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NBCC 2015 Deaggregation Maps for Canada

Michal Kolaj[1*], Stephen Halchuk[1], and John Adams[1]

[1]Seismologist, Natural Resources Canada, Ottawa, ON, Canada
[*]michal.kolaj@nrcan-rncan.gc.ca (Corresponding Author)

ABSTRACT

Natural Resources Canada's 5th Generation seismic hazard model for Canada forms the basis for the seismic design provisions of the 2015 National Building Code of Canada (NBCC 2015). Deaggregation (also called disaggregation) unbundles seismic hazard summary statistics (i.e., mean hazard) to help end users understand the relative contributions of earthquake sources as a function of distance and magnitude. Since 2007, deaggregation calculations have been published for selected cities, and have been provided as an on demand service to engineers for individual sites. For the first time, these calculations have been performed for a grid of more than 30,000 points, covering all of Canada. In order to properly interpret national and regional deaggregation maps of summary statistics, multimodal distributions must be identified, otherwise the reliability of those statistics can be compromised. Using the concept of topographic prominence, we present an automated way of flagging locations for which the hazard may have a multimodal distribution. Using this assessment, we can identify regions where simple deaggregation statistical values are likely inappropriate. For regions that are expected to be unimodal, we present maps of mean and modal magnitudes and distances. These maps can be used to obtain insights into the dominant sources of hazard, nationally and regionally, and as input into engineering or geotechnical analyses and emergency management. This paper presents a preliminary look at this large deaggregation database.

Keywords: National Building Code of Canada, seismic hazard, deaggregation

INTRODUCTION

Most users of national probabilistic seismic hazard maps consider just the mean hazard representation (e.g., NBCC 2020) at an appropriate probability level. The mean hazard at a site is the mathematical sum (in probability space) of the contributions of all sources at the target ground motion level. Each contribution to the shaking hazard comes from an earthquake source with a given magnitude-distance distribution. The process of extracting those contributions is termed "deaggregation" (also called disaggregation), though in fact the extraction is done before the results are "aggregated" to give the mean hazard. A typical NBCC2015 deaggregation result is shown in Figure 1. To create the deaggregated hazard, the magnitude (M) and distance (R) contributions are binned (for the 5th Generation Canadian hazard results 0.1 magnitude units and 20 km bins are used), and the height of the bar for each bin represents its fractional contribution to the total exceedance probability. Other deaggregation schemes are possible, for example the USGS deaggregates on epsilon (the amount of the GMM's upper tail contributing to the height of the bar) and space (azimuth to each magnitude-distance bin). NBCC 2020 deaggregations are described in an accompanying paper [1].

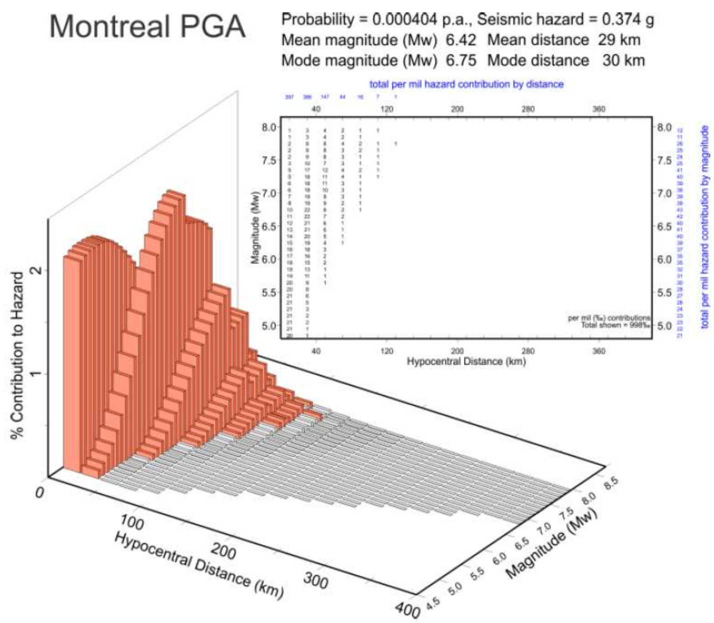

Figure 1. A NBCC2015 deaggregation for the 2% in 50 year peak ground acceleration (PGA) for Montreal (modified from [2]).

While consideration of the full deaggregation distribution (or a more coarsely discretized version) is preferred, mean and modal values are useful summary statistics as they can guide the selection of scenario events for engineering and geotechnical analyses, emergency planning and science communication. Typically, these types of statistics are interpreted for a single site or a suite of sites across a region (e.g., [2]).

A site that lies within a very large seismic source zone (of assumed uniform seismicity) will have a unimodal distribution with a peak at a magnitude-distance bin which depends on the probability and the characteristics of the source, site and ground motions. In general, for longer spectral periods the contributions from larger magnitudes and distances increase, and for lower probabilities the contributions from larger magnitudes and distances decrease. Such deaggregations are reasonably represented by mean or modal values where the mode is the value of the largest magnitude-distance bin and the mean is a weighted average of all the contributions. Some Canadian examples of unimodal deaggregations are illustrated in [2].

