



## PROBABILITIES OF SIGNIFICANT EARTHQUAKE SHAKING IN COMMUNITIES ACROSS BRITISH COLUMBIA: IMPLICATIONS FOR EMERGENCY MANAGEMENT

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### SUMMARY

Seismic hazard in the province of British Columbia (BC) is well studied and extensively discussed within scientific and engineering communities. However, much of the information is presented in a forum or format not readily accessible or digestible by those outside the scientific and engineering communities, including individuals, elected officials, municipal planners, and emergency managers. Seismic hazard calculations were carried out for over 150 BC communities in terms of probabilities of exceeding each of three intensity levels (MMI V - widely felt; MMI VI - threshold for non-structural damage; and, MMI VII - threshold of structural damage) over 10, 50 and 100 year periods. This paper presents a subset of these calculations for 10 communities. The dominant tectonic feature in southwestern BC, where most of the BC population is concentrated, is the Cascadia Subduction Zone. Here, the Juan de Fuca plate is being forced beneath the North America plate, creating three distinct types of earthquakes: shallow (crustal) earthquakes within the North America plate, deep (subcrustal) earthquakes within the Juan de Fuca plate, and “megathrust” earthquakes at the interface of the two plates. Calculations for all earthquakes except those at the Cascadia subduction interface are based on the probabilistic seismic hazard models developed by the Geological Survey of Canada and adopted in the National Building Code of Canada. The probabilities of “structurally” damaging ground shaking due to crustal or subcrustal earthquakes occurring within the next 50 years in the two largest cities of BC, Vancouver and Victoria, are 12% and 21%, respectively. The corresponding probabilities of “non-structurally” damaging ground shaking are 35% and 56%, respectively. The subduction interface earthquake is considered separately using a time-dependent recurrence model. The probability of the next Cascadia subduction interface earthquake occurring in the next 50 years is estimated to be 11%. The uncertainties associated with the probability estimations are discussed and quantified by providing upper and lower boundaries for selected calculations. Results presented in this paper are intended to enable individuals and community decision makers 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 BC, and enable reasoned, defensible funding decisions with respect to emergency preparedness, response, and recovery activities.

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## INTRODUCTION

Estimation of seismic hazard is often considered a fundamental input for seismic design. 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. Although PGA and SA are readily available for over 650 Canadian localities at two different probability levels, 10% and 2% chance of being exceeded in 50 years [1], and have extensive uses in the disciplines of earthquake engineering and engineering seismology, this expression of seismic hazard is not readily applicable or meaningful outside the engineering or scientific community. For example, an individual or elected official presented with “a PGA of 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.

In the seismic design codes the intensity 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 intensity of ground shaking using the identical PSHA procedures and models. By inverting this process and presenting likelihood of a damaging earthquake occurring within a given time frame, provides the non-engineering community with readily understandable and meaningful information upon which to act. In other words, an individual or elected official presented with “there is a 30% chance that a damaging level of ground shaking will occur in your community within a 50 year period” would find the information both simpler to understand and easier to apply. This is particularly relevant in the fields of emergency management and community planning, where clear, easily comprehensible information is critical to timely and effective decision-making [2].

The objective of emergency and disaster management is to minimize life, property and economic losses within communities. Like most jurisdictions, BC’s emergency management framework outlines a “bottom up” emergency management structure, in which, ultimately, each individual is responsible for his or her own safety (<http://www.pep.bc.ca>). In the event of an emergency, local government has a responsibility to provide aid to the greatest extent possible. In turn, should local governments become overwhelmed, the provincial government has a responsibility to provide and coordinate assistance, with national and international support if required.

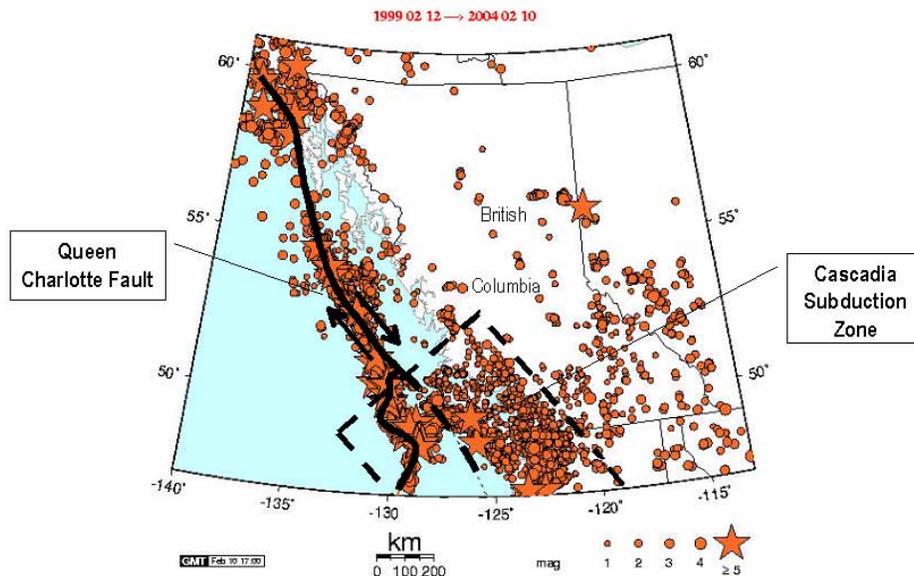
Recognising this emergency management structure in BC, it is therefore incumbent on individuals to be cognisant of the hazards they may be vulnerable to. Similarly, it is the responsibility of governments to provide new and emerging hazard information to individuals through easily accessible forums, in easily understandable formats, and in a timely manner.

