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Revised deaggregation of seismic hazard for selected Canadian cities

Halchuk, S; Adams, J; Anglin, F

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REVISED DEAGGREGATION OF SEISMIC HAZARD FOR SELECTED CANADIAN CITIES

S. Halchuk[1], J. Adams[1] and F. Anglin[1]

ABSTRACT

The Geological Survey of Canada's new seismic hazard model for Canada forms the basis for the seismic design provisions of the 2005 National Building Code of Canada (NBCC). We deaggregate the seismic hazard results for selected cities to help understand the relative contributions of the earthquake sources in terms of distance and magnitude. Deaggregation for a range of probabilities and spectral accelerations (Sa) from 0.2 to 2.0 seconds is performed to examine in detail the hazard for two of Canada's largest urban centres at high risk, Vancouver in the west and Montreal in the east. Additional plots and a summary table of deaggregated seismic hazard are provided for other selected Canadian cities, for Sa(0.2), Sa(1.0) and peak ground acceleration (PGA) at a probability of exceedence of 2%/50 years. In most cases, as the probability decreases, the hazard sources closer to the site dominate. Larger, more distant earthquakes contribute more significantly to hazard for longer periods than shorter periods. Deaggregation plots can provide useful information on the distance and magnitude of predominant sources, which can be used to generate scenario earthquakes and select corresponding time histories for seismic design.

Introduction

The Geological Survey of Canada has produced a new seismic hazard model and thence a suite of new seismic hazard maps for Canada. The final model and maps were issued in 2003 as GSC Open File 4459, (Adams and Halchuk 2003). The method and results given in Open File 4459 were the basis for the seismic design provisions that CANCEE (Canadian National Committee on Earthquake Engineering) recommended for the 2005 edition of the National Building Code of Canada (NBCC). Open File 4459 presented the hazard values used in the NBCC “Design Data for Selected Localities in Canada” table (NBCC 2005 table 2-1), as well as the full Uniform Hazard Spectra (UHS) for 23 cities, all computed for sites on firm soil at the 2% in 50 year probability of exceedence (0.000404 per annum). Additional background information is provided by Adams and Halchuk (2004).

This paper, in conjunction with Halchuk and Adams (2007), supplements those results and through deaggregation helps to explain the typical size and distance of earthquakes making the largest contributions to the seismic hazard for the 2%/50 year probability.

The process of deaggregation (McGuire 1995, Bazzurro and Cornell 1999, Harmsen 1999) has come to be an important tool for understanding seismic hazard. Allocating the total hazard into contributions based on distance and magnitude helps to close the gap between the thousands of earthquakes that go into the hazard models and the scenario design earthquake(s) required for engineering purposes.

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[1] Geological Survey of Canada, Natural Resources Canada, 7 Observatory Crescent, Ottawa, K1A 0Y3 Canada. Email: shalchuk@nrcan.gc.ca

Identifying the predominant sources of hazard will lead to better choices for the design earthquake's characteristics, including depth, azimuth and stress drop, as well as the better choice of time histories. Performing deaggregations at more than one period will help to determine if one source dominates at all periods and also clarify the need for one, or more than one, design earthquake.

Method

The seismic hazard results in Open File 4459 were generated by GSCFRISK, a customized version of the FRISK88 hazard code (FRISK88 is a proprietary software product of Risk Engineering Inc.). GSCFRISK and other new-generation codes allow for the explicit inclusion, for the first time for a national hazard map of Canada, of both aleatory (randomness) and epistemic (model or professional) uncertainty. GSCFRISK was used to generate hazard results for the five ground motion parameters implemented in NBCC2005, Sa(0.2), Sa(0.5), Sa(1.0), Sa(2.0) and PGA, where Sa(T) represents the 5% damped spectral acceleration for period T in seconds, and PGA is the peak horizontal ground acceleration.

The code of GSCFRISK was modified in order to extract the deaggregated seismic hazard. The modifications allowed for the deaggregation of the 4th Generation results, including the full epistemic uncertainty assigned to these models. The deaggregations are a more accurate representation of the contributions to the hazard than those in the 2004 paper by Halchuk and Adams, which used the EZ-FRISK program that did not allow for the incorporation of epistemic uncertainty.

The deaggregations determined by GSCFRISK do not show the relative contributions from various levels of epsilon (ε). Epsilon represents the contribution made to the hazard from ground motions different from the mean (ε = 1 indicates a contribution from the mean plus one standard deviation). In general, where both small and large earthquakes are contributing, the smallest earthquakes contribute at ε > 1 and the largest at ε < 1. Some representations are seen at the USGS website http://eqint.cr.usgs.gov/eq-men/html/deaggint2002-06.html. Typical outcomes like those are the reason why time histories with ε = 1 ground motions from the modal earthquake magnitude are recommended for dynamic analysis (G. Atkinson, personal communication 2006). There is some division of opinion on whether deaggregation in ε is useful; we do not provide it.

Differences between this paper's deaggregated hazard and standard NBCC hazard values

Slight differences exist between "standard" (values published in the 2005 National Building Code of Canada) and "deaggregated" hazard values determined for this paper using the GSCFRISK program. Differences in the computation parameters have generated final hazard values that can vary by 1-5% for the 23 cities determined for this paper. These differences are discussed below.

Standard hazard calculations are interpolated from a set of ground motion levels evenly spaced at approximately 1/8 logarithmic units. Deaggregated values are reached after one or more iterations until the difference between the last 2 iterations is less than 0.1%, or 12 iterations, whichever comes first.

