PROBABILITIES OF SIGNIFICANT EARTHQUAKE SHAKING IN COMMUNITIES ACROSS CANADA

T. ONUR[1], M. SEEMANN[2], S. HALCHUK[3], and J. ADAMS[3]

[1] *Risk Management Solutions, Inc., Newark, CA, USA*
[2] *Department of Geography, University of Victoria, Victoria, BC, Canada.*
[3] *Geological Survey of Canada, Natural Resources Canada, Ottawa, ON, Canada*
E-mail: tuna.onur@rms.com

ABSTRACT:

Seismic hazard in Canada is well studied and extensively discussed within scientific and engineering communities. However, much of this information is presented in forums not readily accessible by those outside these communities, and in formats not easily understood by the "non-engineering" community. To address this, earthquake shaking probabilities were calculated for over 600 communities across Canada at each of three intensity levels (MMI V – widely-felt; MMI VI – threshold for non-structural damage; and, MMI VII – threshold of structural damage) and over 10, 50, and 100 year periods. This paper presents a subset of these calculations for 25 communities. While the dominant tectonic features affecting seismicity in western Canada are the Cascadia Subduction Zone and the Queen Charlotte Strike-Slip Fault Zone along the active western margin of the North America Plate, the most active seismic zone in eastern Canada is the Charlevoix-Kamouraska seismic zone of paleo-rift faults along the St. Lawrence River. Shaking probabilities for all earthquakes are based on the probabilistic seismic hazard models developed by the Geological Survey of Canada and adopted in the National Building Code of Canada. Results presented in this paper are intended to enable officials and the public to better identify and understand the earthquake threat in their communities. This information is offered to encourage and facilitate informed discussion on earthquake threat in Canada, and enable reasoned, defendable seismic funding decisions.

KEYWORDS: Crustal Earthquake, Subcrustal Earthquake, Ground Shaking Probabilities, Canadian Cities

1. INTRODUCTION

Seismic hazard is a fundamental input for a host of societal applications, from planning, design, and construction, to program development, policy formulation and fund allocation. It is typically calculated using the conventional probabilistic seismic hazard assessment (PSHA) procedures and expressed in terms of peak ground accelerations (PGA) or spectral accelerations (SA) at certain periods. PGA and SA values for Canada (Adams and Halchuk, 2003) are readily available for various probabilities and for any Canadian locality at: earthquakescanada.nrcan.gc.ca/hazard/interpolator/index_e.php. Although these values have extensive uses in the disciplines of earthquake engineering and engineering seismology, this expression of seismic hazard is not meaningful or readily applicable outside engineering or scientific communities. A community planner, emergency manager or elected official, for example, presented with "the PGA in this community is a quarter of the acceleration of gravity, with a 10% chance of being exceeded within a 50 year period" would find the information challenging to comprehend at best.

Seismic hazard varies considerably across Canada (Figure 1). In the seismic design codes the level of ground shaking is calculated for a given likelihood or probability level. This process can be reversed to calculate the likelihood of exceeding a certain level of ground shaking using the identical PSHA procedures and models. By inverting this process and presenting the likelihood of a damaging earthquake occurring within a given time frame, one provides the broader, "non-engineering" community with readily understandable and meaningful information upon which to act. Community decision-makers presented with "there is a 30% chance that a damaging level of ground shaking will occur in your community within the next 50 years" are more likely to understand, internalize, and apply this information. For individual Canadians, private-sector business owners, and public-sector decision-makers, such clear, easily comprehensible information is critical to effective decision-making in reducing life, property, and economic losses.

