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DEAGGREGATION OF SEISMIC HAZARD FOR SELECTED CANADIAN CITIES

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SUMMARY

The Geological Survey of Canada's new seismic hazard model for Canada will form 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 spectral accelerations (Sa(0.1) to Sa(2.0) seconds) and for a number of probabilities (2%/50, 5%/50, 10%/50, 20%/50, 40%/50 years) 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) and Sa(1.0) seconds and for 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 [1]. The method and results given in Open File 4459 are the basis for CANCEE's (Canadian National Committee on Earthquake Engineering) recommended seismic design provisions for the next edition of the National Building Code of Canada (NBCC) which will be issued in 2005. Open File 4459 presented the hazard values for the next NBCC "Design Data for Selected Localities in Canada" table, 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 on the input to the seismic provisions intended for NBCC2005 appear in Adams and Halchuk [2].

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This paper, in conjunction with Halchuk and Adams [3], 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 for the selected cities. Locations of most of the cities are shown in Figure 1, which also depicts the hazard for Sa(0.2).

The process of deaggregation (McGuire [4], Bazzurro and Cornell [5], Harmsen [6]) has come to be an important tool for understanding seismic hazard. Dividing 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. 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 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 to be used for 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.

GSCFRISK lacks the capability for deaggregation, and so for the deaggregation plots presented here we used the PC program EZ-FRISK (version 4.3), also a proprietary software product of Risk Engineering Inc. This required the generation of new input model files which will be made available in a future Open File [7]. While EZ-FRISK is capable of deaggregation, it lacks an implementation of epistemic uncertainty. Therefore, before using EZ-FRISK with our new input files we performed computational checks between GSCFRISK and EZ-FRISK using just the "best estimate" parameters of the full **H** and **R** probabilistic models. That is, we ran GSCFRISK to produce a set of "no-epistemic" hazard results from a simplified version of the 4th Generation hazard model, in which the weights were set equal to 1.0 for the best estimate parameters and 0.0 for the alternative values intended to capture the epistemic uncertainty. These results agreed quite well, confirming that the model was correctly implemented in EZ-FRISK. For the 23 cities across Canada, the simplified 4th Generation and EZ-FRISK models produced results that generally differed by much less than 1% for each of Sa(0.2) and Sa(1.0). The largest differences occurred for Sa(1.0) values at Prince Rupert and Queen Charlotte City. Differences here were on the order of 2-3%, which we believe were the result of slightly different implementation of the Queen Charlotte fault zone in the two programs.

The "no-epistemic" hazard values generally differ from the "full epistemic" 4th Generation values by less than 10% but in a few cases by as much as 25-30%. When we came to compute the deaggregations we therefore had two choices: either perform a deaggregation at the 2%/50 years probability for the no-epistemic model, or perform a deaggregation for the ground motion values of NBCC2005 obtained from GSCFRISK (even though the probability of those values would not be 2%/50 years according to EZ-FRISK). We chose the former course, though in fact the differences are usually barely visible on the deaggregation plots. The degree of discrepancy can be seen by comparing the EZ-FRISK values given on the deaggregation figures with the NBCC2005 values given in Table 1. We hope to update the deaggregations in this paper to those from the full-epistemic hazard model at some time in the future.