Standard hazard calculations are done with 50 zone slices, deaggregations are done with 1000 zone slices of 1000. The slice parameter defines the number of integration slices for each contributing source zone. The finer slicing ensures that no biasing occurs and that a number of slices are used to determine the contributions in each magnitude distance bin. This is important especially for the **R** model zones that have a large areal extent. The extreme example for Canada is the **R** model, offshore eastern continental margin (ECM) zone, which is over 5500 km long. In the example in Figure 1a, a 2500-km-long zone with 50 slices would have slice widths of 50 km. Choosing a distance bin size of 20 km would mean that, depending on the distance of the site to the source, only every second or third distance bin would be sampled by the zone slices. The intermediate distance bins would register as "0" hazard contribution. Figure 1b shows the same source zone sampled with 1000 slices. Each slice width is now 2.5 km, ensuring that each 20-km distance bin has contributions from 9 or 10 slices. While this results in some overly-fine slices for smaller zones and adds to the overall calculation time, it was felt that 1000 slices were required for accurate deaggregations.

The differences in the values between the standard NBCC and deaggregated hazard are small. The NBCC values should be used for design computations but as the shapes and values of the deaggregated contributions given in this paper will be virtually identical to a deaggregation of the NBCC hazard value, the results can be used for the choice of time histories, scenario earthquakes, etcetera.

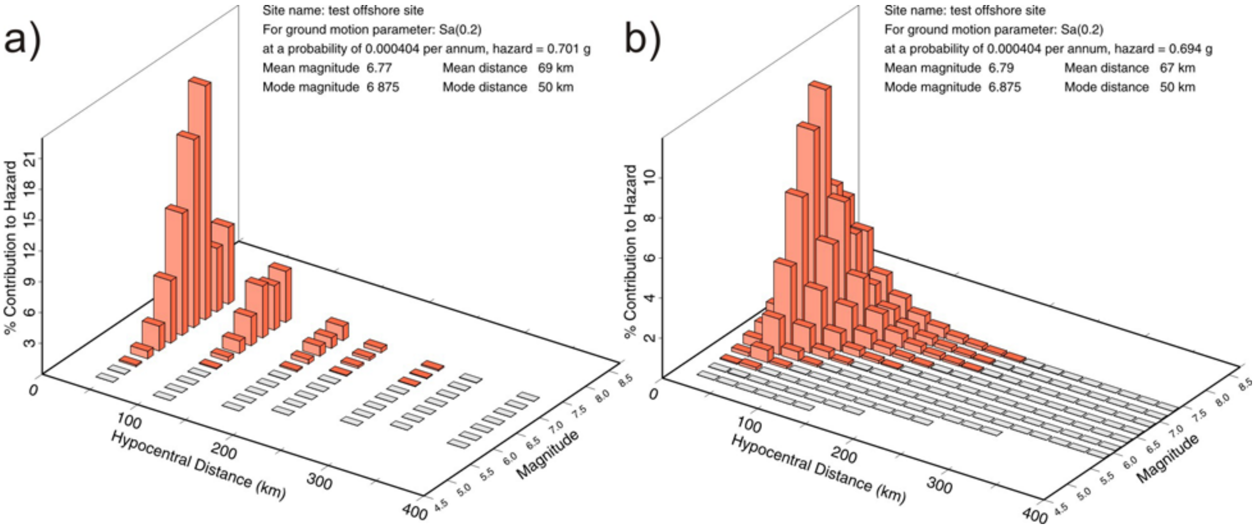

Figure 1. Aliasing occurs when the number of zone slices is too small to properly sample each distance bin. Compare a 2500-km long zone with a) 50 slices and b) 1000 slices. Although the resulting hazard is very similar, the low number of slices in the first example means that there is a zero hazard contribution from some bins.

Layout of the deaggregation plots

The modified version of GSCFRISK now deaggregates the hazard and also generates the output postscript plots directly. A particular enhancement is the box in the upper right portion of Fig. 2 showing numerical per mil (i.e., part per thousand, or 1/10th percent) contributions. These help quantify the visual information on the bar plots, and reveal hazard contributions that may be hidden behind taller bars. Additionally, the total sum of the contributions from each magnitude and distance class are tabulated (see numbers in blue on Fig. 2). An example for the 2%/50 year PGA is given for Montreal in Fig. 2. Due to page constraints, the enhanced deaggregation plots are not shown in the rest of the paper, but will appear in Halchuk and Adams (2007).

The magnitudes on these plots are m_N for eastern Canada and M_L (roughly equivalent to M_w) for western Canada. The bar graphs give a visual impression of the contribution from each magnitude-distance bin, red bars indicate the contribution is more than 1/10 of a percent, light grey bars less than 1/10 of a percent. The tabulated values on each figure give: the amplitude (which may differ from the NBCC 2005 value, see discussion above); the probability level (0.000404 or 2%/50 years,); the mean magnitude and distance; the modal magnitude and distance (note these are the values for the mid-point of the fullest bin and so are quantized by the bin increments).

Halchuk and Adams (2004) used 25 km distance and 0.5 magnitude bins, as did the USGS (e.g., Harmsen 1999), but we found that distance increments of 20 km (out to 750 km) and magnitude increments of 0.25 magnitude units were preferable. Where more than 95% of the total hazard occurred within 400 km of the site, (as is the case for most of the cities) we reduced the distance axis of the final plots to 400 km.