Although the province of BC has the highest earthquake activity in Canada, there has not been a coordinated effort to calculate the likelihood or probability of certain levels of ground shaking intensity in BC communities. Quantifying the earthquake hazard in easy-to-understand terms and presenting the information to end-users outside the engineering community is essential to ensure that adequate earthquake preparedness, response and recovery planning takes place. Recognising these needs, the authors present simple expressions of seismic hazard for selected BC communities. Although this paper focuses on BC, the procedures adopted in this paper are universally applicable to all regions of seismic risk.

## SEISMICITY AND TECTONICS IN BRITISH COLUMBIA

The distribution of seismic activity in BC in the last 5 years is presented in Figure 1. Most of the earthquakes in BC are associated with two major tectonic structures, Cascadia Subduction Zone in southwestern BC and the Queen Charlotte Fault in western BC. The Cascadia Subduction Zone is discussed in detail in the following section due to its proximity to large urban centres as well as its

distinct tectonic and seismic characteristics. The Queen Charlotte Fault 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. The size and frequency of earthquake occurrence decreases considerably with distance from the Pacific coast and the active plate boundaries.



**Figure 1. Seismicity (last 5 years) and major tectonic features in BC (adapted from GSC website: <http://www.pgc.nrcan.gc.ca/seismo/recent/bc.5yr.html>)**

### **Cascadia Subduction Zone**

Subduction zones are known to create the largest magnitude earthquakes recorded around the world. At the Cascadia Subduction Zone (CSZ) plate boundary, the oceanic Juan de Fuca plate is being pushed underneath the continental North America plate (Figure 2). This tectonic setting creates three distinct types of earthquakes: deep (subcrustal) events in the subducting Juan de Fuca Plate (red circles in Figure 2); shallow (crustal) events in the overriding North American Plate (blue circles in Figure 2); and very large magnitude (greater than moment magnitude 8.0) events at the interface of the two plates.

Currently, there is a high amount of small crustal earthquake activity in southwestern BC (Figure 3). They are a mixture of strike-slip and thrust events and do not appear to have distinct alignments indicating locations of active faults [4].

There is a large concentration of subcrustal earthquake activity beneath the Georgia Strait and Puget Sound that affects major urban areas in the region (Figure 3). These earthquakes occur at a depth of about 50 km. Normal faulting predominates the subcrustal earthquake activity, however considerable variability is observed in the focal mechanisms of small earthquakes in Puget Sound [4].

Interplate earthquakes at the subduction interface are sometimes called “megathrust” earthquakes, and are very large magnitude thrust events with an average return period of about 500-600 years [5, 6]. The last megathrust earthquake at the Cascadia subduction interface occurred on January 26, 1700 and had an estimated magnitude of 9.0 [7].

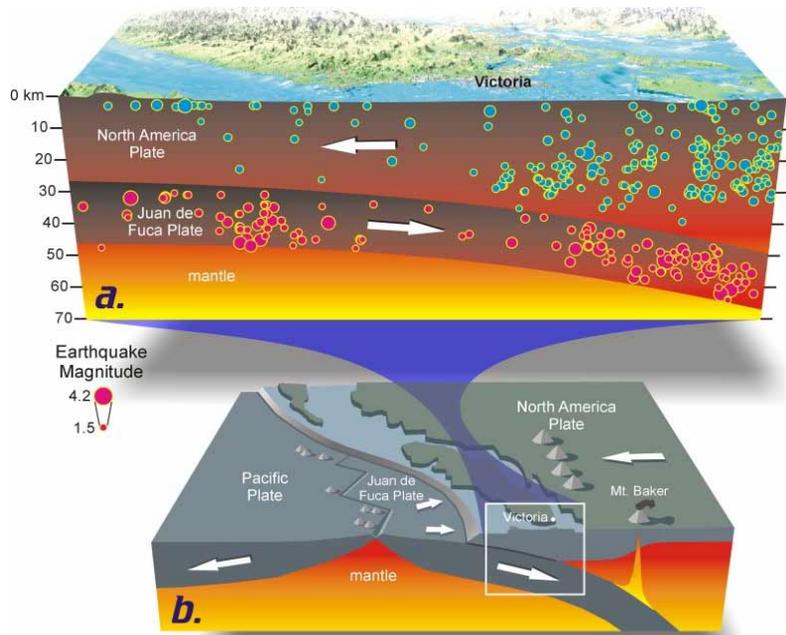


Figure 2. Cascadia Subduction Zone (after Yorath et al. [3])