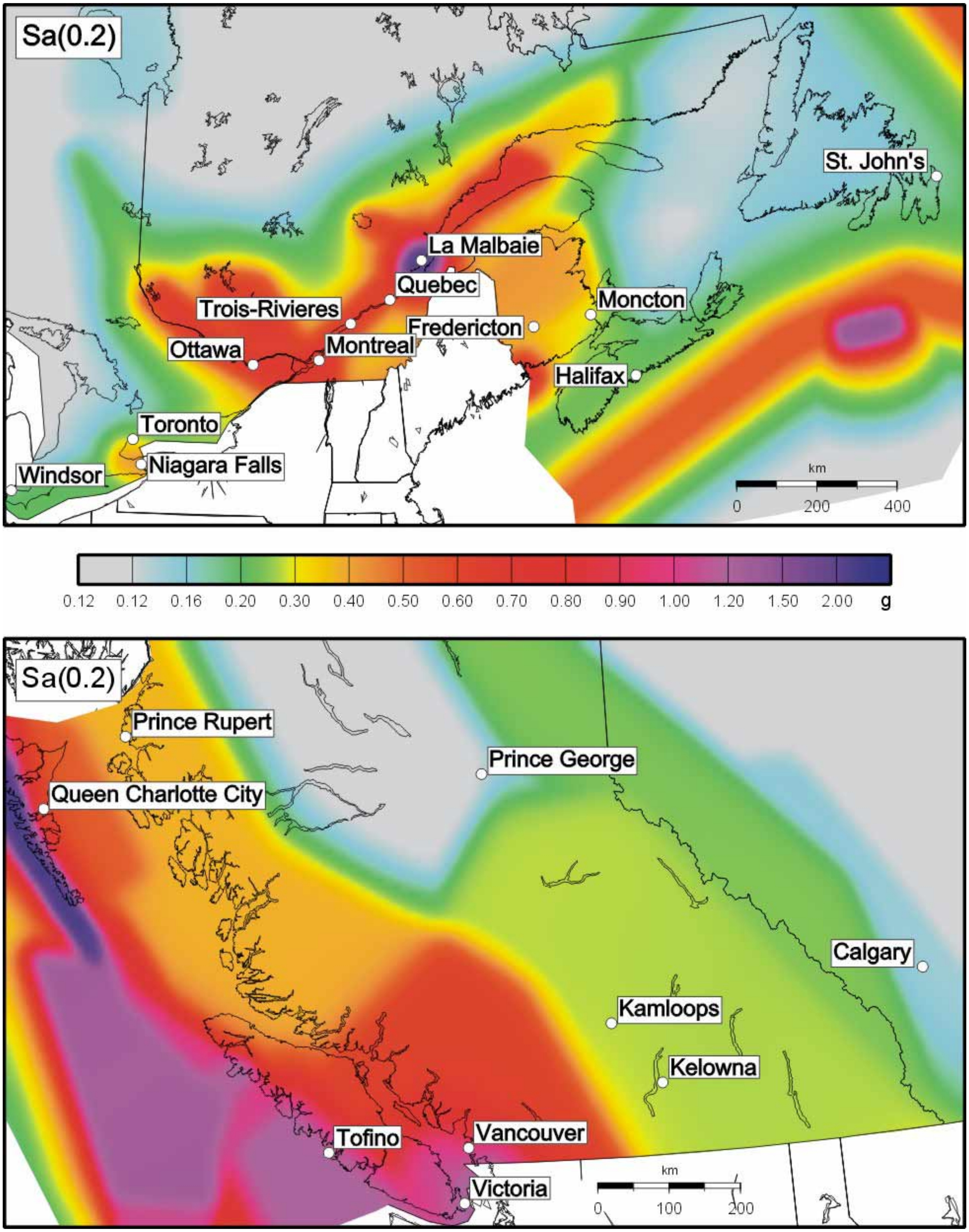

Figure 1. Map of southeastern and southwestern Canada showing Sa(0.2) hazard (median values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years) and the locations of most cities for which deaggregation is performed.

In order to generate smooth deaggregations, in some cases we had to increase the “slice” parameter to 500 or even 1000 from the value of 50 used in GSCFRISK. This parameter defines the number of integration slices for each contributing source zone; for large sources the width of each slice should not be too wide or the assignment into bins may show a spurious aliasing, leading to jagged deaggregations (i.e. plots where the amplitudes of adjacent magnitude/distance bins did not change smoothly). The extreme example for Canada is the **R** model offshore eastern continental margin zone, which is over 5500 km long. Choosing 50 slices would only fill distance bins every 110 km, whereas 1000 slices sample every 5.5 km and ensure contributions from multiple slices to each 25 km bin. A large slice parameter increases the computation time, but this is not the issue for 20-30 cities that it would be for a national grid of hundreds of thousands of hazard points.

To generate the binned results, we tried setting the bin size in EZ-FRISK to small values (5 km and 0.1 magnitude units, Figure 2) in order to generate sets of results with different bin sizes through our UNIX processing (see below), but found the results to be occasionally erratic (perhaps because of the values for the slice parameter, as discussed above). The contribution from individual bins in this case is quite small (note the vertical scale in this figure is in tenths of a percent). While the smooth variation of these very small-binned plots more closely reflects the reality of magnitude and distance distribution, it also proves more difficult to extract simple information from plots like Figure 2. In the past we had used 25 km distance and 0.5 magnitude bins, as did the USGS (e.g., Harmsen [6]), but we found that distance increments of 25 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, (and this is the case for the bulk of the cities) we reduced the distance axis of the final plots to 400 km. In the end we set the EZ-FRISK bin sizes to equal our final choice, 25 km and 0.25 magnitude units.