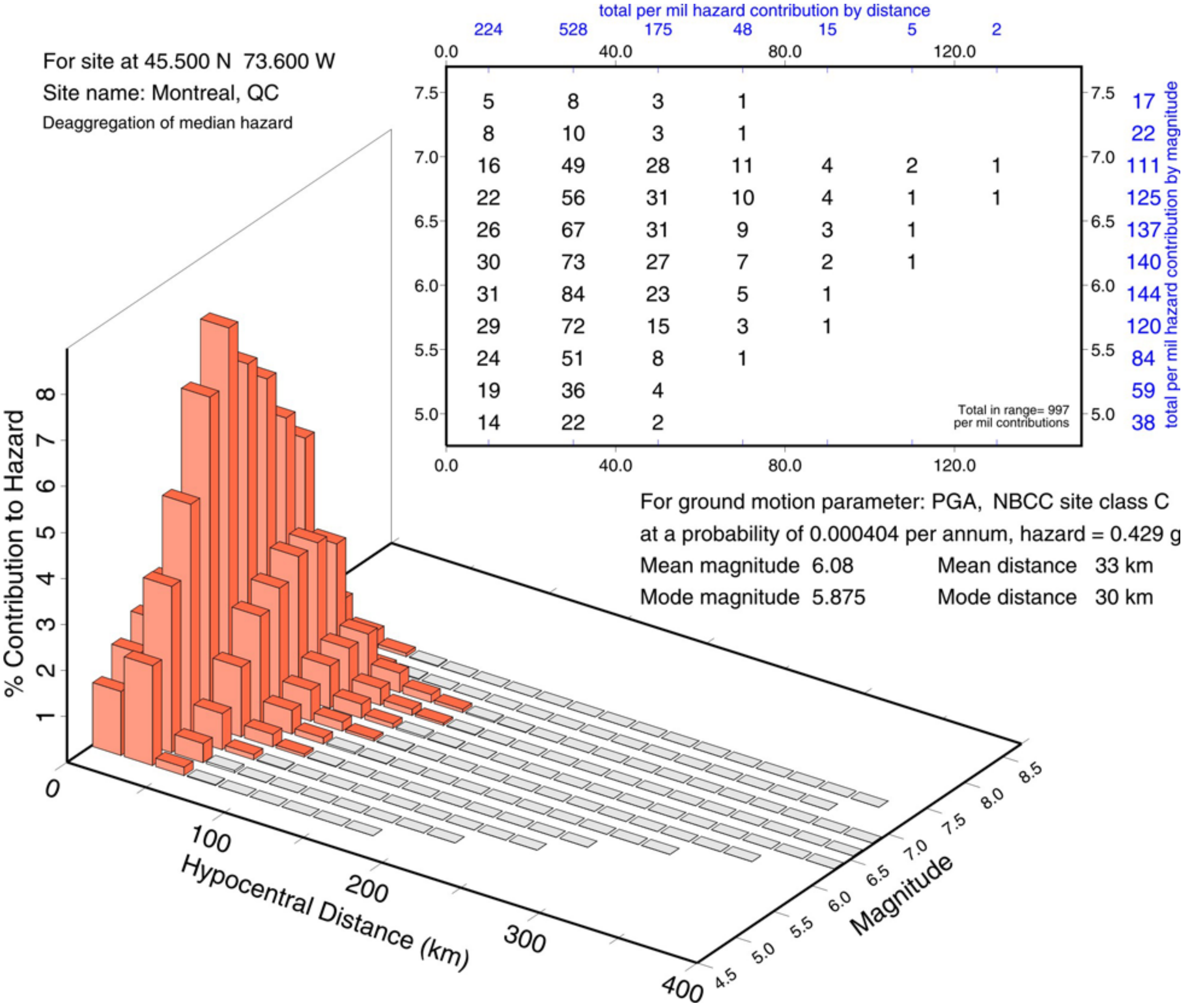

Figure 2. Deaggregation of Montreal PGA for a probability of 2%/50 years. Numerical values in the upper right box allow for an analytical examination (these are *per mil* contributions, divide by 10 to obtain percent contributions). Numbers in blue above and to the right of the box are magnitude and distance bin totals respectively. Red bins indicate contributions of > 0.1%.

Results

Deaggregation as a function of probability level

Before presenting the results for the standard set of Canadian cities we show more complete results for representative eastern and western cities, Montreal and Vancouver, discussed in this and the following section. Figure 3 shows the deaggregation of Sa(0.2) hazard for Montreal and Vancouver. The five plots ***a*** through ***e*** show deaggregations for successively lower probability levels of 40%/50 years, 20%/50 years, 10%/50 years, 5%/50 years, and 2%/50 years, the latter being the standard NBCC2005 probability.

Deaggregation as a function of ground motion parameter

Figure 4 shows, again for Montreal and Vancouver, more complete results for the five ground motion parameters that are used in NBCC 2005. Figure 4 depicts Sa(0.2), Sa(0.5), Sa(1.0), Sa(2.0) and PGA deaggregated hazard for 2%/50 years for these two cities.

Deaggregation for other selected cities

Deaggregated hazard plots for selected eastern and western cities are displayed in Figures 5 and 6 respectively. Each figure displays deaggregations for the 2%/50 year probability level for both Sa(0.2) and Sa(1.0) hazard. Mean and modal magnitude and distance are summarized in Table 1 for all 23 cities.

Table 1. Mean and modal distances (**D**) and magnitudes (**M**) for selected Canadian cities for Sa(0.2), Sa(1.0) and PGA at a probability of exceedence of 2%/50 years.