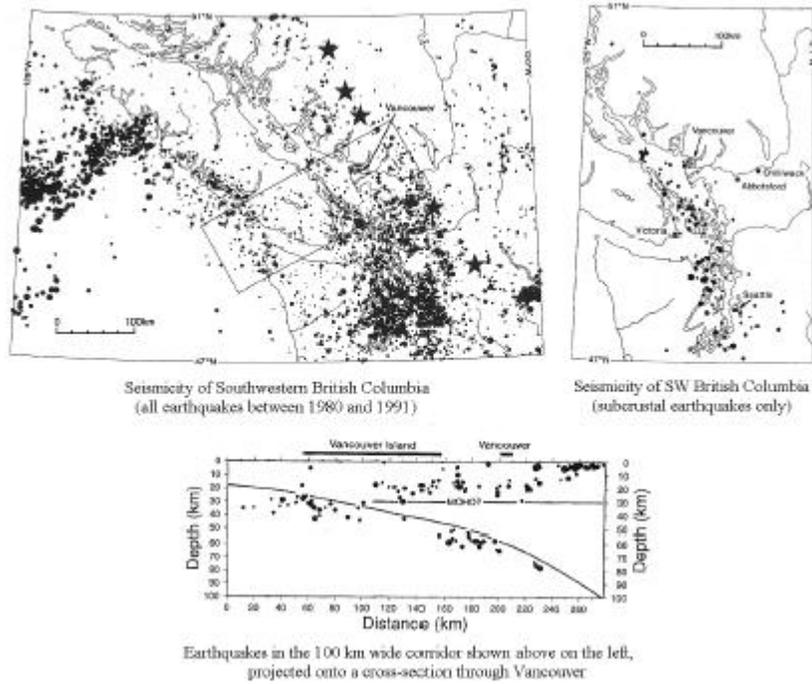


Figure 3. Crustal and subcrustal earthquake activity in southwestern BC (after Rogers [4])

## METHODOLOGY: CALCULATING PROBABILITIES

The probabilities of exceeding certain levels of ground shaking were calculated using the conventional PSHA procedures for all earthquakes except the megathrust earthquakes in the Cascadia subduction interface. Megathrust earthquakes are treated separately due to the following considerations:

- 1) Megathrust earthquakes have a relatively constrained location and magnitude. Accordingly, a distinct non-PSHA approach is required for the treatment of this type of earthquake. PSHA is designed to overcome the lack of detailed knowledge as to where and when a certain earthquake is going to occur, and how severe it will be. Hence it deals with clusters of earthquakes with a range of magnitudes instead of individual recurring events.
- 2) Megathrust earthquakes have a relatively long record of recurrence in Cascadia due to the characteristically large size of the events and the associated large-scale geologic disturbances. Chronostratigraphic evidence of these disturbances, such as correlated tsunami deposits, turbidity currents, vegetative changes, changes in tree rings, diatoms, and land- and sea-level changes, extend over a much larger area and further back in time than that caused by smaller earthquakes.

### Poissonian PSHA Models

Calculations for crustal and sub-crustal earthquakes in BC are based on seismic source zones and recurrence relationships developed by the Geological Survey of Canada, GSC [1] and adopted in the National Building Code of Canada (NBCC). Conventional PSHA procedures are used, which model earthquake occurrence as a Poissonian process, i.e. the probability of the next event is independent of the time of the previous event.