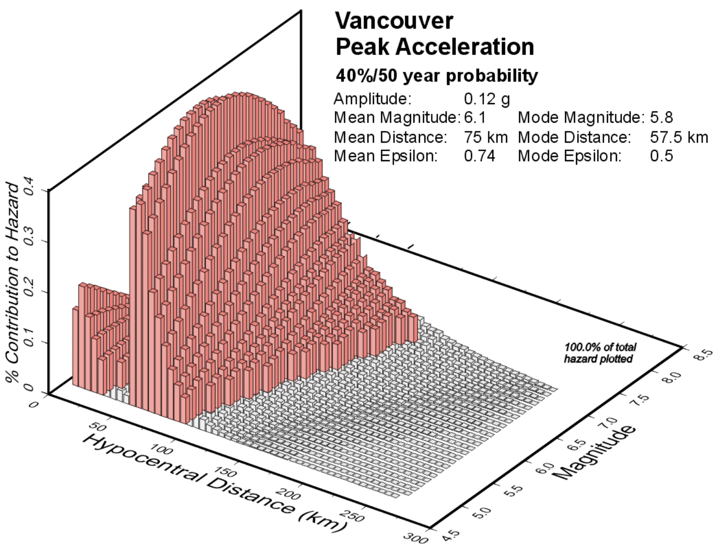

Figure 2. Deaggregation of Vancouver PGA using small-sized bins (5 km distance and 0.1 magnitude units). Although the smoothly varying surface better reflects the magnitude distance distribution, interpretation of the results is difficult as each bin contributes a very small increment of hazard (note vertical scale is in tenths of a percent).

The output from the EZ-FRISK program was transferred to a UNIX machine and modified significantly using the graphics program GMT. A particular enhancement is the box in the upper right portion of the plot 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. An example for the 2%/50 year PGA is given for Montreal in Figure 3. Due to space considerations, the enhanced deaggregation plots are not shown in the rest of the paper.

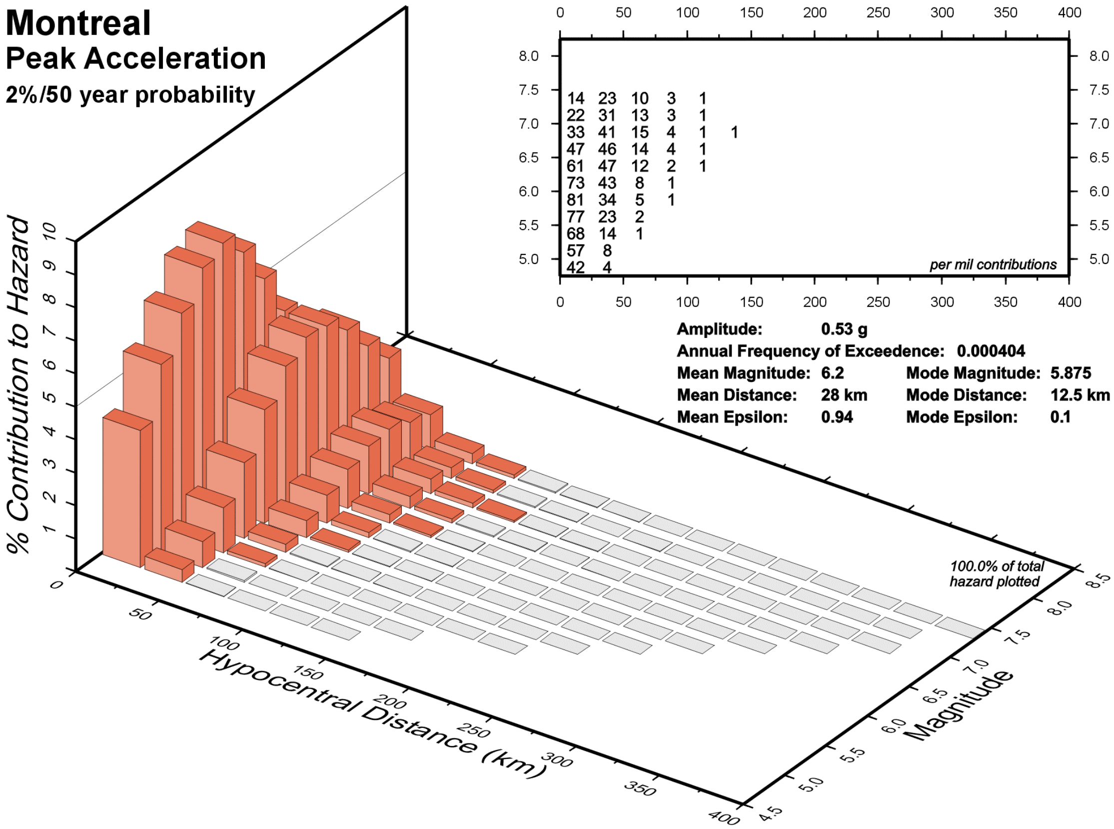

Figure 3. Deaggregation of Montreal PGA for a probability of 2%/50 years. Numerical values in the upper right box allow for an analytical examination (*per mil* contributions, divide by 10 to obtain percent contributions). Red bins indicate contributions of at least 1/10 of a percent.

