



## Crossing the Border Again: Assessing the differences between Canada's 2015 and the United States' 2014 seismic hazard maps

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**ABSTRACT:** The Geological Survey of Canada's new suite of seismic hazard maps were prepared for the seismic design codes in the year 2015 edition of the National Building Code of Canada (NBCC). The United States Geological Survey (USGS) has released a similar set of maps in 2014 covering the conterminous United States for the National Earthquake Hazards Reduction Program (NEHRP). The 2015 NBCC maps now adopt a fully probabilistic model that provides mean hazard values consistent with the approach used by the USGS. This provides an improved basis for comparing the two national models. Correcting for differences in the reference site condition [class C ( $V_{s30} = 450$  m/s) in Canada and the B/C boundary (760 m/s) in the United States], there is general agreement in the pattern of hazard and relative hazard levels, as shown by comparing values between Canadian and appropriate U.S. cities and examining border-region maps. Hazard contours do not necessarily match, however, across the border. Differences in the definition of source zones, choice of ground motion prediction equations, and mode of incorporating Cascadia subduction earthquakes all contribute to these cross-border differences.

## 1. Introduction

In 2015 the Geological Survey of Canada (GSC) and in 2014 the United States Geological Survey (USGS) completed a new generation of seismic hazard maps. At the border, the two agencies have a common set of recorded historical seismicity, share an understanding of the seismotectonics, and agree on the probability levels and ground motion parameters to be mapped. Since the last comparison of the border hazard made by the GSC (Halchuk and Adams, 1999), changes to the implementation of the Canadian model improve the convergence with the USGS model. Both agencies have taken steps to develop an earthquake catalogue expressed in terms of moment magnitude ( $M_w$ ). Both agencies now provide mean hazard values (previously, the GSC provided median values), and both now include the Cascadia subduction zone as a probabilistic source (previously included by the GSC as a separate

deterministic source). While there is thus some overall similarity in how the seismic hazard models are constructed, the approaches differ in detail.

## **2. Models**

### **2.1. Methods**

The methods used by the GSC and the USGS have been well documented (e.g. Adams et al., 2015a, Adams et al., 2015b, Petersen et al., 2014). The GSC applies the traditional Cornell-McGuire (e.g. McGuire, 1993) method of delineating source zones based on historic seismicity and/or regional tectonics. Hazard is calculated with a customized version of the FRISK88 program (a proprietary product of Risk Engineering), which includes epistemic uncertainty. For southeastern Canada the GSC applied the Cornell-McGuire method to three alternative sets of sources, one historical, one geological, and the third a hybrid combination of the two. A revised version of the probabilistic stable craton “floor” model is incorporated directly into the model. The weighting of the GSC’s three alternative source sets will generate hazard that varies from the USGS model which is dominated by historical activity. For western Canada the GSC used a single source zone model incorporating both historical and geological inputs. The Cascadia subduction source is now included in the model as a probabilistic fault source, with separate sources for the Explorer and Winona faults.

The USGS employs spatially smoothed representations of historical seismicity for different magnitude events in combination with data from each known fault. Hazard is computed with a suite of software developed by Frankel et al. (1996), under the assumption that earthquake occurrence is Poissonian with time-independent probability. Probabilistic hazard is calculated without the use of subjective source zones by smoothing the seismicity rate. An adaptive weighting is used to ensure that the rate of earthquakes does not fall below the historic value, the final values maintain the hazard in the areas of historic seismicity, and to provide some additional hazard to low seismicity regions. The USGS considers a whole Cascadia source rupture (similar in philosophy to the GSC) but supplements this with partial ruptures involving different lengths of the southern portion of the subduction zone.

### **2.2. Ground Motion Prediction Equations**

The different physical properties of the crust in eastern and western North America, and different types of earthquakes, require the use of different ground motion prediction equations (GMPEs). The Canadian and US choices are outlined below, with the references being given in Atkinson and Adams (2013) and Petersen et al. (2014) respectively. In Canada, the GSC placed the transition from eastern to western attenuation just west of the eastern edge of the Canadian Rockies (near 113°W at the border). In the United States, the USGS placed the boundary along the eastern edge of the Basin and Range province (near 114°W), including the Rockies in the east.