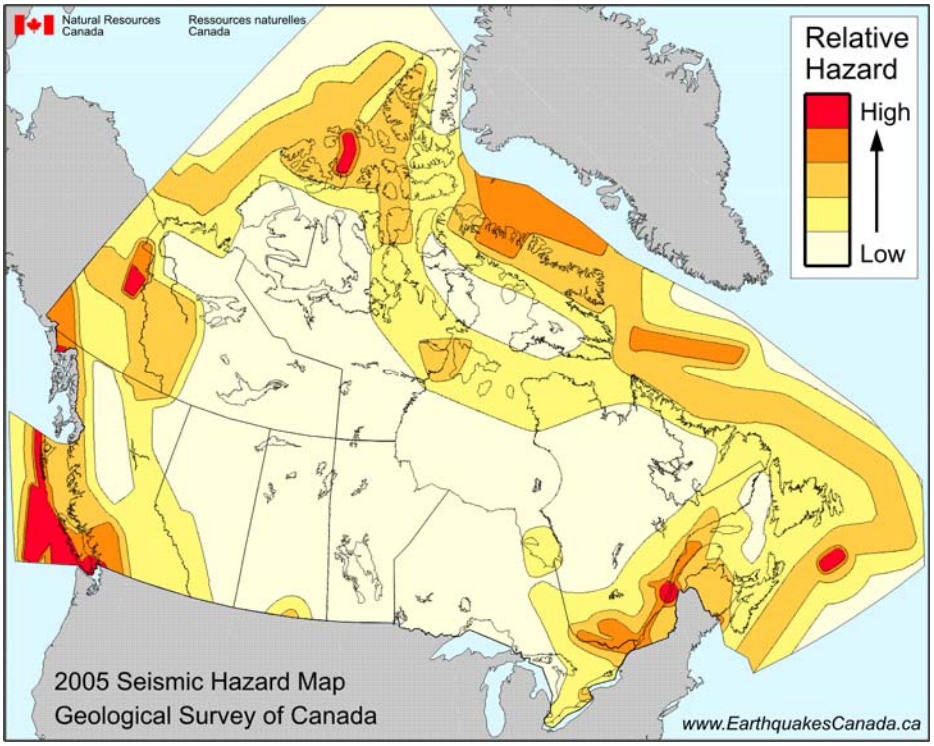

Figure 1. Relative Seismic Hazard in Canada

To date, there has been limited effort to calculate and convey seismic shaking probabilities in a manner meaningful to the layperson. Recent work in British Columbia (BC) calculated and presented simplified earthquake shaking probabilities for 10 communities in that province, as well as the probability of the next Cascadia Subduction Interface earthquake occurring in the next 10, 50, and 100 years – 7.5%, 11%, and 17%, respectively (Onur and Seemann, 2004).

Quantifying the earthquake hazard across Canada in similar, easy-to-understand terms and making the information available to Canadians is essential to ensuring that adequate earthquake preparedness, response and recovery activities take place. Recognising these needs, the methods used in estimating ground shaking probabilities in BC were extended to calculate ground shaking probabilities for over 600 communities across Canada. In this paper, the authors present a subset of probabilities for selected Canadian communities. The probabilities for the remaining Canadian communities will be presented in a future Geological Survey of Canada (GSC) Open File Report.

2. SEISMICITY AND TECTONICS IN CANADA

Located on the western half of the North America Plate, Canada exhibits both seismic and aseismic zones. Much of Canada's interior, east of the Cordillera, is nearly aseismic owing to the stability of the underlying craton, while distinct regions of increased seismic activity can be identified along the country's the west, east, and north coasts. The greatest seismic risk, however, occurs in both southwestern and southeastern Canada where the proximity of built-up urban areas increases life, property and economic exposures.

Western Canadian seismicity is largely associated with two major tectonic structures along the western margin of the North America plate - the Cascadia Subduction Zone (CSZ) in southwestern BC and, the Queen Charlotte Fault in western BC. At the CSZ the oceanic Juan de Fuca plate is being pushed eastward underneath the continental North America plate, creating three distinct types of earthquakes: shallow crustal events in the overriding North American Plate (without distinct alignments that might indicate the location of active faults (Rogers, 1998)); deep subcrustal/inslab events in the subducting Juan de Fuca Plate (at 50 km depth, but close to major urban areas); and very large magnitude (greater than M8.0) events at the interface of the two plates.

Cascadia subduction interface earthquakes are very large magnitude thrust events with an average return period of about 500-600 years (Adams, 1990; Atwater et al., 1995). The last such event occurred on January 26, 1700 and had an estimated magnitude of 9.0 (Satake et al., 1996). Our current paper does not address seismic hazard from the subduction interface earthquakes or their associated aftershocks. A discussion on the Cascadia subduction interface hazard can be found in Onur and Seemann (2004), and a discussion of the aftershock hazard following a Cascadia subduction interface event is presented in Seemann et al. (2008; this conference). The Queen Charlotte Fault, to the north of the Cascadia Subduction Zone is a right-lateral strike-slip fault that runs roughly parallel to the BC coastline, just west of the Queen Charlotte Islands. Although it has a high rate of activity and the potential to create large earthquakes (Canada's largest recorded earthquake was magnitude 8.1 on the Queen Charlotte Fault in 1949), it is distant from densely populated areas.