Layout of the deaggregation plots

The magnitudes on these plots are m_N for eastern Canada and M_L (roughly equivalent to Mw) 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 differs from the NBCC2005 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); and epsilon values, which are defined by McGuire [4] as the number of logarithmic standard deviations that the ground motion lies above or below the median. Apparent errors in the reporting of epsilon occur in our version of EZ-FRISK, and the values reported on our figures should be disregarded. We hope to rectify these problems in a future report.

RESULTS

Deaggregation as a function of probability level.

Before presenting the results for the standard set of cities we show more complete results for representative eastern and western cities, Montreal and Vancouver, discussed in this and the following section. Figure 4 shows the deaggregation of Sa(0.2) hazard for Montreal and Vancouver. The five plots

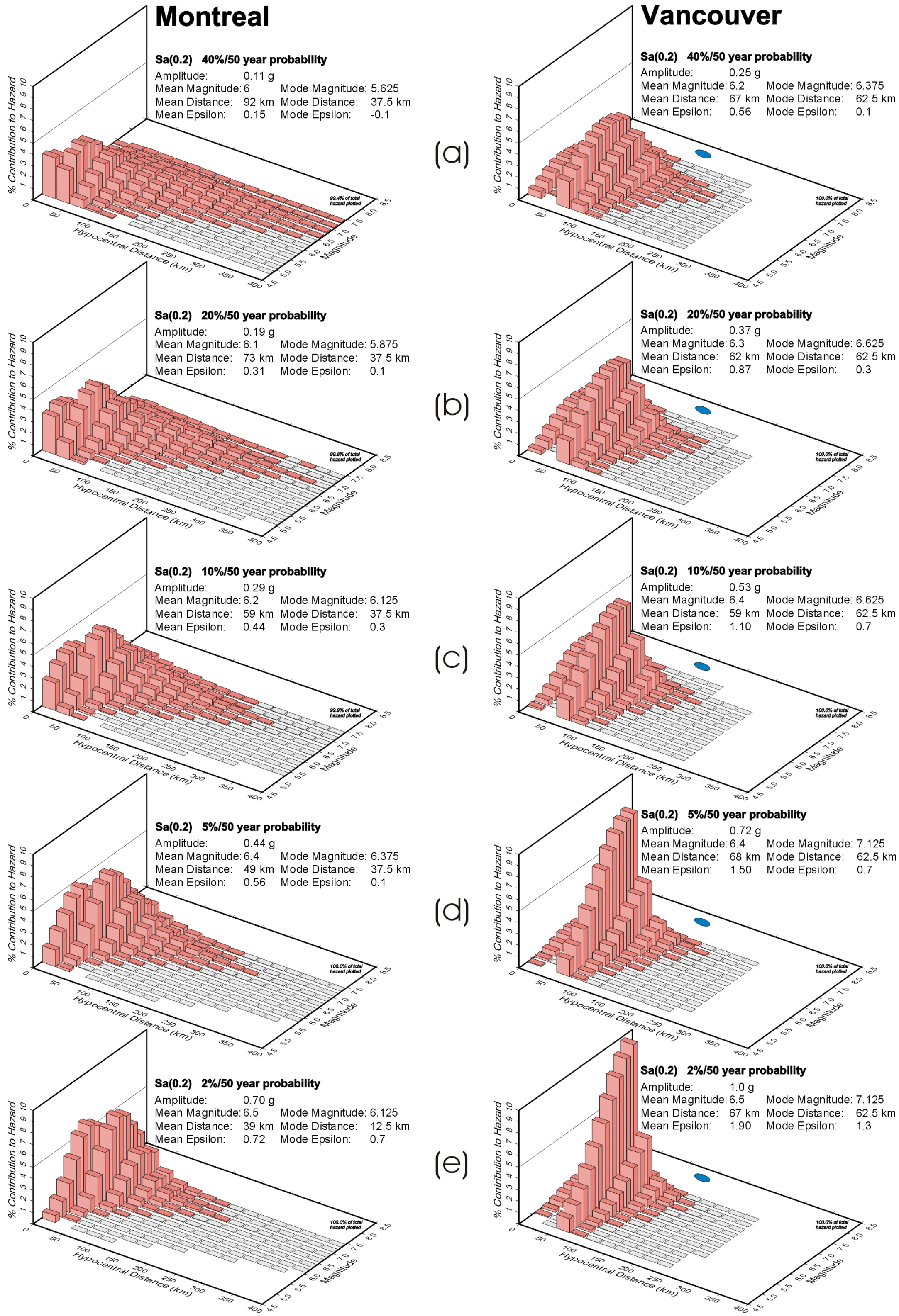

Figure 4. Deaggregation of Montreal and Vancouver Sa(0.2) for increasingly lower probabilities. For Vancouver, the location of the deterministic Cascadia source (not deaggregated) is shown by the blue oval.

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.
Five ground motion parameters are used in NBCC2005. Figure 5 depicts Sa(0.1), Sa(0.2), Sa(0.5), Sa(1.0) and Sa(2.0) deaggregated hazard for 2%/50 years for Montreal and Vancouver.

Deaggregation for other selected cities.
Deaggregated hazard plots for selected eastern and western cities are displayed in Figures 6 and 7 respectively. Each figure displays deaggregations for the 2%/50 year probability level for 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 and magnitudes for selected Canadian cities for Sa(0.2) and Sa(1.0) at a probability of exceedence of 2%/50 years.