However, most seismotectonic settings are not simple, and a site may be influenced by several seismic source zones at varying distances and with varying earthquake activity rates. For these cases the deaggregation distribution may become bimodal or multimodal. Examples of a unimodal and multimodal deaggregations are given in Figure 2. For Victoria (Figure 2, left panel) about half of the hazard comes from nearby deep earthquakes (inslab), about half from the Cascadia subduction interface, and a small remainder comes from nearby shallow earthquakes (crustal). For Victoria, the mode would either represent an interface or inslab scenario (with crustal sources being much less significant) – but a user that only considers a single (modal) scenario would not be capturing the characteristics of a significant subset of the expected events. Similarly, the mean magnitude and distance is between the modes and has no physical basis (i.e., the actual contribution from the mean magnitude-distance bin is very small) and would also be inappropriate. As such, interpretation of multimodal deaggregation requires additional considerations, in particular for the selection of earthquake scenarios for engineering design [3].

The goals of this paper are to 1) present national and regional maps of summary deaggregation statistics (i.e., mean and modal values) and to 2) highlight regions in Canada where a single modal or the mean scenario could be inappropriate and where any single-scenario summary statistic needs to be interpreted with caution.

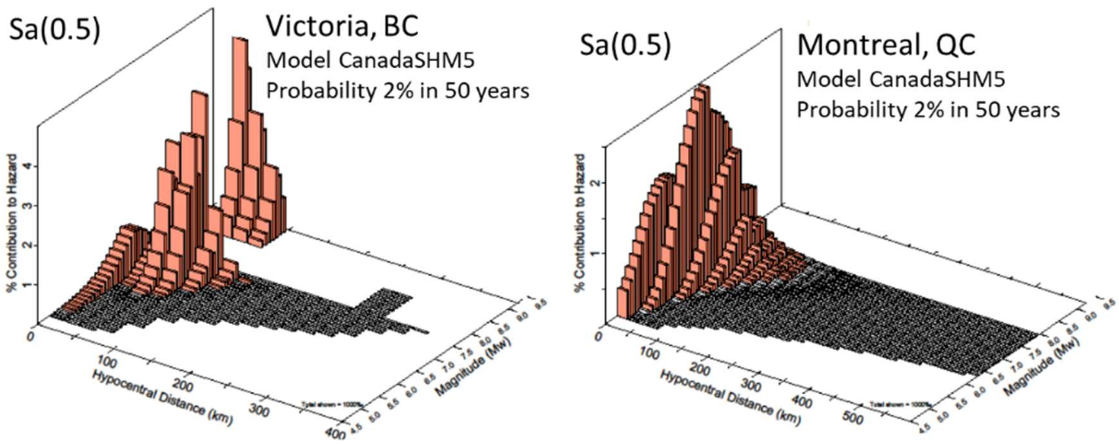

Figure 2. Examples of bimodal (Victoria) and unimodal (Montreal) deaggregation distributions

METHOD

We performed deaggregations for 36163 sites across all of Canada (Figure 3). The grid used is the same grid that was used to generate the national CanadaSHM6 (NBCC 2020) seismic hazard grid. The grid has been generated so as to minimize interpolation errors and is thus denser in regions of steeper hazard gradients. A more complete description of the grid can be found in [4]. The full set of deaggregations was then converted into a database (spreadsheet) which contains summary statistics and the contributions of each magnitude-distance bin to the target hazard value. The full database of deaggregations is planned for publication as an Open File by late 2023.