Two different methods have been applied to the selection of GMPEs. The GSC favours the representative suite approach of Atkinson et al., (2014) while the USGS uses the weighting of multiple GMPEs selected from the literature. The representative suites of GMPEs were the best option for the current hazard calculation software used by the GSC and met the objective of describing the range of ground motion possibilities. Details of the representative suites chosen are given in Atkinson and Adams (2013) and tabulated as model inputs in Halchuk et al. (2014). For each representative suite, a weighting of 0.5 was applied to the best estimate, 0.2 to the lower branch, and 0.3 to the upper branch.

The USGS model for the central and eastern United States (CEUS) employs a suite of nine different ground motion prediction equations with two different weighting schemes, one for distances less than 500 km and one for distances between 500 and 1,000 km. Weights ranged from 0.06 to 0.3 for the different CEUS GMPEs. The five NGA-West2 GMPEs were used to model the crustal ground motions for the western United States (WUS). Weights varied from 0.12 to 0.22. Four GMPEs were applied to the subduction interface and to in-slab earthquakes.

Different source contribution distances are applied in the two countries. In eastern Canada, areal seismic source zones more than 600 km from the site are not allowed to contribute ground motions. In western Canada contributions come from areal sources within 400 km. No distance cut-off is applied to fault sources. In the CEUS, ground motions come from sources that are up to 1,000 km from the site, while in the WUS the maximum distance is 300 km.

### 2.3. Maximum magnitudes and magnitude recurrence

The GSC assigns maximum magnitudes and magnitude completeness years to individual source zones. Sources in the same region and/or with similar tectonic influences will have similar parameters. These parameters are used to determine recurrence rates for each source. Best, upper and lower alternative recurrence rates with weights of 0.68, 0.16, 0.16 are respectively applied. Maximum magnitudes for crustal sources in eastern Canada in the GSC model range from 6.8 to 8.0, versus 6.5 to 8.0 in the USGS eastern U.S. model. In the west, GSC crustal source maximum magnitude ranges from 6.9 to 7.7, and the USGS uses 7.45 and 7.95. Maximum magnitudes for the full Cascadia subduction source are comparable – the GSC uses 9.0 to 9.2, the USGS 8.8 to 9.3.

The assigned GSC completeness years are generally more conservative for the larger magnitudes important for seismic hazard than the corresponding years in the USGS model (Table 1). The shorter completeness intervals of the GSC for larger magnitudes would mean less data to base the recurrence rates on and would lead to more uncertainty in this parameter, thus increasing the final calculated mean hazard slightly. However, the more conservative years of the GSC reduce the chance that the early period is actually incomplete and that the true earthquake rate is actually higher than estimated. The GSC's maximum likelihood estimates (Weichert, 1980) of magnitude recurrence slopes (b-values) near the border range from 0.65 to 1.0 in the east (many sources with b fixed at 0.91), and 0.7 to 1.0 in the west. Two alternative b-values are applied to the Cascadia source (b = -1.52 and -2.17). The slopes had large negative values to fit the paleoseismic data and force the sharp drop off rates of earthquakes close to the maximum magnitude (Adams et al., 2015b).

**Table 1. Comparative completeness years and magnitudes. More conservative dates are given in red. Zone locations can be found in Petersen et al. (2014) and Halchuk et al. (2014)**

Iapetan Rifted Margin and Southern Great Lakes						
Zone	Mw	Year	Mw	Year	Mw	Year
USGS Zone 1	2.7	1970	3.7	1880	4.7	1800
GSC MNT	2.8	1963	3.8	1928	4.8	1880
GSC BSL	2.8	1963	3.8	1938	4.8	1900
Eastern Background and Offshore						
USGS Zone 7	2.7	1980	3.7	1920	4.7	1850
GSC SEB	2.8	1975	3.8	1963	4.8	1900
GSC ECMS	3.3	1964	4.8	1950	6.0	1930
Western Crustal						
USGS	4.0	1963	5.0	1930	6.0	1850
GSC SBC	3.3	1965	4.8	1940	5.8	1899
Western Deep Puget Sound						
USGS	4.0	1963	5.0	1940	—	—
GSC GTP	3.8	1956	4.8	1940	5.8	1899

The USGS generally uses broad regions to define catalogue completeness and determine recurrence rates. A b-value of 1.0 is applied in the CEUS, with the exception of the Charlevoix region, with a b-value of 0.9. In the west, the USGS crustal b-value is 0.8, deep events with a  $M_w$  less than 7.2 have a b-value of 0.4; greater than 7.2 have a b-value of 0.8. The Cascadia source has two branches with  $b=1$  and  $b=0$ .