City	**NBCC 2005**		**Deaggregation Sa(0.2)**				**Deaggregation Sa(1.0)**				**Deaggregation PGA**			
	Hazard Values(g)		**Mean**		**Mode[‡]**		**Mean**		**Mode[‡]**		**Mean**		**Mode[‡]**	
	Sa(0.2	**Sa(1.0)**	**D**	**M**	**D**	**M**	**D**	**M**	**D**	**M**	**D**	**M**	**D**	**M**
St. John’s	0.18	0.060	168	6.2	30[B]	5⅞[B]	301	6.9	350	7⅛	171	5.6	30	4⅞
Halifax	0.23	0.070	131	6.4	130	6⅞	207	6.9	150	7⅛	85	5.8	30	4⅞
Moncton	0.30	0.068	53	6.0	30	5⅞	184	6.7	430[B]	7⅜[B]	33	5.6	30	5⅝
Fredericton	0.39	0.086	48	6.1	30	5⅞	158	6.8	310[B]	7⅜[B]	33	5.7	30	5⅝
La Malbaie	2.3	0.60	20	6.8	10	6⅞	23	7.1	30	7⅜	23	6.4	30	6⅞
Québec	0.59	0.14	39	6.4	30	6⅜	106	7.1	90	7⅜	32	6.0	30	5⅞
Trois-Rivières	0.64	0.12	35	6.4	30	6⅜	68	6.9	30	6⅞	31	6.0	30	5⅞
Montréal	0.69	0.14	39	6.5	30	6⅜	62	6.9	30	6⅞	33	6.1	30	5⅞
Ottawa	0.67	0.14	38	6.4	30	6⅜	64	6.9	30	6⅞	32	6.1	30	5⅞
Niagara Falls	0.41	0.073	30	5.9	30	5⅞	62	6.4	30	6⅝	29	5.6	30	5⅞
Toronto	0.28	0.055	51	6.0	30	5⅞	226	6.8	330[B]	7⅜[B]	41	5.7	30	5⅞
Windsor	0.18	0.040	65	5.8	30	5⅝	214	6.5	30	5⅞	47	5.5	30	4⅞
Winnipeg	0.12	0.023	111	5.9	30	5⅛	180	6.4	30	5⅞	79	5.5	30	4⅞
Calgary	0.15	0.041	30	5.3	10	4⅞	57	5.5	10	4⅞	32	5.2	10	4⅞
Kelowna	0.28	0.089	39	5.9	10	5⅜	134	6.8	130	7⅜	37	5.7	10	4⅞
Kamloops	0.28	0.10	38	5.9	10	5⅜	121	6.9	110	7⅜	35	5.7	10	4⅞
Prince George	0.13	0.041	55	5.8	10	4⅞	151	6.4	70[B]	6⅜[B]	53	5.6	10	4⅞
Vancouver	0.96	0.34	54	6.4	70	6⅞	49	6.7	70[B]	6⅞[B]	66	6.3	70	7⅛
Victoria	1.2	0.38	62	6.5	50	7⅛	63	6.7	70	7⅛	62	6.3	50	6⅞
Tofino*	1.2	0.47	26	8.2	26	8.2	26	8.2	26	8.2	26	8.2	26	8.2
Prince Rupert	0.38	0.15	26	6.2	10	5⅝	98	7.1	210[B]	8⅜[B]	28	6.1	10	4⅞
Queen Charlotte	0.58	0.42	26	6.4	10[B]	5⅞[B]	54	7.9	50	8⅜	37	6.9	50	8⅜
Inuvik	0.12	0.039	111	5.9	30	5⅛	177	6.4	170	6⅞	57	5.3	30	4⅞

[‡] The quantization of the modal values is due to the bin size chosen for deaggregation (20 km x 0.25 magnitude units).

[B] Distribution is bimodal.

* At Tofino, the deterministic Cascadia earthquake provides the NBCC 2005 hazard values. The hazard has not been deaggregated. The distance and magnitude values represent the values for the deterministic Cascadia event used to determine the hazard.

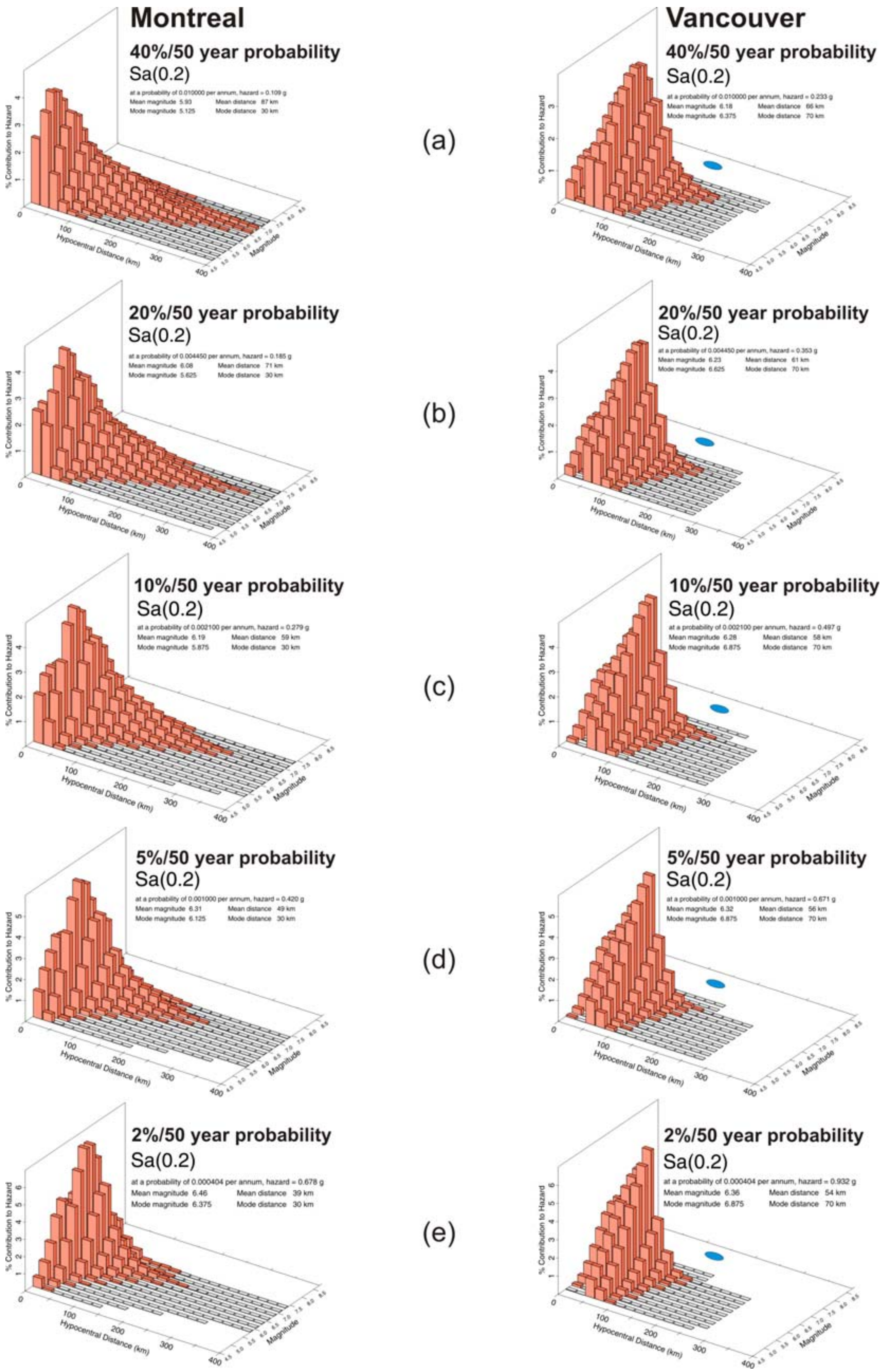

Figure 3. Deaggregation of Montreal and Vancouver Sa(0.2) for increasingly lower probabilities. For Vancouver, the blue oval shows the deterministic Cascadia source (not deaggregated).