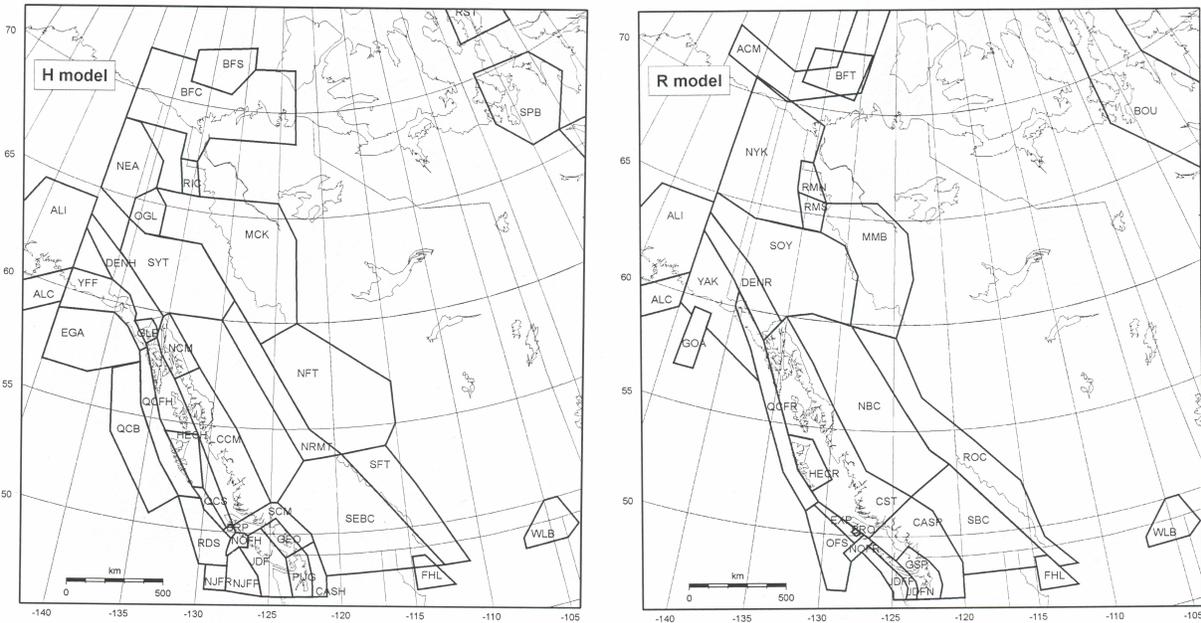
Three levels of ground shaking are determined to be of interest: MMI V represents a widely felt event, MMI VI and MMI VII are considered the thresholds for non-structural damage and structural damage, respectively (Table 1).

**Table 1. Description of selected MMI levels (adapted from [8])**

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.

Two probabilistic seismic source zone models developed by GSC [1] are used, H model and R model (Figure 4). These models are based on the same catalogue of earthquakes in western Canada up to 1991, and represent two different interpretations of the seismicity and tectonics in western Canada. The best, lower and upper estimates of the recurrence parameters of these two models are given in [1]. Shallow

earthquake depths (less than 10 km) are assigned to all earthquake source zones, except three in southwestern BC, GSP in R Model and GEO and PUG in H Model, which represent subcrustal earthquakes in the CSZ with an assigned depth of 50 km. The attenuation relationships used in the seismic hazard calculations are Boore et al. [9] for all shallow source zones and Youngs et al. [10] for the three deep zones in southwestern BC.



**Figure 4. Western Canada source zones: H Model and R Model (after Adams and Halchuk [1])**

### Time-dependent Models for “Megathrust” Earthquake Occurrence

Cascadia megathrust earthquakes are modelled as a single recurring event with relatively well-constrained magnitude and location. The last such event is known to have occurred on Jan 26, 1700 based on written records of a tsunami in Japan [8], which is consistent with other lines of evidence such as turbidity currents, tsunami deposits, vegetative changes, changes in tree rings, diatoms, and land- and sea-levels [5, 6, 11, 12, 13].

Although various lines of evidence reasonably agree on the year of the last event, current research does not accord the same level of agreement for earlier events. Two widely referred to studies indicate different mean return periods for earthquakes at the interface of the CSZ. According to Adams [5], based on turbidite deposits off the Oregon-Washington margin, the recurrence is fairly regular with a mean return period of  $590 \pm 170$  years, which was subsequently updated to  $590 \pm 105$  years [14]. Atwater and Hemphill-Haley [15], on the other hand, using evidence from land level changes (subsidence), abrupt changes in sea levels, and tsunami deposits, report large variations in the return periods. Their best estimates are 500-540 years for the average return period (mean = 520 years), 30-350 years for the shortest return period (mean=190 years) and 700-1300 years for the longest (mean=1000 years) return period.

Based on these figures, two recurrence estimates of  $590 \pm 105$  years, and  $520 \pm 330$  years are used in this study. In the second recurrence model, the shortest return period is used for determining the amount of variation instead of the longest, since there is a physical constraint on the shortest return period. In other words, a minimum amount of time has to pass to build enough strain to cause great earthquakes at the subduction interface.

For the treatment of Cascadia megathrust earthquakes, the Poisson probability distribution is abandoned, as this earthquake is a regularly recurring earthquake with a relatively well-constrained magnitude. In the Poisson model, regardless of when the last earthquake occurred, the probability of the next event is the same over time. However, according to the elastic rebound theory, elastic strain energy accumulates over a long period of time. Hence, the longer it has been since the last earthquake, the higher the probability of the next earthquake. Probability functions such as normal (Gaussian) and lognormal probability distributions have been proposed in the past to model such time-dependent conditional earthquake occurrence [16, 17]. In a comparative study, Jara and Rosenblueth [18] conclude that, out of four probability distributions they investigated, lognormal, gamma, inverse Gaussian, and Weibull, lognormal probability distribution performs best in modelling occurrence of subduction zone earthquakes. Brownian Passage Time (BPT) is another model used in describing the statistical distribution of earthquake occurrence, which yields values that are very similar to the lognormal probability distribution except near the end of the return period [19]. For the Cascadia Subduction Zone, Petersen et al. [20] have used and compared Brownian Passage Time (BPT) and lognormal density functions. They found that both models provide similar results through the middle of the recurrence interval. The results, however, are sensitive to “aperiodicity” or the coefficient of variation, which describes how regular or irregular the return period is and is equal to the ratio of the standard deviation to the mean of the return period.