### 3. Comparisons at the Canada-United States Border

In Table 2 we group selected Canadian and U.S. cities we consider to have similar seismic hazard. Where we believe that each agency's model is adequate, we provide both sets of results for  $S_a(0.2)$  and  $S_a(1.0)$  for a direct comparison. Site conditions used for the US calculations ( $V_{s30}=760$  m/s Site Class B/C) are slightly firmer than for Canada ( $V_{s30}=450$  m/s Site Class C). Therefore we have increased the USGS  $S_a(0.2)$  values by a factor of 1.176 and the  $S_a(1.0)$  values by 1.443 in order to match USGS results to those of the GSC, with the factors based on Atkinson and Adams (2013). The same factors were applied to the US values before we contoured Figures 1 - 3. Remembering that neither agency endorses the use of its hazard values beyond its border and that edge effects come into play near the bounds of each model, one can still see similarities and differences in the application of the two countries' methods to a common area of significant size.

In western North America there is a narrow band between 48°N and 50°N where the two models overlap and can be directly compared (Figure 1). There is reasonable agreement (within 20%) in the northern Puget Sound/southern Vancouver Island region, with GSC values lower at short periods and the same or slightly higher than the USGS at long periods. The probabilistic treatment of the Cascadia subduction source by the GSC has made the new model more congruous with the USGS. The short-period differences observed at Vancouver and Victoria are largely due to the chosen GMPEs, particularly the treatment of observed motions from the 2011 M9 Tohoku earthquake, as detailed in Atkinson and Adams (2013). Although Seattle lies outside the Canadian model, one can observe in the USGS results that the Seattle short period values are higher than the Canadian cities. This is due to the influence of the local Seattle crustal fault source.

Kelowna and Spokane are both mid-cordilleran cities and have comparable hazard levels (Table 2). There are significant differences between the two agencies' hazard estimates in this region. GSC hazard is, on average, half the USGS estimate. This is reflected in the Table 2 results for Kelowna. Differences in recurrence slopes (GSC b-value = 1.01, USGS b-value = 0.8), incremental seismicity rates, and the choice of GMPEs combine to generate these differences. Calgary, Billings and Denver have broadly similar seismotectonic environments along the edge of the Cordillera. While their hazard results cannot be compared directly, the GSC places Calgary midway between the two U.S. sites in terms of short period hazard, and at almost the same level for long-period hazard. In the central part of the continent, Winnipeg and Grand Forks are representative locations in the stable cratonic core. The two agencies' models produce similar low levels of hazard in this region.

In eastern North America the models overlap between 41°N and 50°N allowing for a more extensive region of direct comparison (Figures 2 and 3). In regions where significant historical events occurred with relatively low levels of modern activity, the GSC model produces higher hazard. Compare, for example, the hazard in Figure 2a) and 2b) at Temiscaming, Saguenay, and St Stephen. In regions where there is ongoing moderate activity (e.g. west Quebec, La Malbaie, and Miramichi), the USGS model produces higher hazard estimates.