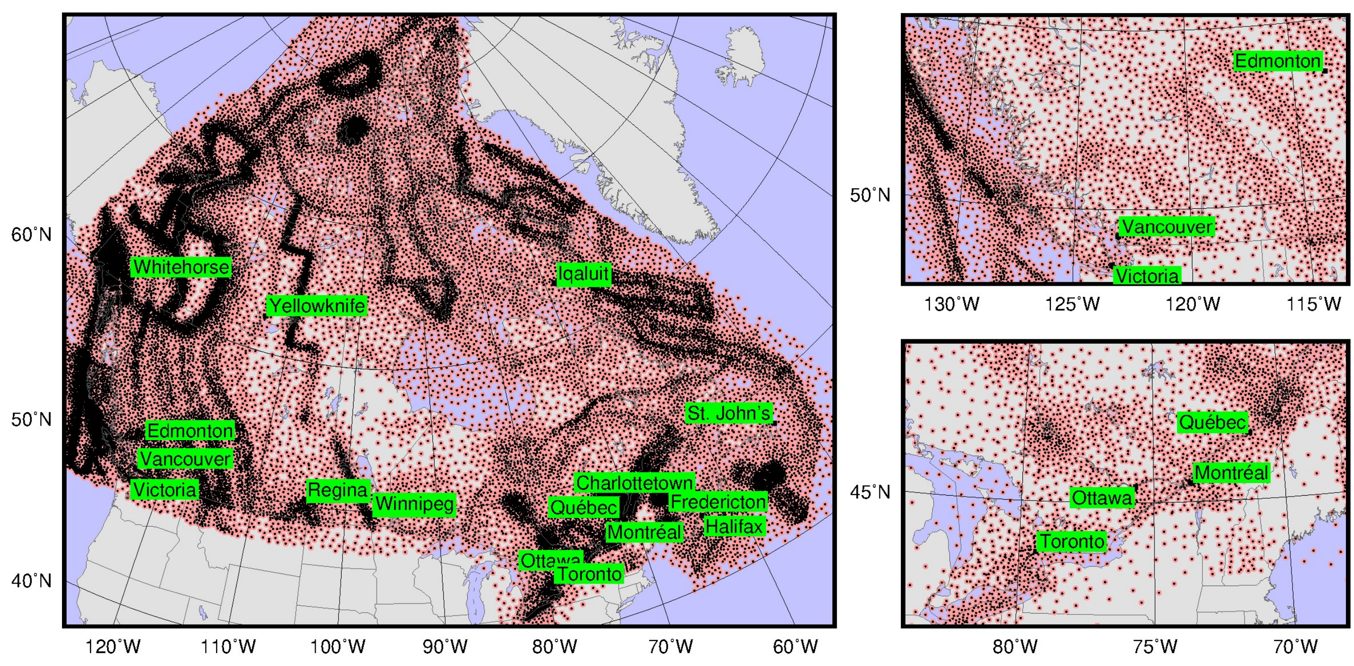

Figure 3. National and zoomed-in regional (southwestern and southeastern Canada) views of the variably-spaced grid of points used to generate the deaggregation database. In general, an increased density of points is used in regions of high hazard gradients or along model boundaries.

To identify regions where the summary statistics may not be reliable requires an algorithm that assesses whether a 2-dimensional distribution is unimodal or multimodal. For this work we have chosen to use topographic prominence [5] as the measure to evaluate the “modality” of each deaggregation distribution. Topographic prominence is a measure of the degree to which a peak stands out from its surroundings and is defined as the difference in height between a peak and the lowest contour which surrounds it and no higher peak. Topographic prominence is often used in mountaineering, as it is a measure of the significance of a peak. Figure 4 provides a depiction of prominence estimation in 1-dimension.

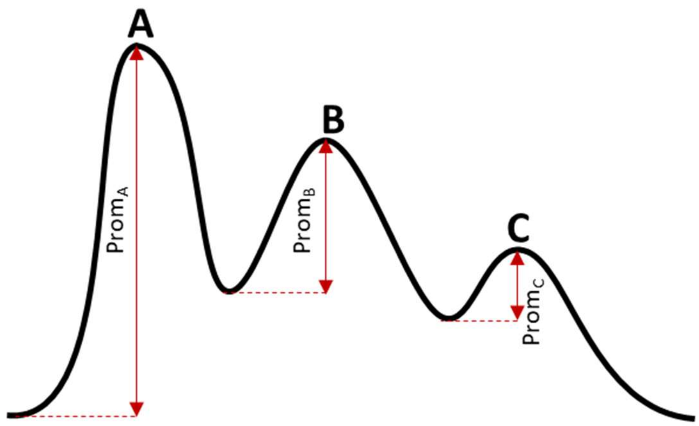

Figure 4. Simplified view of topographic prominence (Prom) as determined for three (A, B, C) peaks.

Prior to calculating the prominence some pre-processing is required to stabilize the data:

1. Normalized the bin values to give the tallest bin a maximum value of 1.0.
2. Smoothed using a 3-by-3 moving average (i.e., ± 0.1 magnitude and ± 30 km). This was needed in order to remove some of the jaggedness that is present in the CanadaSHM5 hazard data due to the manner in which areal sources are discretized.
3. Contoured using increments of 0.1 (of the maximum).

Peak prominence is calculated by finding the height of each peak above the lowest encircling contour line which contains no larger peak [5]. With 1D data (e.g., Figure 4) this can be calculated by 1) extending a horizontal line from each peak and finding the first intersection on either side, 2) finding the minimum value between the intersection and the peak and 3) by calculating the difference between the peak height and the higher of the two minima. We implement this same approach in two dimensions to obtain a list of peaks and their associated prominence. The largest peak is assigned a prominence of 1.0. We introduce the term “degree of multimodality” which equals the fractional height of the second highest prominence. A large degree of multimodality implies that there are one or more sub-equal peaks while a low number implies that there is only one significant peak. The rationale is based on the notion that if the second-highest prominence is below some set threshold, the distribution is likely well described as being “unimodal” (or vice-versa). Performing this procedure on Figure 2 provides a degree of multimodality of 0.9 for Victoria (i.e., likely multimodal) and 0.0 for Montreal (i.e., likely unimodal) for the 2% in 50 year Sa(0.5) hazard. This interpretation is consistent with the visual assessment of the two distributions.

