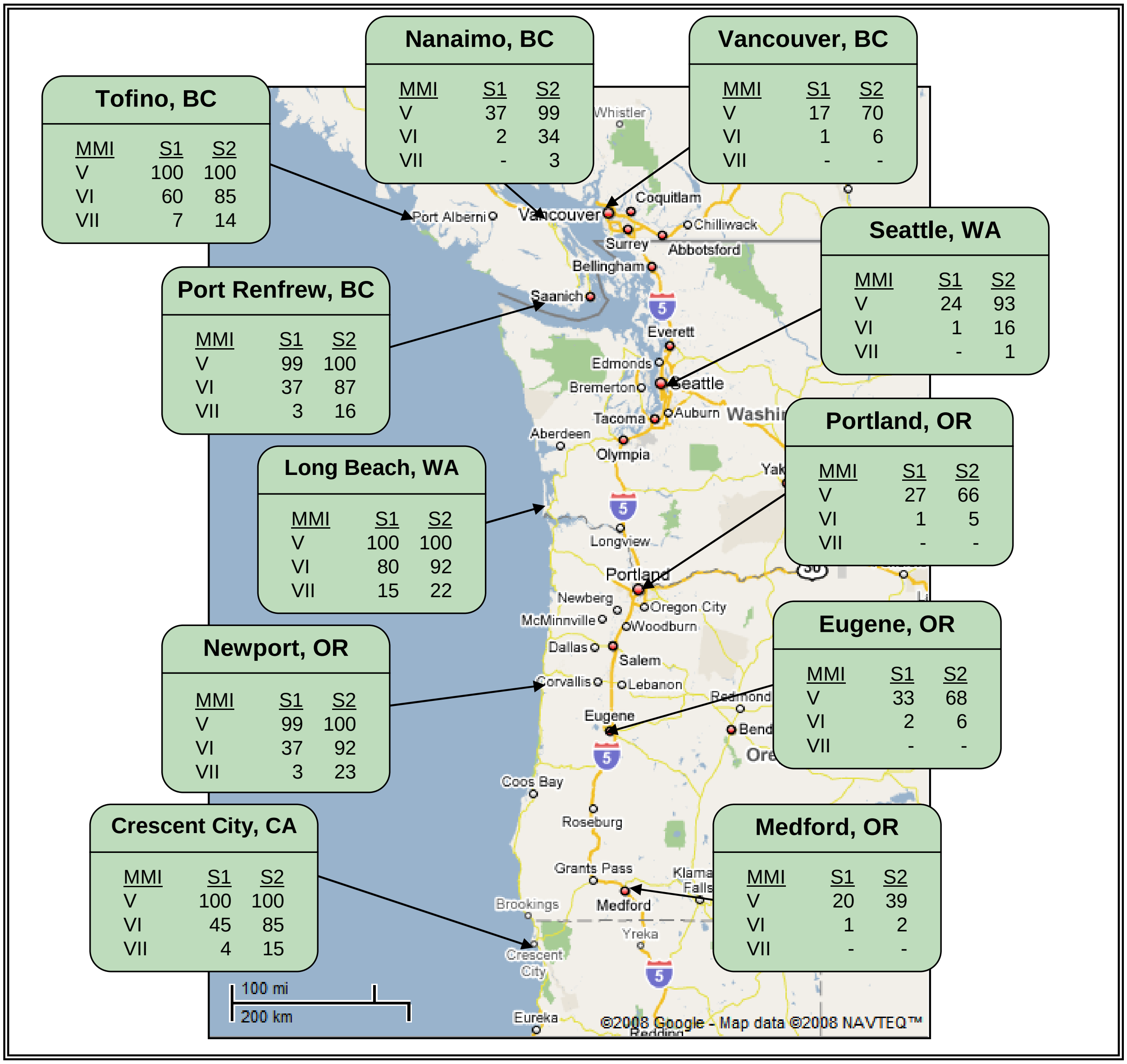

Figure 3. Earthquake shaking probabilities in a subset of communities due to aftershocks within 12 months of a Cascadia megathrust earthquake (assuming firm ground conditions)

Results are presented in simple, easy-to-understand terms, and the authors consciously avoid imposing any sort of hazard classification scheme with respect to the data (e.g. ‘low’, ‘medium’, or ‘high’ hazard). Accordingly, it is left to communities to determine their respective tolerances to the Cascadia megathrust aftershock hazard given two plausible scenarios.