In this study, the lognormal probability model was selected to represent the time-dependence of earthquake occurrence. It is a variation on the traditional normal (or Gaussian) probability distribution, such that instead of the random variable the logarithm of the random variable is normally distributed. It is computationally straightforward, has been tested for modelling earthquake recurrence in subduction zones, and appears to produce reasonably reliable estimates as discussed above.

## RESULTS AND UNCERTAINTIES

### Earthquake Shaking Intensities and Their Probabilities of Being Exceeded

The two most common parameters for describing the intensity 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 certain location (Table 1). PGA is defined as the peak amplitude of a ground acceleration trace recorded at a certain location. Several empirical relationships are available to convert one to the other, e.g. [21, 22, 23]. The Wald et al. [22] relationship (Equation 1) is used in this study (PGA in  $\text{cm/s}^2$ ). It was developed in relation with the ShakeMap project in California [22], and produces the most conservative results for the purposes of this study.

$$\text{MMI} = 3.66 \log(\text{PGA}) - 1.66 \quad (\text{Equation 1})$$

Three levels of ground shaking were considered in this study, MMI V, MMI VI, and MMI VII (Table 1), which correspond to PGA ranges of  $0.067\text{g} \pm 0.018\text{g}$ ,  $0.13\text{g} \pm 0.04\text{g}$ , and  $0.24\text{g} \pm 0.07\text{g}$ , respectively (Equation 1). The western Canada PSHA models described earlier are entered into the software EZ-FRisk V4.1 [24] to calculate annual rates of exceedances for each ground shaking level at several locations throughout BC. 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.

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 probability of a site experiencing damage is generally higher for structures on weaker soils. Quantifying the magnitude of this affect is beyond the scope of this paper.

“Best estimates” of probabilities of MMI V, VI and VII being exceeded in 10-, 50- and 100-year periods are calculated using the best estimates of the recurrence parameters [1] and mean values of the attenuation relationships. In order to investigate the sensitivity of the results to the parameters and models selected, “upper bound” and “lower bound” estimates are also calculated for two cities, Vancouver and Victoria for MMI VII. The PSHA parameters and models for which the uncertainties are investigated are:

- 1) **MMI-to-PGA conversion uncertainties (within a single relationship):** As mentioned earlier, there are several MMI-PGA conversion relationships, and the results may vary from one to the next. However, even within a single relationship, each MMI level (for example MMI VI) corresponds to a range of PGAs. In this study, Wald et al. [22] relationship was used and only the variations within this relationship were considered in the uncertainty investigations. The mean value of PGA is used for best estimates, while lower and upper limits of the range are used for the lower and upper bound estimations, respectively.
- 2) **Model (source zone boundary) uncertainties:** Two source zone models, H Model and R Model, are used in this study as described earlier. Calculations are carried out once using H model and once using R model. The mean of the two results is presented as best estimates, while lower and higher of the two represent lower and upper bound estimates, respectively.
- 3) **Recurrence uncertainties:** The recurrence parameters for each source zone are:  $\beta$  (ln10 times the Gutenberg-Richter b-value, which defines the exponential distribution of earthquakes),  $N$  at minimum magnitude (mean annual number of earthquakes larger than minimum magnitude, also called the “activity rate”), and maximum magnitude. Best estimates of these parameters [1] are used for the best estimates of the probabilities, while lower and upper estimates [1] are used for the limit values of the probabilities.
- 4) **Attenuation relationship uncertainties:** Uncertainties in the attenuation relationships constitute the highest amount of uncertainties in the overall estimations. Mean values are used for best estimate calculations. For the uncertainty estimations, initially Mean+1 Standard Deviation (SD) and Mean-1 SD values were used for lower and upper bound estimates, respectively. However, it was observed that when added to the rest of the uncertainties, they push the bounds to the possible limits of the results, i.e. the probabilities practically end up having a lower bound of 0% and an upper bound of 100%. Therefore, these uncertainties were removed from the overall uncertainty estimations.

As mentioned earlier, all calculations were carried out for the same “firm ground” conditions. Hence variations in geology or ground conditions were not included as part of the uncertainty investigations.