Central Canada is largely aseismic but seismicity increases significantly again across southern Quebec, the St. Lawrence and Ottawa river valleys (Adams and Basham, 1991), including Charlevoix-Kamouraska which exhibits eastern Canada's greatest onshore earthquake hazard. Five historical earthquakes in the Charlevoix-Kamouraska region were greater than magnitude 6.0, and given the region's proximity to sizeable communities, this source poses a significant risk.

3. METHODOLOGY: CALCULATING PROBABILITIES

The probabilities of exceeding certain levels of ground shaking were calculated using the conventional PSHA procedures for earthquakes across Canada. These procedures model earthquake occurrence as a Poissonian process, i.e. the probability of the next event is independent of the time of the previous event.

Calculations for these events are based on seismic source zones and recurrence relationships developed by the GSC (Adams and Halchuk, 2003) and adopted in the 2005 National Building Code of Canada (NBCC). Three probabilistic seismic source zone models developed by GSC are used, termed H, R and F. These models are based on the same catalogue of earthquakes, but represent different interpretations of the seismicity and tectonics. The ground motion attenuation relationships are those used by the GSC (Adams and Halchuk, 2003). The calculations are for "firm ground" as defined by an average shear wave velocity of 360 m/s to 750 m/s at the upper 30 m.

The two most common parameters for describing the strength of ground shaking are Modified Mercalli Intensity (MMI) scale and peak ground acceleration (PGA). MMI is a descriptive scale based on how severely the shaking was felt and how much damage certain types of structures suffered at a given location (Table 1). PGA is defined as the peak amplitude of a ground acceleration trace recorded at a site. Three levels of ground shaking intensity are determined to be of interest: MMI V represents a widely-felt event, MMI VI and MMI VII are considered the thresholds for non-structural damage and structural damage, respectively (Table 1).

Table 1. Description of selected MMI levels (adapted from Wood and Neumann, 1931)

MMI	DESCRIPTION OF EFFECTS
V	Felt indoors by practically all, outdoors by many or most. Buildings tremble throughout. Broken dishes, glassware to some extent. Hanging objects, doors swing generally. Pictures knocked against walls or swung out of place.
VI	Felt by all, indoors and outdoors. General excitement, some alarm. Damage slight in poorly built buildings. Fall of plaster, cracks in plaster and fine cracks in chimneys in some instances. Broken dishes, glassware in considerable quantity, as well as some windows. Overturned furniture in many instances.
VII	General alarm, all run outdoors. Some or many find it difficult to stand. Damage negligible in buildings of good design, slight to moderate in ordinary buildings and considerable in poorly built or badly designed buildings. Cracked chimneys to considerable extent and walls to some extent. Fall of plaster in considerable to large amounts. Dislodged brick and stone. Overturned heavy furniture.

Several empirical relationships are available to convert between PGA and MMI (e.g. Trifunac and Brady, 1975; Wald et al., 1999; Atkinson and Sonley, 2000 for western North America; Kaka and Atkinson, 2004 for eastern North America; Atkinson and Kaka, 2007 for central North America). The reason for different relations for east and west is that the ground motion frequency content varies across the continent. Atkinson and Kaka (2007) illustrate that even for their detrended residual data (their Figure 12) MMI in eastern North America is about 0.5 intensity unit higher than predicted from western North American data. Note that the scatter in the relationships is very large, with standard deviations of the order of 0.8 intensity unit (e.g. Figure 13 of Atkinson and Kaka, 2007).