A national map of the degree of multimodality for the 2%/50 year PGA is provided in Figure 5. For this hazard parameter there is strong multimodality along the western edge and in parts of south-western British Columbia. The multimodality along the western coast is due to a change from hazard being dominated by large offshore events (i.e., the Queen Charlotte and Haida Gwaii faults) to local/regional crustal events further inland. In southwestern British Columbia there are contributions from inslab, interface and crustal events (each with relatively distinct ranges of magnitudes and contributing distances) and multimodal distributions arise when these source types have significant contributions to the total hazard value. Less intuitive are the zones of multimodal distributions in eastern Canada. These predominantly arise along the boundaries of low and moderate/high hazard regions and are due to the shift in the source of the predominant hazard contributions from moderate local sources to larger more-distant ones (e.g., west Quebec or the Charlevoix seismic zone).

The degree of multimodality is not only a function of location but also of the hazard parameter being investigated. A similar map could have been generated for any probability and ground motion measure. PGA is used for Figure 5 as a representative map, but it is important to note that for any location some ground motions may be multimodal while others will not be. For example, in Vancouver Sa(0.5) is multimodal due to significant contributions from both inslab and interface events while Sa(10.0) is dominated by interface events and is largely unimodal. A full database of values of the multimodality assessment will be included in the upcoming 2023 Open File on the deaggregation database.

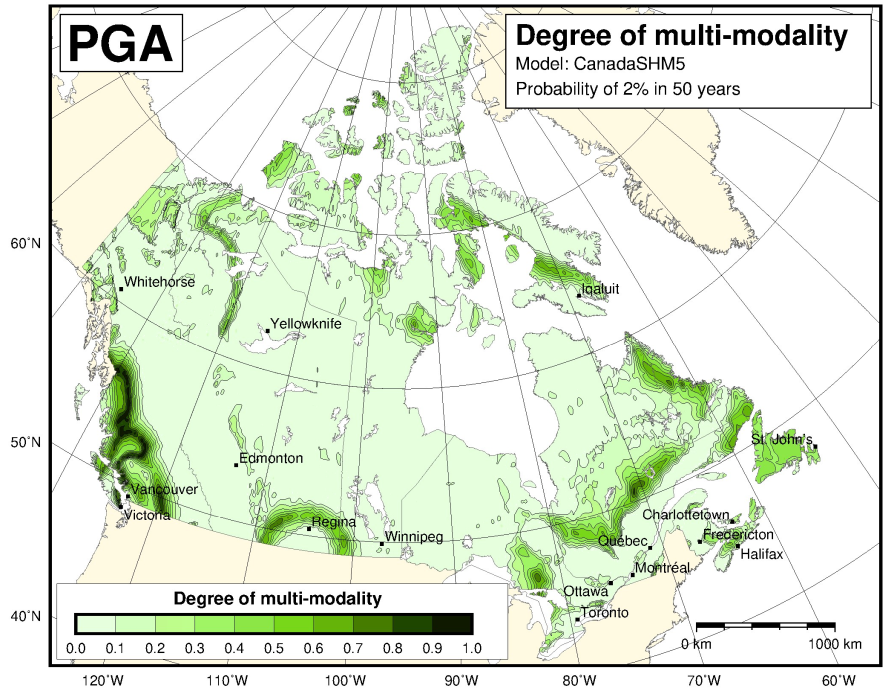

Figure 5. National map of the degree of multimodality of the 2% in 50 year PGA. Low values represent predominantly unimodal results.

NATIONAL DEAGGREGATION MAPS

For regional to national maps of modal and mean values it is important to not over-interpret summary statistics (i.e., mean and mode) in regions where the deaggregations may be multimodal because their summary statistics can be grossly incorrect (e.g., in the case of a mean value between two distinct clusters) or not fully representative (e.g., only representing one of the modes of a multimodal distribution). In this paper we have chosen a threshold of 0.4 to mask values. That is to say that where the degree of multimodality is greater than 0.4 the summary statistics may be unreliable. A value of 0.4 was chosen based on a qualitative assessment of maps generated for various hazard values and from inspection of deaggregations and the associated degree of multimodality in regions with known multimodal distributions (i.e., south-western British Columbia).

National maps of the mean magnitude and distance and modal magnitude and distance for the peak ground acceleration (PGA) are shown in Figure 6. The map of mean magnitude is in general fairly similar to the overall distribution of hazard [6]; zones of high mean magnitudes correspond to areas of relatively higher hazard (e.g., stable craton of Canada has a mean magnitude of 5-6 while Vancouver Island has magnitude 9). However, mean magnitude values must also be interpreted along with their mean distance, for instance while the mean magnitudes are slightly larger away from the St. Lawrence Valley, the corresponding distances also increase, reflecting a change in the mean event from a moderate local to a large regional earthquake. The modal values are slightly more variable as they are more sensitive to the distribution of seismic sources and lack the inherent “smoothing” of the mean. Regardless, these types of national maps are well suited for broad regional and national assessments of relevant earthquake scenarios.