The resulting best, lower bound and upper bound estimates of the probabilities of MMI VII being exceeded in Vancouver and Victoria in 10-, 50-, and 100-year periods are given in Table 2. The best estimates are for Vancouver are 2.5% chance in 10 years, 12% in 50 years, and 22% in 100 years. The corresponding probabilities for Victoria are 4.5%, 21%, and 37%, respectively. The variation in values from lower to best and from best to upper estimates is high. The 10-year probabilities vary nearly four times, the 50-year values slightly more than three times, and the 100-year values about 2.5 to 3.5 times.

**Table 2. Probabilities of MMI  $\geq$  VII in Vancouver and Victoria in 10-, 50-, and 100-years with uncertainties (for firm ground)**

Community	Probability (%) of MMI $\geq$ VII in:								
	10 years			50 years			100 years		
	Lower	Best	Upper	Lower	Best	Upper	Lower	Best	Upper
Vancouver	0.60	<b>2.5</b>	9.6	3.0	<b>12</b>	40	5.8	<b>22</b>	64
Victoria	1.1	<b>4.5</b>	17	5.4	<b>21</b>	61	10	<b>37</b>	85

Best estimates of MMI V, MMI VI and MMI VII being exceeded in the rest of the selected BC communities in 10-, 50-, and 100-year periods are presented in Table 3. The 100-year best estimates are plotted in Figure 5 on a map of BC to display the distribution of earthquake hazard due to crustal and subcrustal earthquakes across the province. Communities in southwestern BC (Vancouver and Victoria are presented here), and on Queen Charlotte Islands (Sandspit is presented here) have the highest earthquake shaking probabilities. For example MMI V within a 100 years is practically a certainty in these communities. In some communities, such as Smith River in northern BC and Prince Rupert in western BC, structurally damaging earthquake shaking (MMI VII) probabilities are low (3.8% and 1.2%, respectively) while probabilities of widely felt shaking (MMI V) are high (67% and 59%, respectively). In the eastern and northeastern parts of the province the probabilities of all levels of earthquake shaking are low.