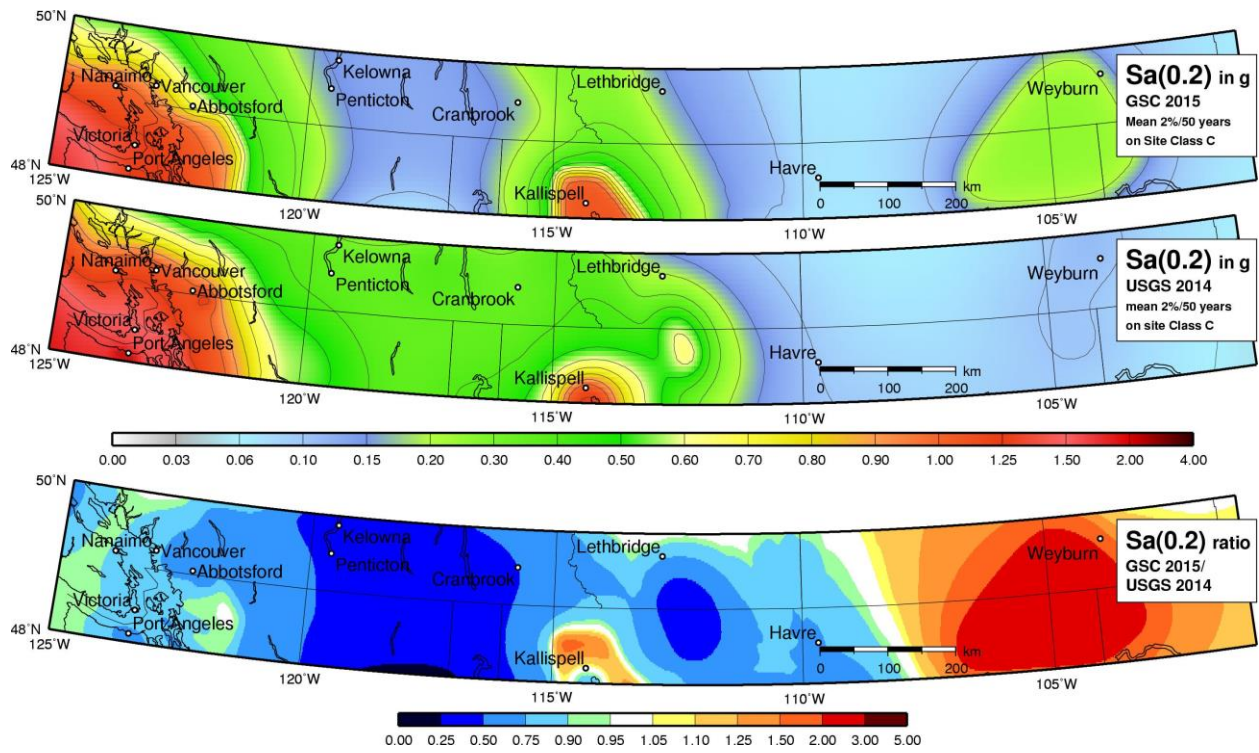
At Windsor and Detroit, the GSC's hazard is consistently lower, particularly at long periods, albeit at very low ground motion levels. The difference occurs because of the inclusion of the New Madrid seismic zone in the USGS model (the two cities fall within the 1000 km cut-off applied in the USGS model) but not the GSC model. In the southern Great Lakes region represented by Toronto, Cleveland, and Buffalo the short-period GSC values are almost a factor of 2 higher than the USGS values. This shows the effect of smoothed seismicity versus defined areal sources, and differences in recurrence slopes. The GSCs source zones allow earthquakes to occur much closer to these three localities than the USGS', where the earthquakes remain largely at their historical distances. The flatter magnitude recurrence slope of the GSC model zones ( $b=0.91$  along the south shore of Lake Erie and  $b=0.85$  in western Lake Ontario) in comparison to the USGS ( $b=1.0$  across the region) would also increase the hazard.

**Table 2 – Comparison of mean spectral accelerations (5% damped, 0.000404 annual exceedance probability, units in g) at selected Canadian and US cities for NBCC Soil Class C ( $V_{s30} = 450$  m/s).**