In this study, we adopt the Wald et al. (1999) relationship (Eqn. 4.1; PGA in cm/s^2) for western Canada, and for consistency elect to apply it to eastern Canada as well. A more detailed discussion on this topic is presented in the discussion section.

$$MMI = 3.66 \log(PGA) - 1.66 \qquad (4.1)$$

Three levels of ground shaking were considered in this study, MMI V, MMI VI, and MMI VII (Table 1), which correspond to PGA values of 0.067g, 0.13g, and 0.24g, respectively (Eqn. 4.1). Annual rates of exceedances were calculated at each PGA value for 600 communities across the country, a subset of which is present below. The annual rates of exceedances are then converted to probabilities of being exceeded within 10-, 50-, and 100-year periods using the conventional Poisson-exponential probability model.

4. RESULTS

Estimates for MMI V, MMI VI and MMI VII being exceeded in 25 selected Canadian communities over 10-, 50-, and 100-year periods are presented in Table 2. The 50-year estimates are mapped in Figure 2 to display the distribution of earthquake hazard across the country. Given the uncertainty in the MMI-PGA relationships, the relative rankings of the communities is more important than small differences in the values between cities.

Table 2. Probabilities of exceeding MMI V, VI, and VII on firm ground in selected Canadian communities over 10-, 50-, and 100-year periods. Values are rounded to nearest whole number, and values less than 0.5% are represented by a dash.

Community	**P[MMI ≥ V] (%) in:**			**P[MMI ≥ VI] (%) in:**			**P[MMI ≥ VII] (%) in:**		
	10	**50**	**100**	**10**	**50**	**100**	**10**	**50**	**100**
Yellowknife, NT	—	2	3	—	1	1	—	—	—
Inuvik, NT	—	2	3	—	1	1	—	—	—
Whitehorse, YK	2	9	17	—	2	3	—	—	1
Sandspit, BC	28	81	96	6	28	48	1	4	9
Victoria, BC	35	88	99	15	56	80	5	21	38
Vancouver, BC	23	73	93	8	35	59	2	11	21
Kamloops, BC	2	11	21	1	3	5	—	—	1
Cranbrook, BC	2	11	20	1	2	5	—	—	1
Calgary, AB	1	3	7	—	1	2	—	—	—
Edmonton, AB	—	2	3	—	1	1	—	—	—
Regina, SK	—	2	3	—	1	1	—	—	—
Winnipeg, MB	—	2	3	—	1	1	—	—	—
Thunder Bay, ON	—	2	3	—	1	1	—	—	—
Windsor, ON	1	5	10	—	2	4	—	1	1
Sudbury, ON	1	4	7	—	1	2	—	—	1
Toronto, ON	3	14	26	1	5	9	—	1	2
Ottawa, ON	13	50	75	5	23	41	2	9	17
Montreal, QC	14	54	78	6	26	45	2	9	18
Quebec, QC	11	44	69	4	18	33	1	7	13
Riviere-du-Loup, QC	29	82	97	14	54	79	5	24	43
Fredericton, NB	4	21	37	2	8	15	1	3	6
Charlottetown, PE	1	3	7	—	1	2	—	—	1
Halifax, NS	2	9	17	1	3	5	—	1	1
St. John's, NF	1	5	9	—	1	3	—	—	1
Iqaluit, NU	—	2	3	—	1	1	—	—	—