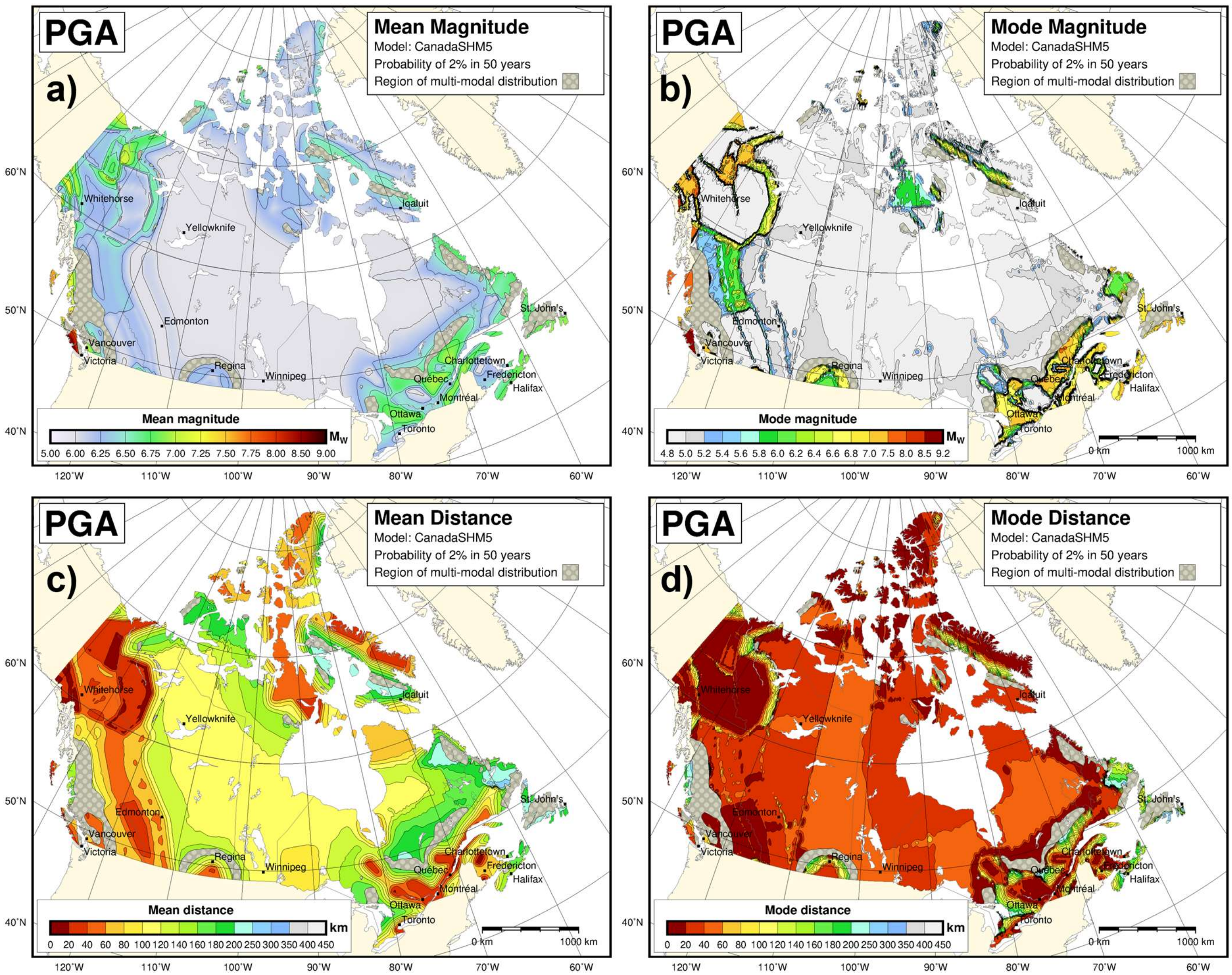

Figure 6. National maps showing a) mean magnitude, b) mode magnitude, c) mean distance, and d) mode distance. For these and all subsequent maps, zones with a degree of multimodality > 0.4 have been masked (grey stipple).

REGIONAL DEAGGREGATION MAPS

Regional maps for southeastern and southwestern Canada for Sa(0.5) and Sa(2.0) are shown in Figures 7-10. This set of maps cannot be exhaustive but rather showcases a relevant portion of the data. The periods chosen are relevant to small-stiff (0.5s) and larger (2.0s) structures and the regions chosen are the parts of Canada with the most significant earthquake risk. Note that, as mentioned previously, the regions of multimodality also change with the ground motion parameter (e.g., Sa(2.0) is multimodal in parts of southern Ontario while Sa(0.5) is unimodal).