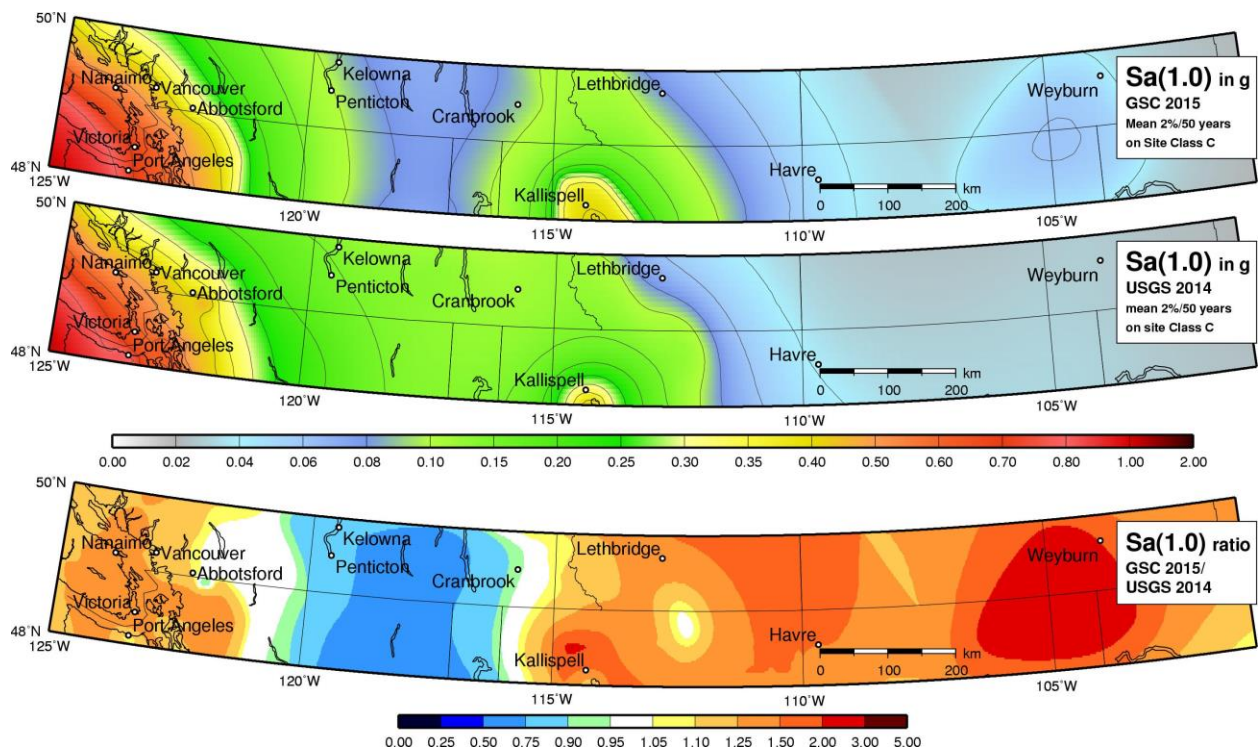
GSC values are given in red, USGS values in blue, ratios (where available) in black. USGS values have been adjusted to match Canadian site conditions. Values have been left blank for those locations that fall outside the extent of their neighbouring countries' hazard model. USGS values for Kelowna and Winnipeg are at the very edge of the U.S. model and may be less reliable.

Location	Lat. N	Lon. W	GSC Sa(0.2)	USGS Sa(0.2)	GSC/ USGS	GSC Sa(1.0)	USGS Sa(1.0)	GSC/ USGS
Vancouver, BC	49.25	123.12	0.85	1.1	0.78	0.42	0.42	1.0
Victoria, BC	48.43	123.37	1.3	1.5	0.85	0.68	0.62	1.1
Seattle, WA	47.60	122.30	-	1.8		-	0.60	
Kelowna, BC	49.88	119.48	0.14	0.33	0.44	0.091	0.14	0.65
Spokane, WA	47.70	117.40	-	0.36		-	0.14	
Calgary, AB	51.05	114.08	0.19	-		0.072	-	
Billings, MT	45.80	108.50		0.15			0.067	
Denver, CO	39.70	105.00		0.24			0.070	
Winnipeg, MB	49.89	97.15	0.054	0.043		0.016	0.017	
Grand Forks, ND	47.90	97.05	-	0.052		-	0.020	
Windsor, ON	42.30	83.02	0.096	0.12	0.81	0.035	0.056	0.63
Detroit, MI	42.35	83.05	0.094	0.12	0.81	0.035	0.056	0.62
Toronto, ON	43.65	79.38	0.25	0.14	1.8	0.063	0.049	1.3
Buffalo, NY	42.90	78.90	0.31	0.18	1.8	0.070	0.052	1.3
Cleveland, OH	41.50	81.70	0.33	0.16	2.1	0.063	0.059	1.0
Ottawa, ON	45.42	75.69	0.44	0.442	0.99	0.12	0.11	1.1
Montréal, QC	45.51	73.55	0.60	0.480	1.2	0.15	0.12	1.2
Plattsburgh, NY	44.70	73.45	0.49	0.51	0.96	0.13	0.12	1.1
Boston, MA	42.30	71.10	-	0.29		-	0.076	
Québec, QC	46.80	71.23	0.49	0.48	1.0	0.13	0.15	0.90
La-Malbaie, QC	47.65	70.15	1.7	2.0	0.87	0.45	0.54	0.84
Fredericton, NB	45.95	66.65	0.21	0.243	0.87	0.071	0.082	0.87
St. Stephen, NB	45.20	67.28	0.78	0.264	3.0	0.16	0.082	2.0
Portland, ME	43.70	70.30	0.20	0.325	0.63	0.069	0.087	0.79