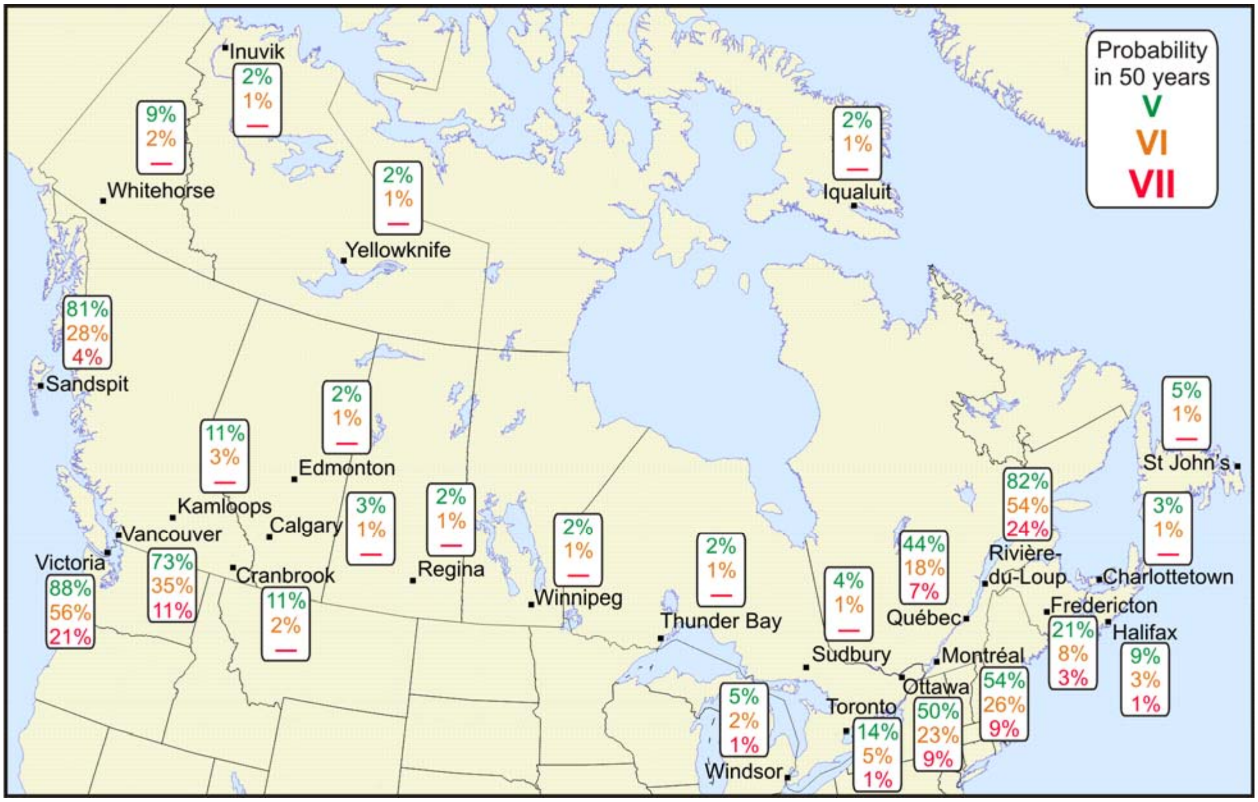

Figure 2. Distribution of earthquake shaking probabilities across Canada within a 50-year period (for firm ground and excluding Cascadia subduction earthquakes)

5. DISCUSSION

This paper conducts seismic hazard calculations for twenty-five communities across Canada and presents probabilities of exceeding each of three intensity levels, MMI V, MMI VI, and MMI VII, over 10, 50 and 100 year periods. Communities in southwestern BC (Vancouver and Victoria), on Queen Charlotte Islands (Sandspit), and Charlevoix region of Quebec (Riviere-du-Loup) have the highest earthquake shaking probabilities, higher than 70% for MMI V within 50 years. In some communities, such as Ottawa, Montreal, and Quebec City, structurally-damaging (MMI VII) shaking probabilities are less than 10% while widely-felt (MMI V) shaking probabilities are greater than 40%. In central Canada, and in eastern Canada away from the Ottawa-St Lawrence valleys, the probabilities of these levels of earthquake shaking are predominantly less than 10%.

The probability of one of Canada's three largest cities (Toronto, Montreal, and Vancouver) experiencing structurally-damaging earthquake shaking (MMI ≥ VII) in 50 years is significant. It is also interesting to note that the nation's capital, Ottawa (MMI VII = 9%), has a similar likelihood of experiencing structurally-damaging ground shaking as Vancouver (MMI VII = 11%) in 50 years, although the likelihood of widely-felt ground shaking is significantly greater in Vancouver.

In interpreting the results, it should be noted that the "probabilities of exceedance" calculated in this study are not probabilities of earthquake occurrence; rather they are probabilities of certain ground shaking intensities being exceeded at specific locations with uniform ground conditions, i.e. "firm ground". Therefore, these probabilities would be higher for softer ground. However, quantifying the effect of variations in ground conditions is beyond the scope of this paper. The exceedance probabilities are given for a certain time interval and are time-independent, i.e. passage of time will not affect those probabilities due to the Poissonian probability models used in the calculations.