City	NBCC 2005 Hazard Values(g)		Deaggregation Sa(0.2)[†]				Deaggregation Sa(1.0)[†]			
			Mean		Mode[‡]		Mean		Mode[‡]	
	Sa(0.2)	Sa(1.0)	D	M	D	M	D	M	D	M
St. John's	0.18	0.060	170	6.4	37.5 [B]	5⅞ [B]	300	6.9	337.5	7⅛
Halifax	0.23	0.070	130	6.5	112.5	6⅞	230	6.9	187.5	7⅛
Moncton	0.30	0.068	49	6.1	12.5	5⅞	170	6.7	437.5 [B]	7⅜ [B]
Fredericton	0.39	0.086	43	6.3	12.5	5⅞	160	6.8	312.5 [B]	7⅜ [B]
La Malbaie	2.3	0.60	20	6.9	12.5	7⅛	22	7.1	12.5	7⅜
Québec	0.59	0.14	41	6.4	12.5	6⅛	100	7.1	87.5	7⅜
Trois-Rivières	0.64	0.12	37	6.5	12.5	6⅛	72	6.9	37.5	6⅞
Montréal	0.69	0.14	39	6.5	12.5	6⅛	65	6.9	37.5	6⅞
Ottawa	0.67	0.14	39	6.5	12.5	6⅛	67	6.9	37.5	6⅞
Niagara Falls	0.41	0.073	27	6.1	12.5	5⅞	56	6.4	37.5	6⅝
Toronto	0.28	0.055	51	6.2	37.5	6⅛	240	6.7	337.5 [B]	7⅜ [B]
Windsor	0.18	0.040	63	6.0	12.5	5⅛	230	6.5	12.5	5⅝
Winnipeg	0.12	0.023	100	6.0	37.5	5⅝	190	6.4	37.5	5⅞
Calgary	0.15	0.041	28	5.3	12.5	4⅞	55	5.5	12.5	4⅞
Kelowna	0.28	0.089	39	5.9	12.5	5⅜	140	7.0	137.5	7⅝
Kamloops	0.28	0.10	37	5.9	12.5	5⅜	120	7.1	112.5	7⅝
Prince George	0.13	0.041	50	5.8	12.5	4⅞	160	6.5	62.5 [B]	6⅛ [B]
Vancouver	0.96	0.34	67	6.5	62.5	7⅛	47	6.9	62.5 [B]	6⅞ [B]
Victoria	1.2	0.38	63	6.5	62.5	7⅛	64	6.7	62.5	7⅛
Tofino*	1.2	0.47	26	8.2	26	8.2	26	8.2	26	8.2
Prince Rupert	0.38	0.17	24	6.2	12.5	5⅞	110	7.3	187.5 [B]	8⅜ [B]
Queen Charlotte	0.66	0.50	30	6.7	12.5 [B]	6⅛ [B]	46	8.0	37.5	8⅜
Inuvik	0.12	0.039	100	6.0	37.5	5⅝	180	6.4	162.5	6⅞

† Deaggregation has been done using a simplified version of the hazard models, as described in the text.

‡ The quantization of the modal values is due to the bin size chosen for deaggregation: 25 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 Cascadia event used to determine the hazard.