Figures 7 and 8 depict the mean parameters for southeastern Canada. Within the moderate-to-high hazard regions of the west Quebec seismic zone and along the Iapetan rift structures within the St. Lawrence Valley the mean magnitudes for Sa(0.5) and Sa(2.0) are approximately 6.75 and 7.0, respectively. The mean distances and magnitudes are in general both larger for Sa(2.0) and longer periods, reflecting the larger hazard contribution of earthquakes that are more distant and larger.

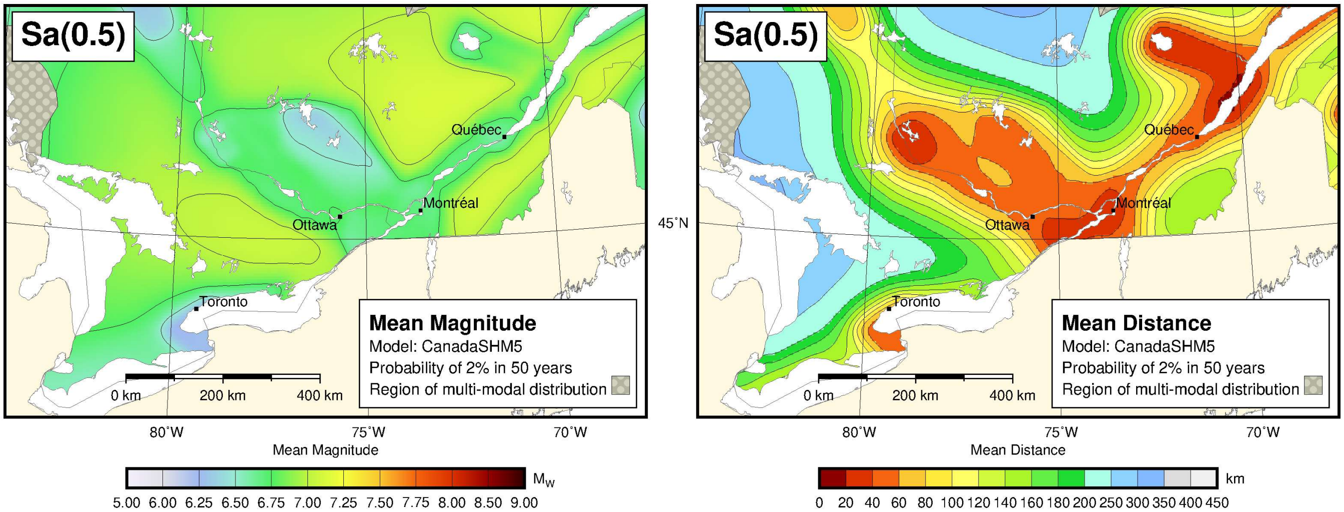

Figure 7. Distribution of mean magnitude and mean distance for the 2% in 50 year Sa(0.5) in southeastern Canada.

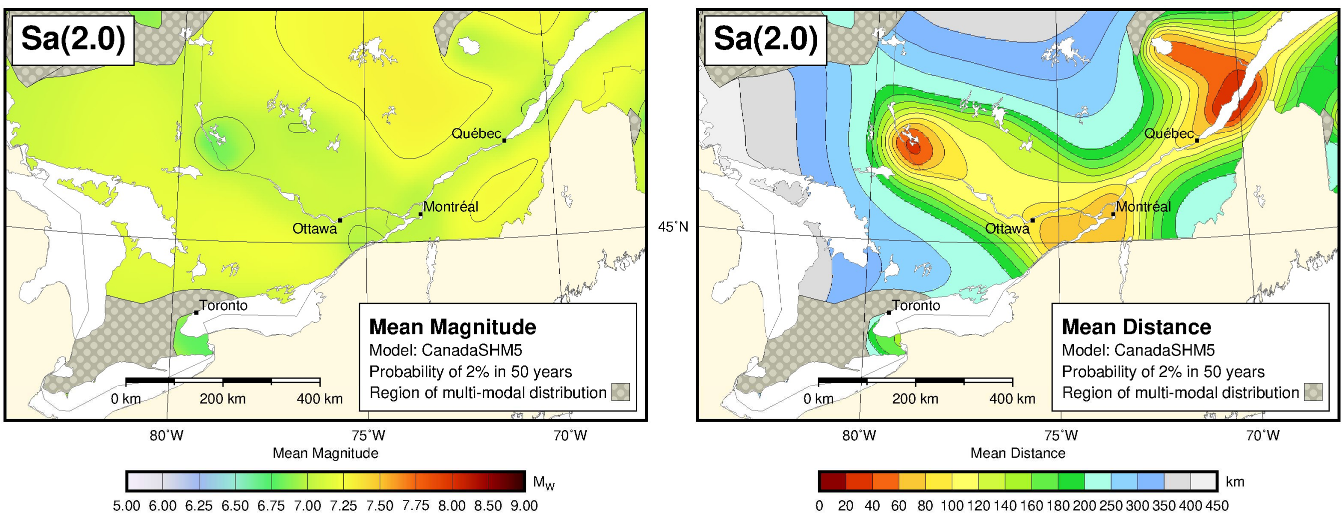

Figure 8. Distribution of mean magnitude and mean distance for the 2% in 50 year Sa(2.0) in southeastern Canada.