REFERENCES

Adams, J. and Halchuk, S. (2003). Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada. Geological Survey of Canada Open File 4459. http://earthquakescanada.nrcan.gc.ca/hazard/OF4459/index_e.php.

Adams, J. and Weichert, D. (1994). Near-term probability of the future Cascadia megaquake. Proceedings of the Workshop on Paleoseismology, United States Geological Survey Open-File Report 94-568.

Atwater, B.F. and Hemphill-Haley, E. (1997). Recurrence intervals for great earthquakes of the past 3500 years at the northeastern Willapa Bay, Washington. United States Geological Survey Professional Paper 1576.

Atwater, B.F., Nelson, A.R., Clague, J.J., Carver, G.A., Yamaguchi, D.K., Bobrowsky, P.T., Bourgeois J., Darienzo, M.E., Grant, W.C., Hemphill-Haley, E., Kelsey, H.M., Jacoby, G.C., Nishenko, S.P., Palmer, S.P., Peterson, C.D., and Reinhart, M.A. (1995). Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone. *Earthquake Spectra*, 11:1, 1-18.

Clague, J.J. (1997). Evidence for large earthquakes at the Cascadia Subduction Zone. *Reviews of Geophysics*, **35:4,** 439-460.

CREW (Cascadia Region Earthquake Workgroup) (2005). Cascadia Subduction Zone Earthquakes: A magnitude 9.0 earthquake scenario." Oregon department of Geology and Mineral Industries Open File Report O-05-05.

Flück, P., Hyndman, R.D., and Wang, K. (1997). Three-dimensional dislocation model for great earthquakes of the Cascadia subduction zone. *Journal of Geophysical Research*, **102**, 20539-20550.

Lay, T., Kanamori, H., Ammon, C.J., Nettles, M., Ward, S.N., Aster, R.C., Beck, S.N., Bilek, S.L., Brudzinski, M.R., Buttler, R., Deshon, H.R., Edstrom, G., Satake, K., and Sipkin, S. (2005). The great Sumatra–Andaman earthquake of 26 December 2004. *Science*, **308**, 1127–1133.

Mishra, O.P., Kayal, J.R., Chakrabortty, G.K., Singh, O.P., and Ghosh, D. (2007a). Aftershock investigation in the Andaman-Nicobar Islands of India and its seismotectonic implications, *Bulletin of the Seismological Society of America*, **97**, S71-S85.

Mishra, O. P., Singh, O. P., Chakrabortty, G. K., Kayal, J. R. and Ghosh, D. (2007b). Aftershock Investigation in the Andaman-Nicobar Islands: An Antidote to Public Panic? *Seismological Research Letters* **78:6,** 591-600.

Onur, T., and Seemann, M. (2004). Probabilities of Significant Earthquake Shaking In Communities Across British Columbia: Implications For Emergency Management. Proceedings of the 13th World Conference in Earthquake Engineering, Vancouver, BC, Canada, Paper No. 1065.

Risk Engineering, Inc. (1997). EZ-Frisk™ (Version 4.0) User's Manual.

Satake, K., Shimazaki K., Tsuji, Y., and Ueda, K. (1996). Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami record of January 1700. *Nature*, **379**, 246-249.

Shcherbakov, R., Turcotte, D.L., and Rundle, J.B. (2004). A generalized Omori's law for earthquake aftershock decay. *Geophysical Research Letters*, **31**, L11613, doi:10.1029/2004GL019808.

Sipkin, S.A. (2003). A correction to body-wave magnitude mb based on moment magnitude Mw. *Seismological Research Letters* **74:6**, 739-742.

Utsu, T. (2002). Relationship between magnitude scales. In *International Handbook of Earthquake & Engineering Seismology Part A*, Eds. W. H. K. Lee, H. Kanamori, P.C.Jennings, and C. Kisslinger Academic Press, San Diego, 733-746.

Wald, D., Quitoriano, V., Heaton, T., Kanamori, H., Scrivner, C., and Worden, C. (1999). TriNet ShakeMaps: Rapid generation of peak ground motion and intensity maps for earthquakes in southern California. Earthquake Spectra, 15, 537-555.

Wang, K., Wells, R., Mazzotti, S., Hyndman, R., and Sagiya, T. (2003). A revised dislocation model of interseic deformation of the Cascadia subduction zone. *Journal of Geophysical Research*, **108:B1**, 2026, ETG 9-1 – 9-13.