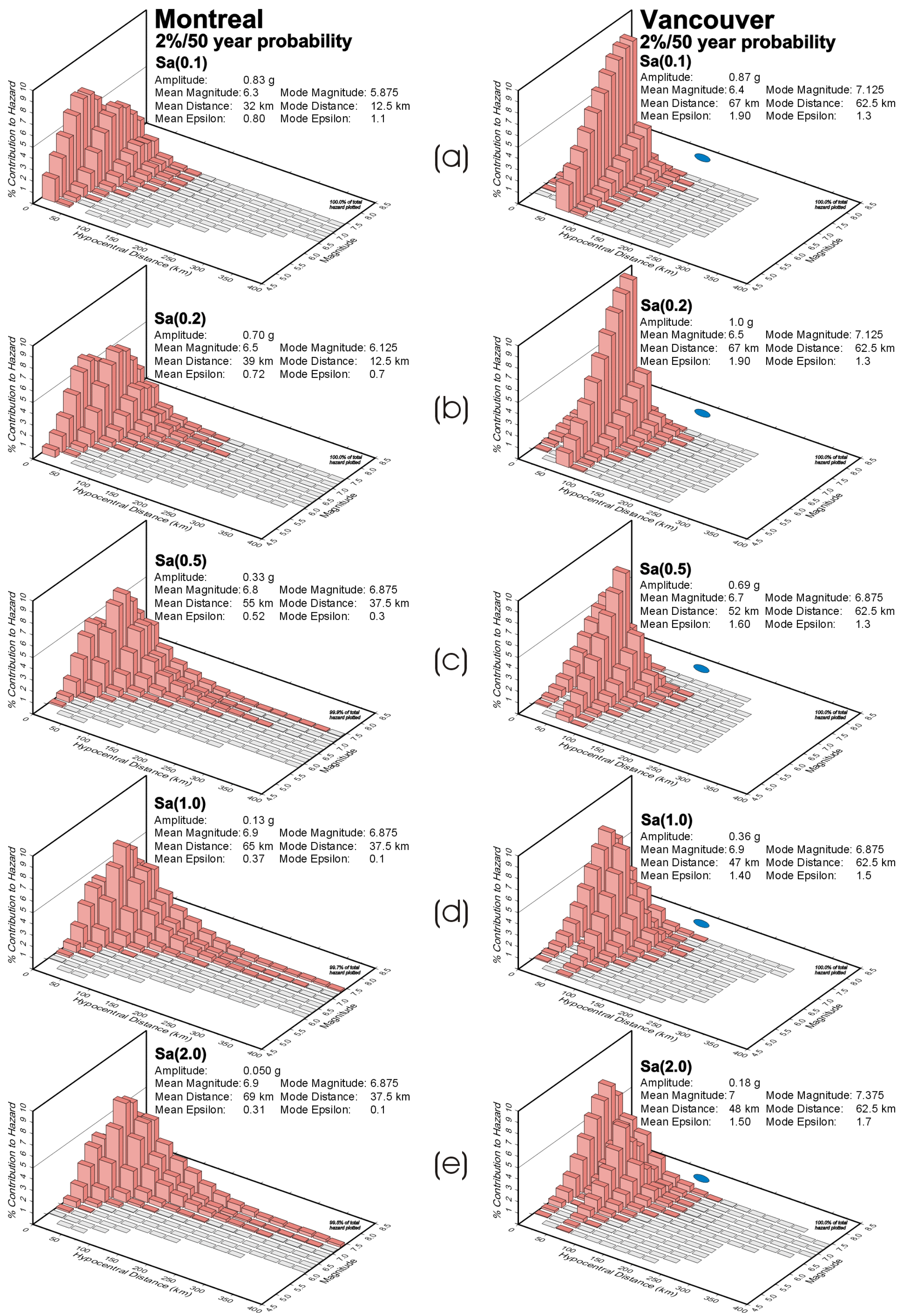

Figure 5. Deaggregation of Montreal and Vancouver for a probability of 2%/50 years for increasingly longer spectral periods.