a) Sa(0.2)



b) Sa(1.0)



**Figure 1 – Western GSC 2015 and USGS 2014 border region seismic hazard values for spectral acceleration at a) 0.2 and b) 1.0 seconds (units g). The triplet of maps for each parameter show the GSC results, USGS results, and ratio of GSC/USGS values.**

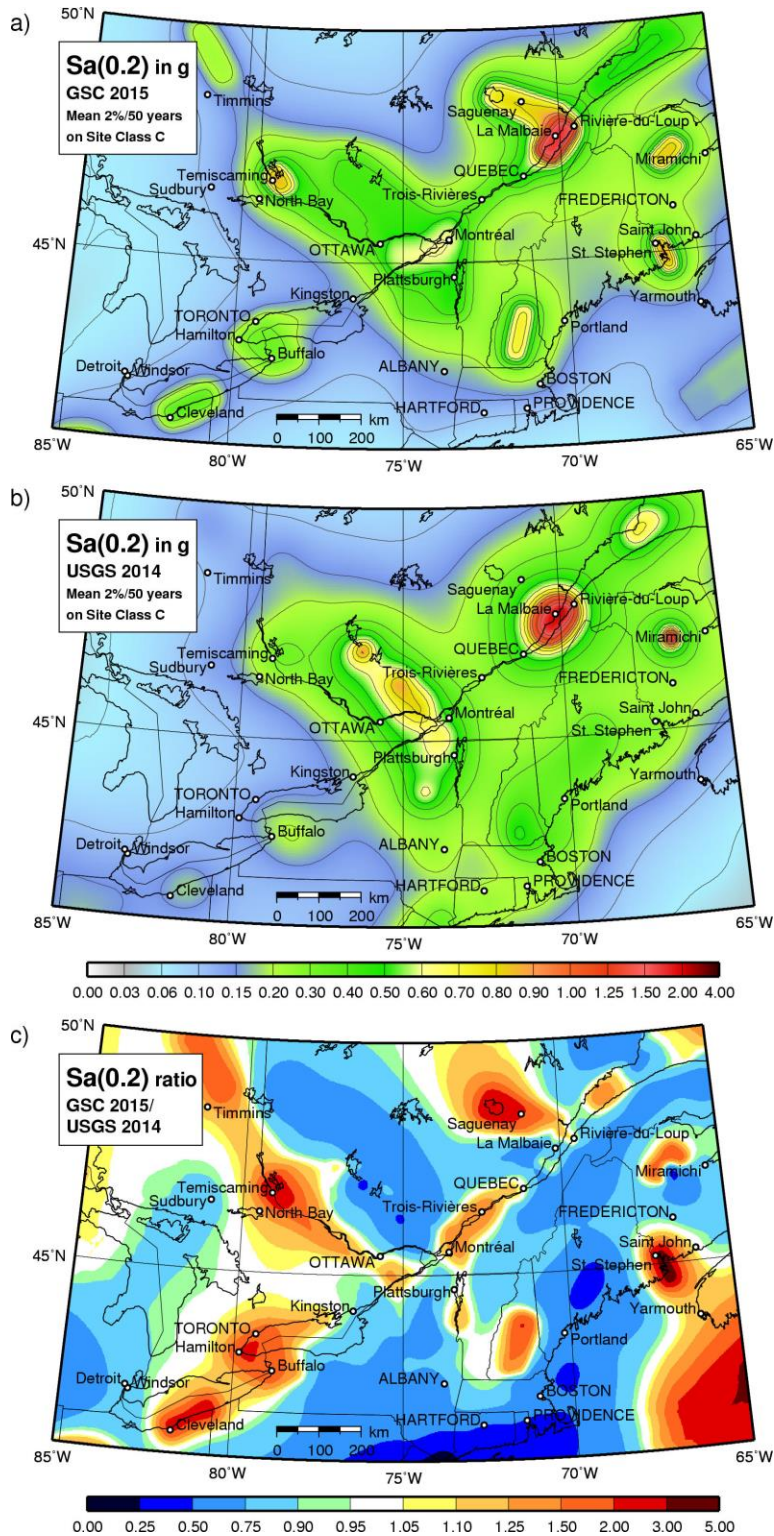


Figure 2 – Eastern GSC 2015 and USGS 2014 border region seismic hazard values for spectral acceleration at 0.2 seconds (units g). The maps show the a) GSC results, b) USGS results, and c) ratio of GSC/USGS values.