Similar maps are shown for southwestern British Columbia in Figures 9 and 10. For the short-period measure the mean parameters are highly influenced by the controlling event type; in southern Vancouver Island that corresponds to subduction interface events while in the mainland it largely corresponds to subduction inslab events. Further inland the magnitudes and distances decrease as the contributions of local crustal events dominate. For long periods (Figure 10), the dominant hazard is largely from large subduction interface events (Cascadia, plus the Queen Charlotte and Haida Gwaii faults in northern British Columbia), which is evident from the large mean magnitudes and the progressive eastward-increasing distance away from those offshore sources.

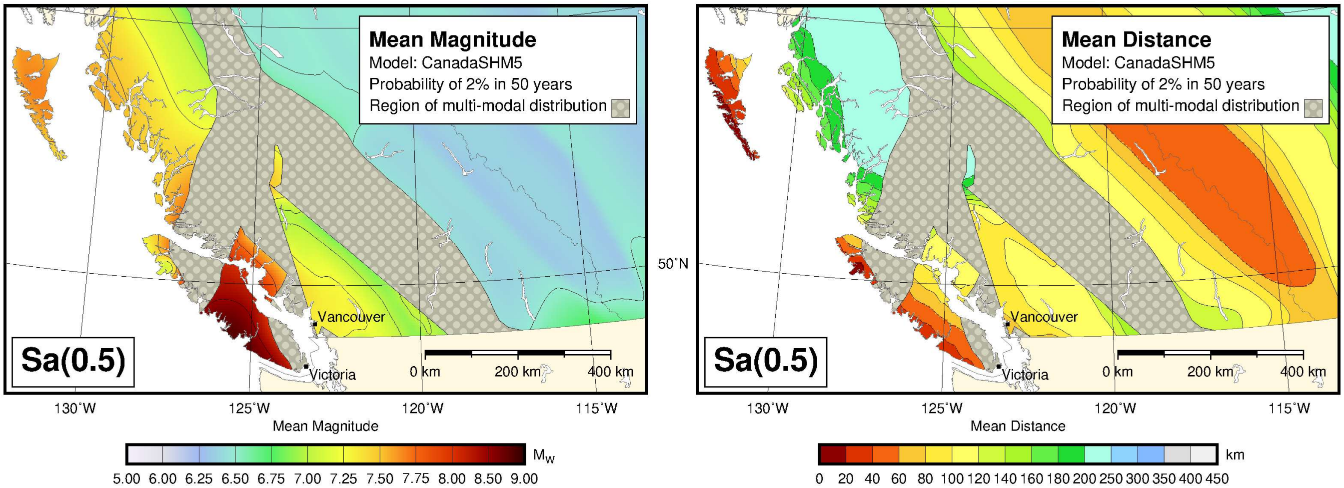

Figure 9. Distribution of mean magnitude and mean distance for the 2% in 50 year Sa(0.5) in southwestern Canada.