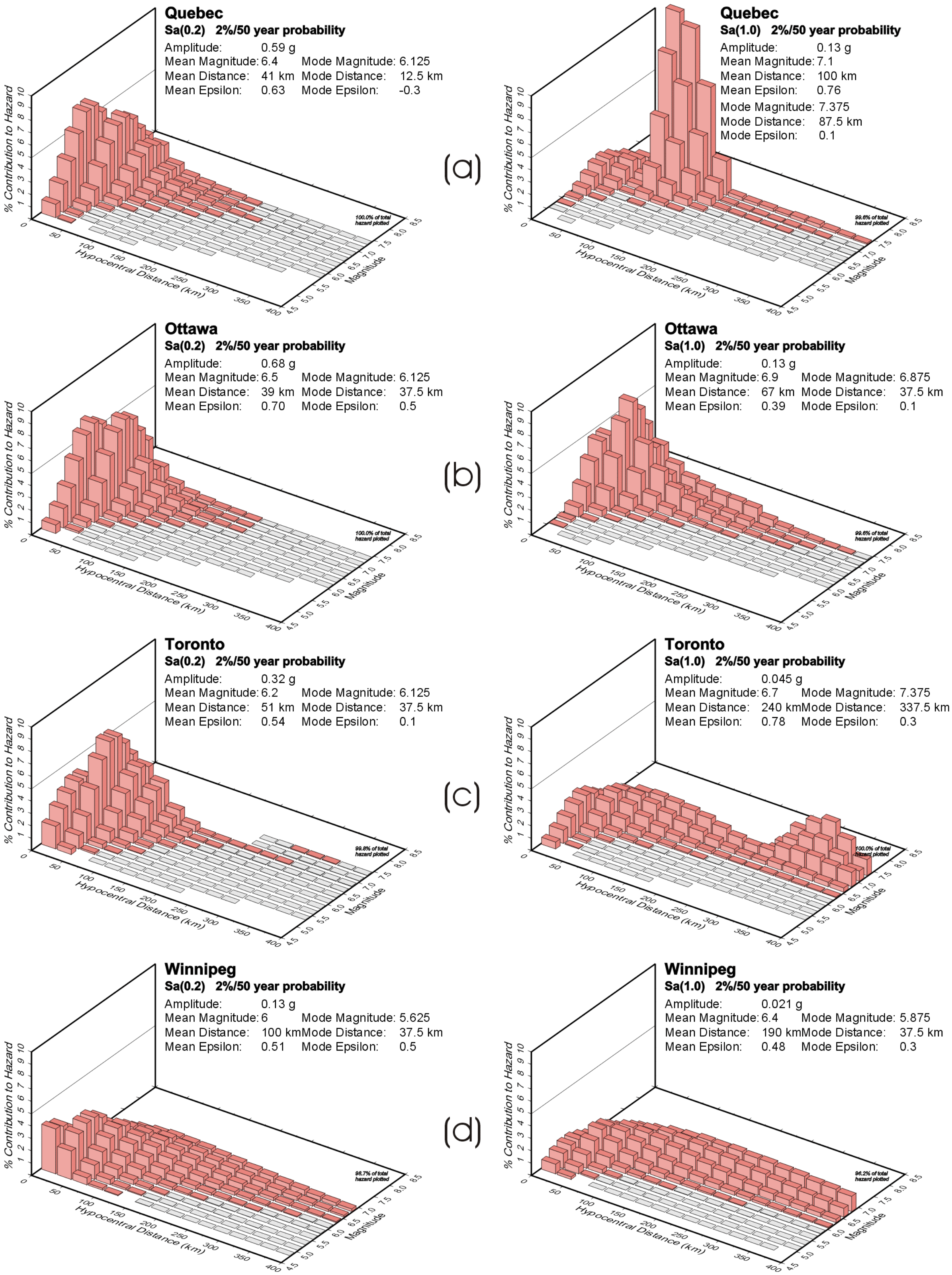

Figure 6. Deaggregation of selected eastern cities Sa(0.2) and Sa(1.0) hazard for a probability of 2%/50 years.