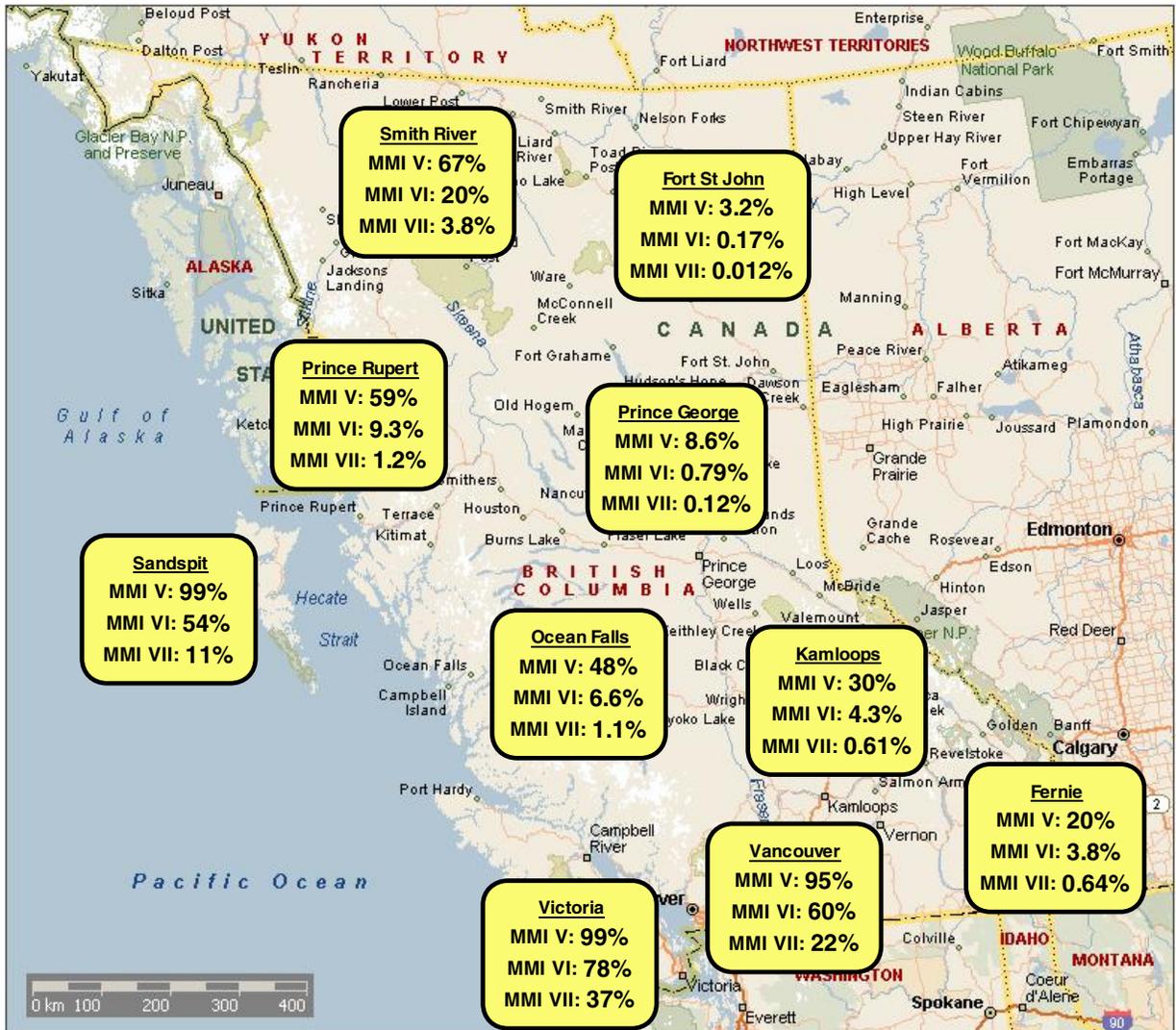


Figure 5. Distribution of earthquake shaking probabilities in BC within a 100-year period (for firm ground)

**Table 3. Probabilities of exceeding MMI V, VI, and VII on firm ground in 10, 50, and 100 years (selected communities)**

Community	P[MMI ≥ V] (%) in:			P[MMI ≥ VI] (%) in:			P[MMI ≥ VII] (%) in:		
	10 years	50 years	100 years	10 years	50 years	100 years	10 years	50 years	100 years
Vancouver	26	77	95	8.6	36	60	2.5	12	22
Victoria	35	88	99	14	53	78	4.5	21	37
Kamloops	3.5	16	30	0.44	2.2	4.3	0.061	0.31	0.61
Prince George	0.89	4.4	8.6	0.079	0.40	0.79	0.012	0.058	0.12
Fort St John	0.33	1.6	3.2	0.017	0.083	0.17	0.001	0.006	0.012
Prince Rupert	8.5	36	59	0.97	4.7	9.3	0.12	0.59	1.2
Fernie	2.2	11	20	0.39	1.9	3.8	0.064	0.32	0.64
Sandspit	35	88	99	7.4	32	54	1.2	5.7	11
Smith River	11	43	67	2.2	11	20	0.39	1.9	3.8
Ocean Falls	6.3	28	48	0.68	3.4	6.6	0.11	0.53	1.1

**Probability of the Next Cascadia Megathrust Earthquake**

The subduction interplate earthquake occurrence was treated differently. The time-dependence of interplate earthquake occurrence was modelled by lognormal probability distribution function using the mean and the standard deviation of the estimated return period as well as the date of the last event established from paleoseismic and geologic evidence.

- 1) *Model (probability distribution function) uncertainties:* The results are sensitive to the probability distribution function chosen to model the earthquake recurrence, such as lognormal, normal (Gaussian), and Brownian Passage Time. In this paper, lognormal and normal probability distribution functions are included in the uncertainty estimations since the Brownian Passage Time model produces results that are similar to those obtained from lognormal probability distribution as discussed earlier.
- 2) *Uncertainties in mean and standard deviation of the return period:* Different studies suggest different return periods for interplate earthquakes at the Cascadia Subduction Zone as discussed earlier. The two widely referred to estimates are  $590 \pm 105$  [14] and  $520 \pm 330$  years [15]. The former is used for lower bound, the latter for upper bound estimates.

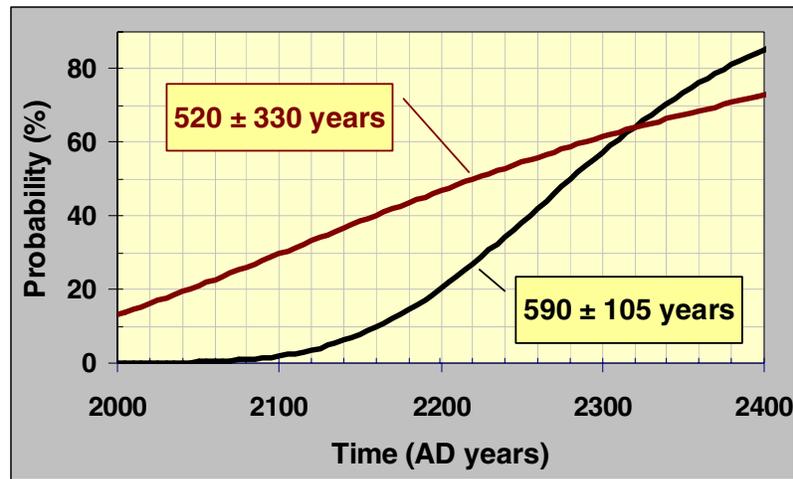
The resulting best, lower bound, and upper bound estimates of the probability of a Cascadia megathrust earthquake occurring within the next 10, 50, and 100 years are presented in Table 4.