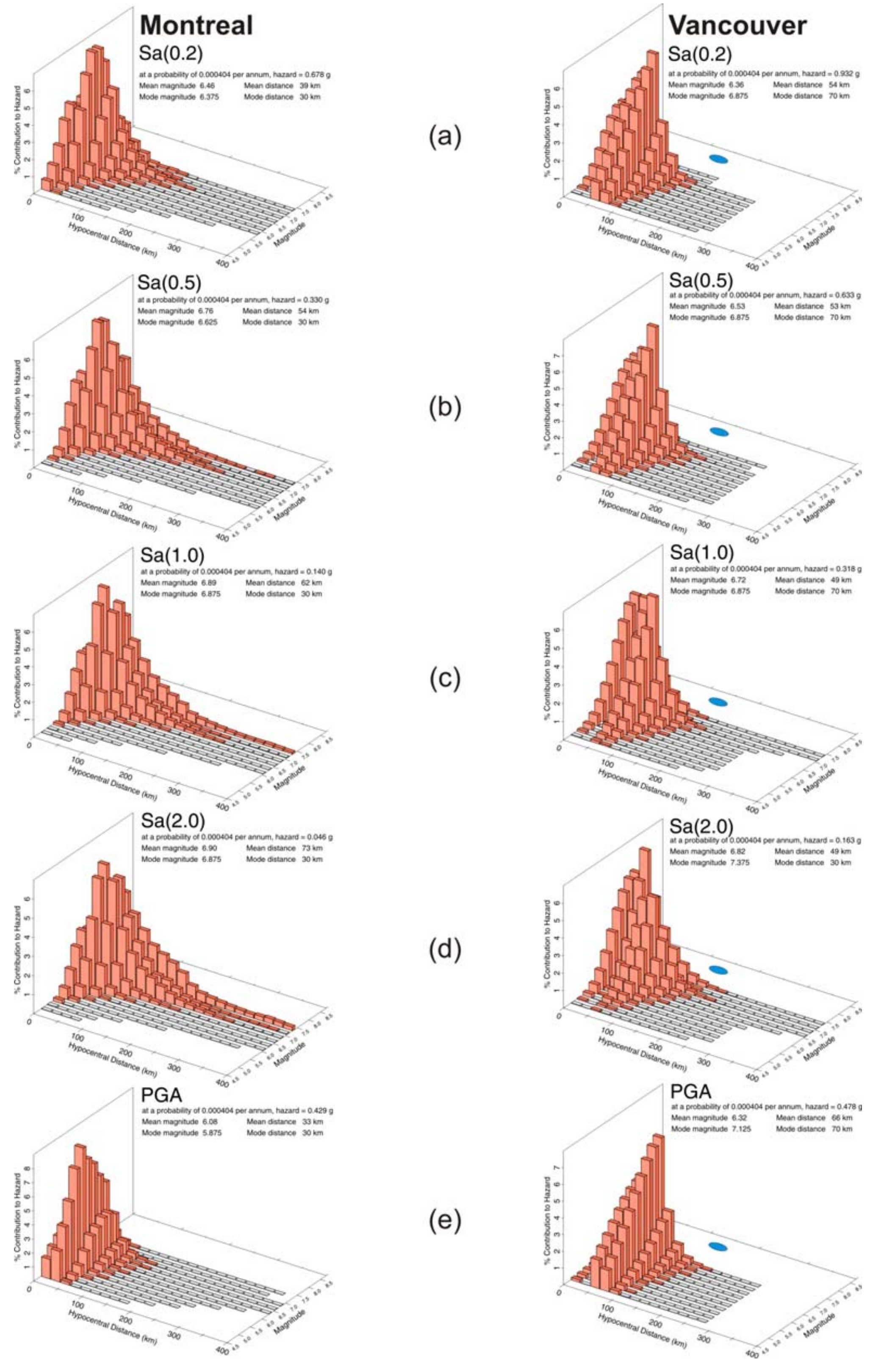

Figure 4. Deaggregation of Montreal and Vancouver for a probability of 2%/50 years for the five National Building Code parameters.