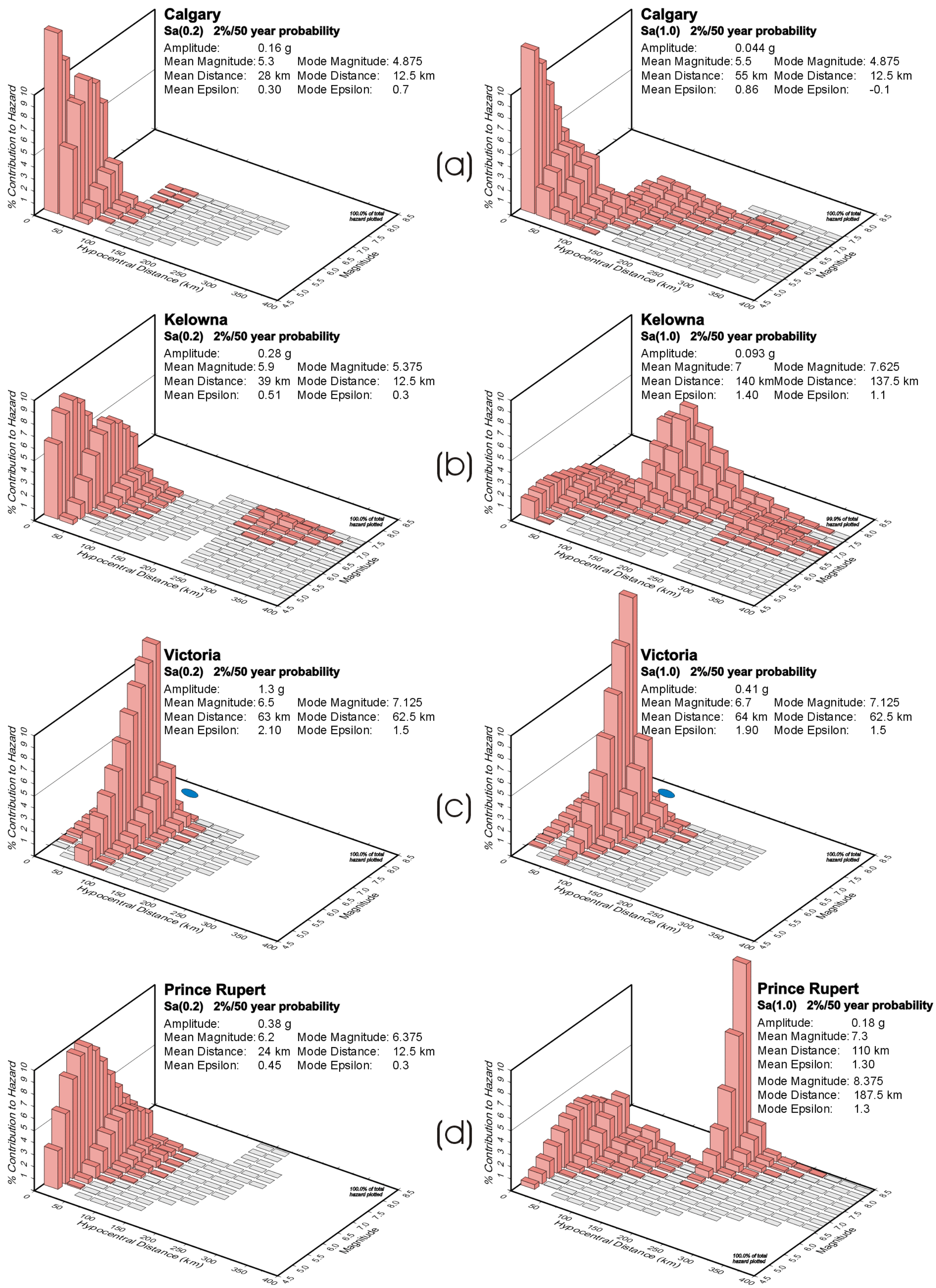

Figure 7. Deaggregation of selected western cities Sa(0.2) and Sa(1.0) hazard for a probability of 2%/50 years.

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, with a skew from small, close earthquakes to large, distant ones.

Deaggregation as a function of probability level.

Examination of the five parts of Figures 4 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 5, 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 for selected cities.

Comments on each city (not all illustrated) considered in the GSC deaggregation open file [3] are (three or four letter codes refer to the contributing seismic source zones as detailed in [1]):

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 (IRM); long-period hazard dominated by Charlevoix (CHV) – Figure 6a.

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 5.

Ottawa. Similar to Montréal but with a more important short-period contribution from moderate-distance, large-magnitude events (GAT) – Figure 6b.

Niagara Falls. Dominant contributions are from nearby events (NAT) with a tail 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 6c.

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 [3]. 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 6d.

Calgary. Short period hazard dominated by small, nearby earthquakes (SFT); long period hazard has a contribution from SEBC – Figure 7a.

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 7b.

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 [1]. Excluded from the deaggregation is the contribution of great earthquakes on the Cascadia subduction zone (which are treated deterministically, see Open File 4459 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. Unlike 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 strongly bimodal deaggregation – Figure 5.

Victoria. Substantially as for Vancouver, except that the deep earthquakes (here, PUG) are even more dominant – Figure 7c.

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 7d.

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.

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 3) may be useful for the design of foundations resistant to liquefaction hazard. The deaggregations represent one more aspect of the 2005 NBCC design provisions that will lead to improved earthquake resistant structures.

ACKNOWLEDGEMENTS

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