**Table 4. Probabilities of a Cascadia megathrust earthquake within the next 10, 50, and 100 years**

Cascadia megathrust earthquake occurrence probability (%) within the next:								
10 years			50 years			100 years		
Lower	Best	Upper	Lower	Best	Upper	Lower	Best	Upper
0.034	7.5	15	0.31	11	22	2.3	17	31

Between the two sources of uncertainties, the second (i.e. the return period estimates) produces the largest variance. For the point we are at in the earthquake cycle, use of lognormal versus normal probability distributions causes less than 11% difference in the probabilities. The lower bound and upper bound values in Table 4 are from lognormal distribution since it provides lower values for  $590 \pm 105$  years

return period and higher for  $520 \pm 330$  years. Hence Table 4 provides a comparison of using  $590 \pm 105$  years versus  $520 \pm 330$  years for return period, lower bound values being the former and upper bound the latter. The same comparison is presented graphically in Figure 6.



**Figure 6. The effect of return periods on the probability estimations**

The difference between the two curves is significant, and reflects the difference in minimum return period estimates, i.e. 485 years (will not be reached until 180 years into the future, hence this recurrence estimate produces lower probabilities), and 190 years (already reached 115 years ago, hence this recurrence estimate produces higher probabilities). The steepness of the curve is determined by the variability, i.e. the higher the uncertainty ( $\pm 330$ ), the flatter the curve.

Recent research into episodic tremor and slip events suggests that the probability of a Cascadia megathrust earthquake may be elevated during periods of slip activity at the interface [25]. The implications on the megathrust earthquake probabilities are not addressed in this study.

## DISCUSSION AND CONCLUSIONS

This paper conducts seismic hazard calculations for ten BC communities and presents probabilities of exceeding each of three intensity levels, MMI V, MMI VI, and MMI VII, over 10, 50 and 100 year periods. In general, southwestern BC, including the largest city of the province, Vancouver, has the highest earthquake shaking probabilities. The best estimate of the probability of experiencing structurally damaging earthquake shaking ( $\text{MMI} \geq \text{VII}$ ) in Vancouver due to crustal and subcrustal events, within a 50-year period, is considerable (12%). In addition, the probability of a Cascadia “megathrust” earthquake occurring within the next 50 years is calculated using a time-dependent probability model and is estimated at 20%. The earthquake shaking probabilities for the remaining 140 BC communities are presented in a pending publication due later this year. Future research will consider combining these probabilities in a rational manner to provide a simpler picture of hazard in areas that are affected by all three types of earthquakes.

In interpreting the results, it should be noted that the “probabilities of exceedance” calculated for crustal and subcrustal earthquakes 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. The probabilities for the Cascadia “megathrust” earthquake, on the other hand, are conditional probabilities of a “megathrust” earthquake occurring in the next X number of years, given that the last one was in 1700. Therefore, these probabilities will change with time and will be different 15 years from now.

Furthermore, it is important to note that unlike the probabilities presented for crustal and subcrustal events, the probability of occurrence for the Cascadia megathrust event does not reflect likelihood of damage at any given location. This is due largely to our lack of understanding of the impacts of these large events. While the location of a megathrust earthquake is relatively well constrained and distant from major cities (e.g. 150 km from Vancouver), the large magnitude (8.0 or higher), long duration of shaking (1 to 5 minutes) and low frequency of shaking associated with this type of earthquake may cause more damage and higher MMI levels than would normally be expected from other types of earthquakes. For example, past subduction zone earthquakes in Alaska (1964, isoseismals available at USGS web site: [http://neic.usgs.gov/neis/eq\\_depot/usa/1964\\_03\\_28\\_iso.html](http://neic.usgs.gov/neis/eq_depot/usa/1964_03_28_iso.html)) and Mexico (1985, isoseismals available at UNAM web site: <http://www.ssn.unam.mx/SSN/Doc/Sismo85/sismo85-idx.htm>) caused MMI levels of VIII-IX up to 200 km from the epicenter.

In parts of the province, particularly southwestern British Columbia, the probabilities are high enough to demand comprehensive earthquake preparedness, response and recovery planning. This planning needs to take place at all levels of governance, beginning with individuals and extending through to local, regional, provincial and federal governments. Accordingly, this study, estimating earthquake hazard in terms of ‘probabilities’ instead of ‘ground accelerations’, is intended to help community emergency management both at the individual and community decision-maker levels. For individuals, it is intended to encourage personal and family earthquake preparedness. Specific tips and advice on earthquake preparedness is available through the Provincial Emergency Program ([www.pep.bc.ca](http://www.pep.bc.ca)) and through Public Safety and Emergency Preparedness Canada ([www.ocipep.gc.ca](http://www.ocipep.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 for earthquakes. 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 BC’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.

## **ACKNOWLEDGEMENTS**

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