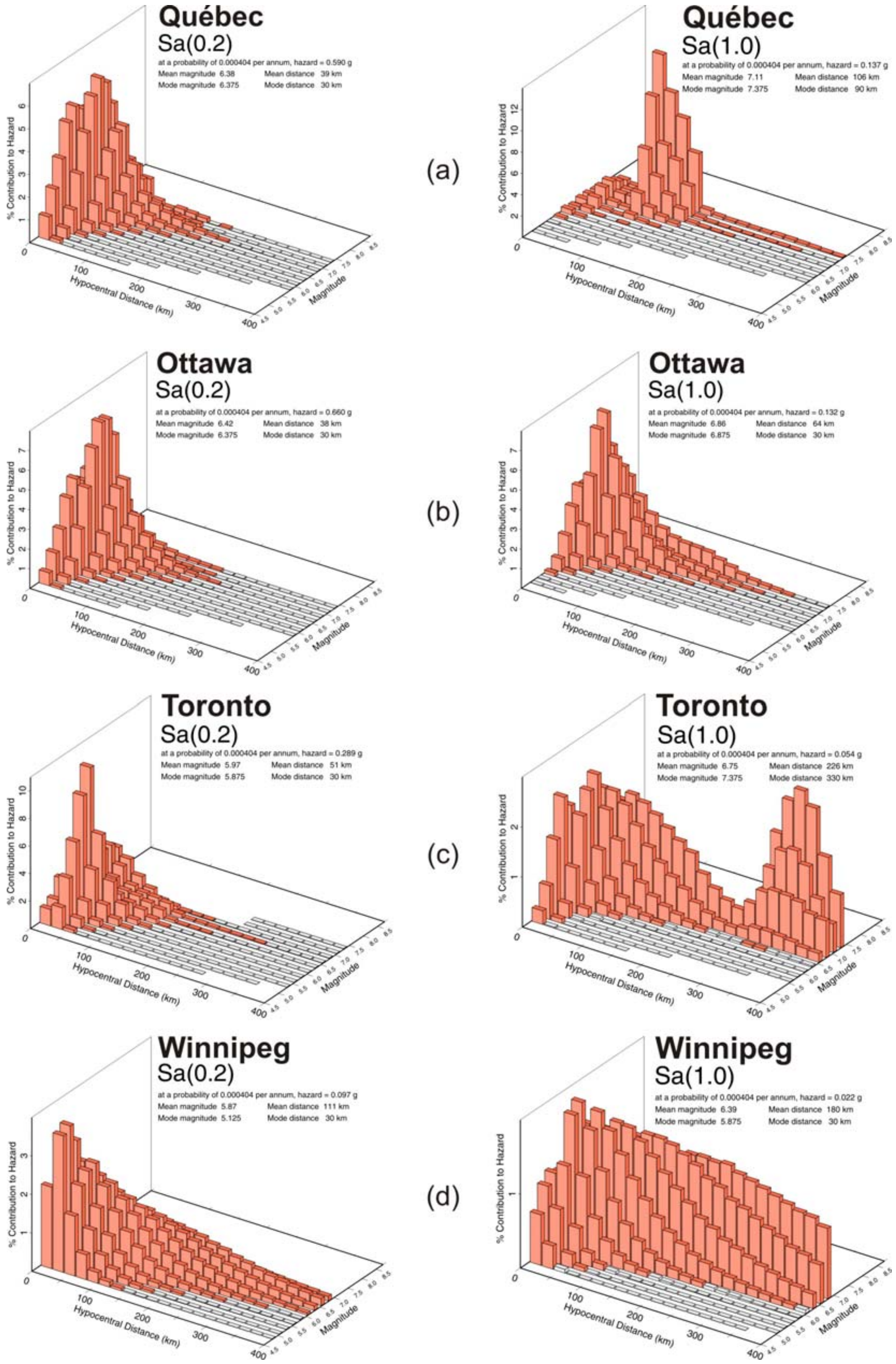

Figure 5. Deaggregation of eastern cities Sa(0.2) and Sa(1.0) hazard for a probability of 2%/50 years.

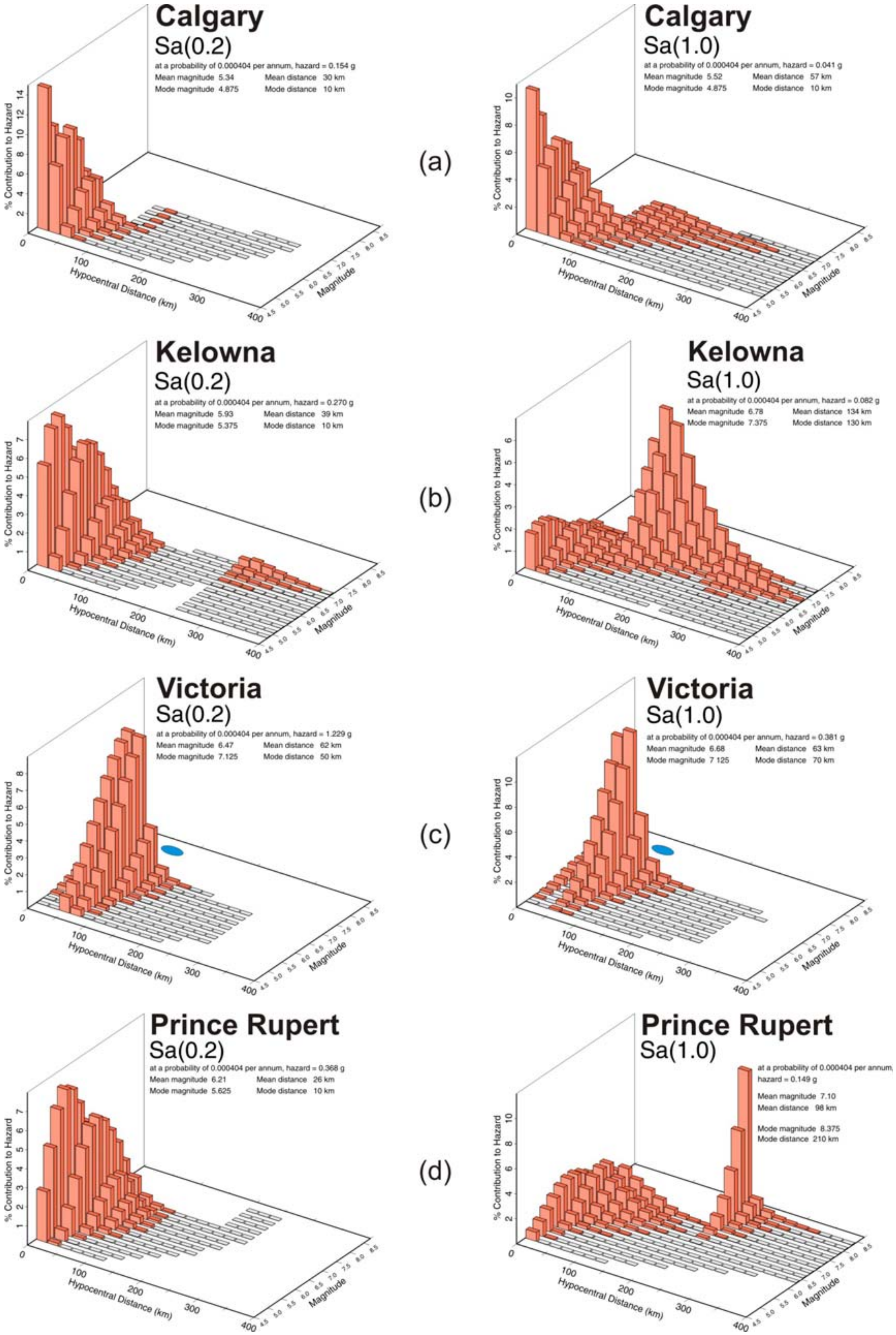

Figure 6. Deaggregation of western cities Sa(0.2) and Sa(1.0) hazard for a probability of 2%/50 years.