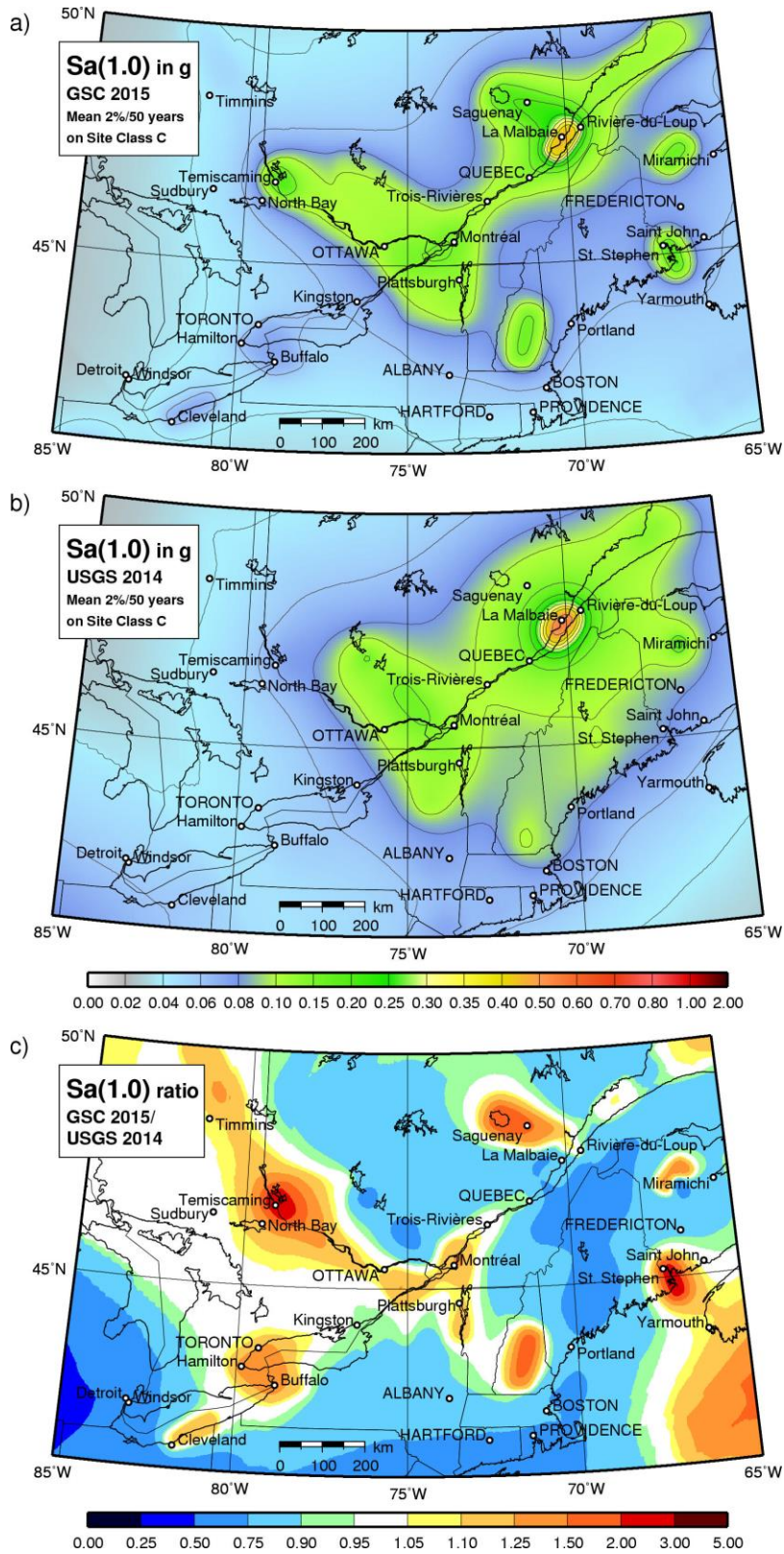


Figure 3 – Eastern GSC 2015 and USGS 2014 border region seismic hazard values for spectral acceleration at 1.0 seconds (units g). The maps show the a) GSC results, b) USGS results, and c) ratio of GSC/USGS values.



Ottawa, Montréal, and Plattsburgh show the similar hazard levels modelled for the west Quebec and northern Adirondack regions. The two models are in good agreement, although the GSC values for Montréal are slightly higher. The flatter magnitude recurrence slope in the GSC model is likely the main contributor to this difference. Boston is included here for comparison. The GSC would model hazard values based on Boston being close to a passive margin that could generate rare but large events like the 1929 “Grand Banks” M7.2 earthquake, whereas the USGS hazard values are based on the short historical record. Accounting for this tectonic feature may lead to higher estimates as suggested in Halchuk and Adams, (1999).

The hazard for Quebec City and La Malbaie is dominated by the Charlevoix seismic source in both models. There is good agreement in the GSC and USGS hazard values for Quebec City, which lies roughly 70 km from the edge of the active source. In contrast, in the centre of the Charlevoix source, the GSC’s values for La Malbaie are lower than the USGS values. The 2015 GSC model gives about 80% weight to the historical activity. In contrast, in 2014 the USGS implements a new repeated large magnitude earthquake (RLME) source to supplement their smoothed seismicity model for the Charlevoix zone. The RLME source is based on a rupture-frequency model taken from available historical and paleoseismic evidence.