Conversions between recorded ground motion amplitudes and MMI are central to this study, and we would have preferred to use Wald et al. (1999)'s PGV to MMI conversions as it is recognized that PGV is less susceptible to the different nature of ground motions across Canada. However, the attenuation relationships for western Canada used for NBCC do not include PGV. Similarly, although special relationships have been developed for eastern Canada (e.g. Kaka and Atkinson, 2004), these were available only for spectral accelerations and PGV, not for PGA. Therefore, for consistency in methodologies and parameters across the country, we chose to use the PGA to MMI conversion factors by Wald et al. (1999). We are exploring the option of an adjustment to the Wald et al. (1999) relationship for eastern Canada. We are also investigating ways to apply Kaka and Atkinson (2004) relationship in eastern Canada without compromising consistency with western Canada.

Finally, we would like to note that some probability values reported in this paper for western Canada may differ slightly from those published in Onur and Seemann (2004) due to differences in the software codes used to calculate seismic hazard and in the way H and R models were incorporated.

6. CONCLUSIONS

In parts of the country, particularly southwestern British Columbia and southern Quebec and Ontario, the earthquake shaking probabilities are high enough to demand comprehensive earthquake preparedness, response and recovery planning. This planning needs to take place individually and at all levels of governance - from local, to regional, provincial and federal governments. Accordingly, this study, estimating earthquake hazard in terms of 'probabilities' instead of 'ground accelerations', is intended to aid all decision-makers in our communities to better understand and plan for the earthquake hazard. For individuals, it is intended to encourage personal and family earthquake preparedness. Specific tips and advice on earthquake preparedness is available through Public Safety Canada (www.publicsafety.gc.ca). For elected officials, this study is intended to highlight the earthquake threat in their community and encourage appropriate funding to ensure adequate preparedness takes place. For municipal planners and emergency managers the results are intended to help highlight the earthquake risk within their jurisdiction relative to other hazards, and to encourage appropriate planning and mitigative activities to minimize life, property and economic losses.

Finally, while every effort was made to quantify and present Canada's earthquake hazard information in simple, easy-to-understand terms, the authors consciously did not impose any sort of hazard classification scheme upon the data (such as 'low', 'medium', or 'high' hazard). As a result, it is left to individuals and their communities to determine their respective tolerances to the earthquake hazard, risk and vulnerability in their area of responsibility.

REFERENCES

Adams, J. (1990). Paleoseismicity of the Cascadia subduction zone: Evidence from turbidites off the Oregon-Washington margin. *Tectonics,* **9**, 569-583.

Adams, J. and Basham, P.W. (1991). The seismicity and seismotectonics of eastern Canada. Chapter 14 Neotectonics of North America, *Decade of North American Geology* **DMV-1,** 261-276.

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.

Atkinson, G.M. and Kaka, S.I. (2007). Relationships between Felt Intensity and Instrumental Ground Motionin the Central United States and California. *Bulletin of the Seismological Society of America*, **97:2**, 497-510.

Atkinson, G.M. and Sonley, E. (2000). Empirical relationships between Modified Mercalli Intensity and response spectra. *Bulletin of the Seismological Society of America,* **90:2,** 537-544.

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.

Kaka, S.I., and Atkinson, G.M. (2004). Relationships between Instrumental Ground-Motion Parameters and Modified Mercalli Intensity in Eastern North America. *Bulletin of the Seismological Society of America*. **94:5**, 1728-1736.

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.

Rogers, G.C. (1998). Earthquakes and earthquake hazard in the Vancouver area. In Clague JJ, Luternauer JL, Mosher DC, Editors. Geology and natural hazards of the Fraser River delta, British Columbia. GSC Bulletin 525, 17-25.

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.

Seemann, M.R., Onur, T., and Cassidy, J.F. (2008). Seismic hazard resulting from aftershock activity following a Cascadia subduction earthquake. Proceedings of the 14th World Conference in Earthquake Engineering, Beijing, China.

Trifunac, M.D. and Brady, A.G. (1975). On the correlation of seismic intensity with peaks of recorded strong ground motion. *Bulletin of the Seismological Society of America*, **65:1,** 139-162.

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.

Wood, H.O. and Neumann, F. (1931). Modified Mercalli Intensity scale of 1931. *Bulletin of the Seismological Society of America*, **21,** 277-283.