Discussion

Shape of Deaggregation plots

Typical simple deaggregations (e.g., Montreal, Ottawa) have a unimodal distribution, often with the modal peak close to the site and a "tail" that includes larger, more distant earthquakes. Bimodal distributions (e.g., Toronto, Vancouver) occur more frequently in long-period deaggregations, where the influence of larger earthquakes from greater distances is more significant. For the "stable Canada" region (e.g., Winnipeg) an area of low activity and in most places remote from high activity zones, the contributions come from a wide range of magnitudes and earthquakes. This results in a broad peak of hazard contributions, which extends from small, close earthquakes to large, distant ones.

Deaggregation as a function of probability level

Examination of the five parts of Figures 3 shows that as the probability level drops the dominant earthquakes contributing to the ground motion become larger and occur closer to the city.

Deaggregation as a function of spectral parameter

On the left side of Figure 4, parts ***a*** through ***e***, Montreal shows the typical variation in deaggregation with spectral parameter. As the period increases, larger and more distant earthquakes make increasing contributions to the hazard. This shows why there is often a need for more than one design earthquake for engineering purposes. The situation for Vancouver is more complex (see discussion below), with hazard coming from both crustal and subcrustal zones. Despite this complexity, the pattern of increasing contributions from larger and more distant earthquakes can still be seen in the Vancouver suite of deaggregation plots.

Deaggregation of Sa(0.2) and Sa(1.0) for selected cities

Comments on each city (not all illustrated) considered in the GSC deaggregation open file (Halchuk and Adams 2007) are (three or four letter codes refer to the contributing seismic source zones as detailed in Adams and Halchuk 2003):

St. John's. Nearby, low magnitude hazard is coming from the zone local to the city (AOBR); and the distant, larger magnitude hazard is from the offshore ECM zone; this is more dominant for the long-period hazard.

Halifax. As for St. John's, but the offshore contribution occurs at closer distances.

Moncton. Short-period hazard is dominated by local moderate earthquakes; longer period hazard has a contribution from the Charlevoix zone (CHV) at 400 km distance.

Fredericton. As for Moncton, except at longer periods the R model zone IRM contributes at distances greater than 300 km.

La Malbaie. Short- and long-period hazard dominated by Charlevoix earthquakes at close distances.

Québec. Short-period hazard dominated by moderate to large earthquakes nearby (IRM); long-period hazard dominated by Charlevoix (CHV) – Figure 5a.

Trois-Rivières. Short- and long-period hazard dominated by moderate and large earthquakes of the underlying IRM zone.

Montréal. Substantially as for Trois-Rivières, but with contributions from the GAT zone – Figure 4.

Ottawa. Similar to Montréal but with a more important short-period contribution from moderate-distance, large-magnitude events (GAT) – Figure 5b.

Niagara Falls. Dominant contributions are from nearby events (NAT) with a small contribution at long periods from more distant events (IRM).

Toronto. Short-period hazard is from the NAT zone, (more distant than for Niagara Falls); long-period hazard has a significant contribution from large, distant earthquakes (IRM), resulting in a bimodal deaggregation – Figure 5c.

Windsor. Local hazard contributions from moderate earthquakes of the underlying SGL zone.

Winnipeg. Represents the large central portion of Canada designated as the “stable Canada” region (Adams and Halchuk 2003). Nearby low-probability moderate-sized earthquakes provide the bulk of the short-period hazard. Long-period hazard is made up of a large number of small contributions from distances out to several hundred kilometers – Figure 5d.

Calgary. Short-period hazard dominated by small, nearby earthquakes (SFT); long-period hazard has a contribution from SEBC – Figure 6a.

Kelowna. Short-period hazard from small nearby earthquakes (SEBC); long-period hazard is from large distant earthquakes (CASR). Note that the dominant model changes between short (**H**) and long (**R**) periods – Figure 6b.

Kamloops. As for Kelowna.

Prince George. Similar to Kamloops and Kelowna, but the long-period hazard comes from closer, smaller earthquakes (SEBC and NRMT).

Vancouver. Simple deaggregation works well where simple areal crustal sources are involved. In Vancouver (and most of southwestern British Columbia) the situation is more complex. The crustal and subcrustal earthquake sources have very different activity rates and also cause very different ground moitons at the surface. Two different strong ground motion relations need to be used (Adams and Halchuk 2003). Excluded from the deaggregation is the contribution of great earthquakes on the Cascadia subduction zone (which are treated deterministically, see Adams and Halchuk 2003, Figure 6), though they dominate the hazard on the west coast of Vancouver Island. For both short- and long-period hazard the largest contribution comes from earthquakes at distances just larger than 50 km. This is due to the dominant contribution of the subcrustal zone PUG of the **H** model for short periods, and subcrustal zone GSP of the **R** model for long periods, both representing earthquakes within the down-going slab (Adams and Halchuk 2000). Unlike earthquakes in the crustal zones dominating many of the other cities, none of the subcrustal earthquakes can occur within hypocentral distances of 50 km of the city because they happen at a depth greater than 50 km. The contribution of the crustal zone, for distances less than 50 km, is greatest for the long period hazard (CASR), where it contributes to a bimodal deaggregation – Figure 4.