The cities of Fredericton, NB and Portland, ME show generally comparable hazard in the northern Appalachians, though for both periods the GSC value is lower than that of the USGS. St Stephen, which lies between the two cities at the southern end of the New Brunswick/Maine border, shows a different pattern. GSC hazard values are twice those of the USGS for long period hazard and thrice for short-period hazard. The hazard from the Passamaquoddy Bay region, site of three historical magnitude 5.0 or larger events and ongoing low-level seismicity, is much lower in the USGS model.

#### **4. Discussion and Conclusions**

While many differences have been featured in this paper, it should be emphasized that the similarity in level and pattern across the Canada-US border is generally good. Despite the use of different methods and GMPEs, values for cities in similar tectonic environments (neglecting the specific exceptions discussed in the text) generally agree to within 25%. Given the similar (but not identical) earthquake catalogues and strong ground motion relations, this level of imprecision is not unexpected.

It is very difficult to assess whether the weighting within the logic trees has had a significant effect on the hazard because the logic trees themselves are so different. For example the USGS weights 3 branches based on the smoothed-seismicity rates of M3, M4 and M5 earthquakes. It does not have a branch for uniform seismicity, however, as used in the GSC’s source zones (alternatively, it can be considered to have many unspecified branches like that one, all with weight = 0). Therefore we conclude the difference is dominated by the different logic trees and not the relative weighting of seismicity rate models within either.

Understanding these differences will lead to closer harmonization in the methods used by the two agencies. Developing a consistent North American seismic hazard model would be of benefit to numerous communities, including the insurance industry (e.g. Thenhaus et al., 2015).

#### **5. Acknowledgements**

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