Victoria. Substantially as for Vancouver, except that the deep earthquakes (here, PUG) are even more dominant – Figure 6c.

Tofino. Although the deterministic Cascadia contribution dominates the robust hazard estimate, the Tofino probabilistic deaggregation is dominated by contributions from CASR. At both periods there is a small contribution from the subcrustal earthquake zones at distances of about 130 km (GSP).

Prince Rupert. The short-period hazard comes from moderate nearby earthquakes (CST and HEC). The long-period hazard has a bimodal distribution, with a contribution from these earthquakes, together with a far larger contribution from the Queen Charlotte Fault – Figure 6d.

Queen Charlotte City. The short-period hazard comes from small local earthquakes and larger events on the Queen Charlotte Fault. Note that there is no nearby, large magnitude contribution (i.e. for magnitude > 7 and distance < 25 km). The long-period hazard all comes from large earthquakes on the Queen Charlotte Fault.

Inuvik. The short-period hazard comes from the “stable Canada” model and is the same as the deaggregation for Winnipeg. The long-period hazard is dominated by earthquakes approaching magnitude 7 at a distance of about 150 km, i.e., the RMN zone.

Comparison of the summarized results of Table 1 in this paper to results to Table 1 of Halchuk and Adams (2004) (which was determined from “no-epistemic” simplified models using the program EZ-FRISK) shows only small changes. Mean and modal magnitudes all changed less than 0.2 magnitude units while mean distances changed less than 10%. Modal magnitude changes in some cases appear to be quite large but this is due in large part to the coarse bin size. For example, an actual modal value of 21 km would report as 12.5 km if 25-km distance bins were chosen, but as 30 km if 20-km distance bins were chosen. In almost all instances the modal values occurred in the same or adjacent bins for the 23 cities.

Deaggregation of Peak Ground Acceleration

For deaggregations of PGA the modal bin is often the closest, smallest magnitude bin. For example, for both Calgary and Prince George (Figure 7) the modal bin is M 4⅞ at 10 km. As is apparent in Figure 7, the lower magnitude cutoff at 4¾ significantly truncates the deaggregation mound. We realize that magnitude less than 4¾ earthquakes with ε > 1 ground motions should contribute to the 2%/50 year hazard. However, for NBCC the decision was made that earthquakes with magnitudes of less than 4¾ would have negligible engineering consequence and their contributions should be ignored. The significance of this is that while the modal values seem appropriate for spectral acceleration at many sites (e.g. Ottawa and Vancouver), they do not for PGA.

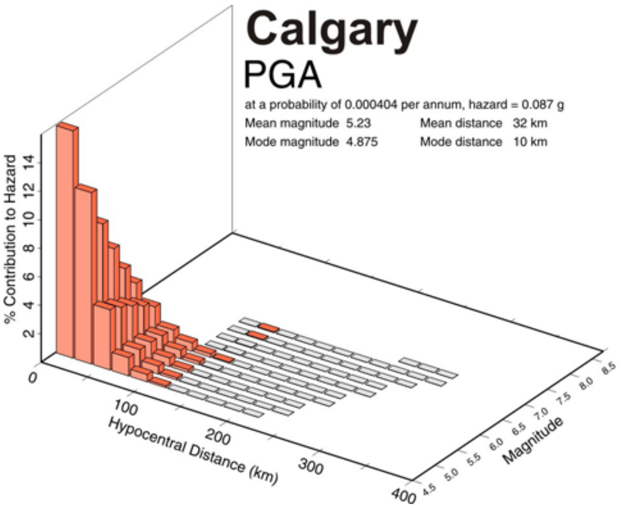

Figure 7. Deaggregation of PGA for Calgary and Prince George. The modal bin is from the shortest distance and smallest magnitude in both cases

Special note on the deaggregation of PGA

The National Building Code of Canada uses spectral acceleration values but has retained PGA in the table of climatic values, chiefly for use by geotechnical engineers. When PGA is applied to liquefaction analysis, it appears one has to decide if the “true” scientific PGA (for all earthquakes) or an “engineering” PGA based on a minimum-magnitude cutoff is to be used. The level of the cutoff can have a significant effect on PGA (see Table 2). This issue is more significant in low-seismicity areas where the truncation has a greater influence. Compare the effect of PGA deaggregations of Calgary and Prince George (Figure 7) with that of Montreal (Figure 2), where the truncation is not as significant. If it is believed that only PGAs from earthquakes with, say, magnitudes greater than 5.3 will lead to liquefaction, then smaller earthquakes shouldn’t be included in the calculation of the PGA to be used in liquefaction analysis. As it would be preferable to consider the consequences for liquefaction of each magnitude contributing, ideally one should be deaggregating the liquefaction risk directly.

Table 2. Effects of magnitude cutoff on peak ground acceleration values at 2%/50 year probability.

City	**2%/50 year peak ground acceleration (g) at different magnitude cutoff values**					
	4.25	4.5	4.75	5.0	5.25	5.5
Montreal	0.43	0.43	0.43	0.43	0.42	0.40
Winnipeg	0.070	0.066	0.059	0.054	0.047	0.040
Calgary	0.11	0.10	0.088	0.065	0.054	0.043
Vancouver	0.48	0.49	0.48	0.48	0.47	0.46

Conclusions

The results contained in this paper and the forthcoming deaggregation Open File should help to explain how the typical size and distance of earthquakes making the largest contributions to the seismic hazard varies both with probability level and with spectral parameter. For most locations, the deaggregations reveal that more than one design earthquake will be required for engineering purposes. Deaggregation of PGA (for example Figures 2 and 7 and Table 1) may be useful for the design of foundations resistant to liquefaction, with the caution that the effect of the magnitude cutoff needs to be considered. The deaggregations represent one more aspect of the 2005 NBCC design provisions that will lead to improved earthquake-resistant structures.

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** Available for download from the Earthquake Hazard section of the Earthquakes Canada website: http://earthquakescanada.nrcan.gc.ca