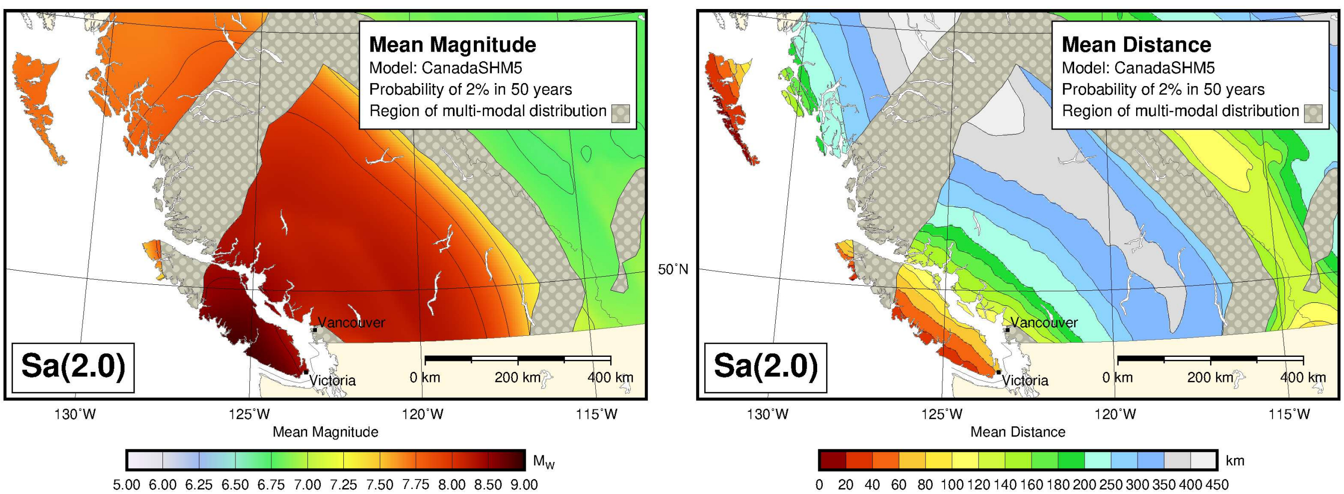

Figure 10. Distribution of mean magnitude and mean distance for the 2% in 50 year Sa(2.0) in southwestern Canada

INTERROGATING DEAGGREGATION RESULTS

In addition to mapping summary statistics such as the mean and mode, the database of deaggregations can be used to answer questions about the significance of specific scenarios or groups of scenarios to the total hazard. For instance, in Figure 11 we show the percent contribution of magnitude ≥6 (left panel) and ≥7 (right panel) to the total 2% in 50 year PGA hazard in southeastern Canada. The inverse of the left panel (i.e., 100% minus the mapped values) represents the contributions of earthquakes smaller than magnitude 6; these are clearly significant over a large region in southeastern Canada along the St. Lawrence Valley and in the West Quebec and Lake Ontario seismic zones. The contributions of very large (magnitude ≥7) earthquakes are lower, but clearly still significant in much of the region, arguing for the importance of considering these large (but relatively rare) earthquakes in southeastern Canada.

In Figure 12 we show the percent contribution of great magnitude ≥8 earthquakes to the short-period (0.5s) and long-period (2.0s) hazard in southwestern British Columbia. These great earthquakes (subduction interface events) are the dominant source of hazard in southern Vancouver Island across all periods. Further inshore, for Victoria and Vancouver, the contributions are reduced (in particular for short periods) as a large portion of the hazard is due to subduction inslab events which have magnitudes smaller than the magnitude 8 threshold.

In lieu of the examples above, alternative views of the data would be for the fractional contributions of specific scenarios (e.g., bin centered at magnitude 6 and 30 km). These types of assessments would be useful in quantitatively determining the applicability of specific event scenarios to a particular region (e.g., for earthquake risk scenarios, emergency planning, etc.).

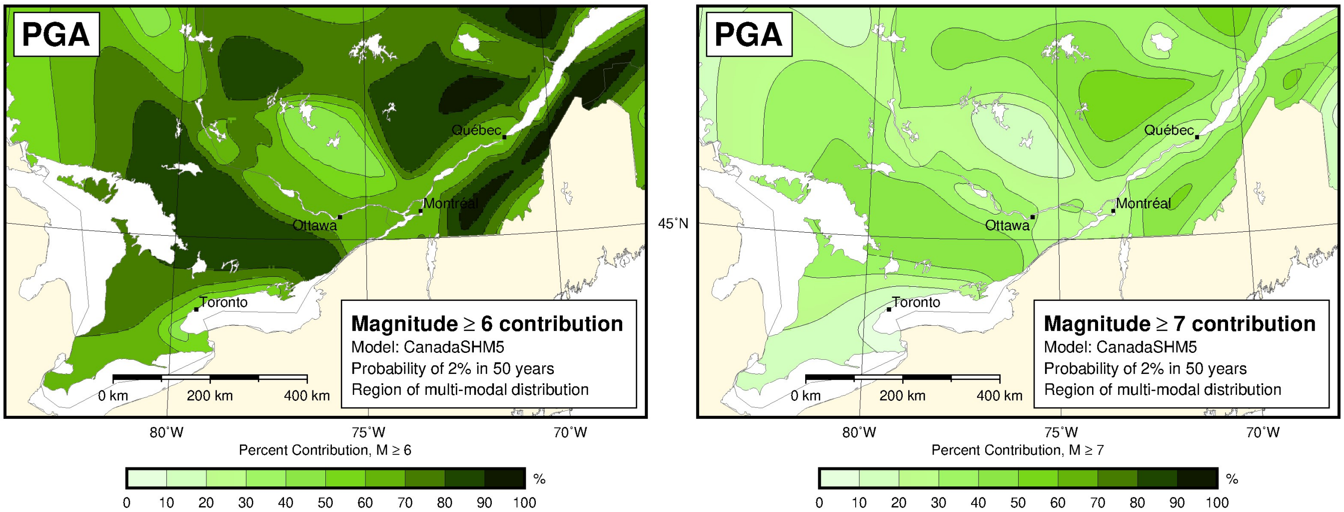

Figure 11. Percent contribution of magnitude 6 or greater and magnitude 7 or greater earthquakes to the 2% in 50 year PGA hazard in southeastern Canada.

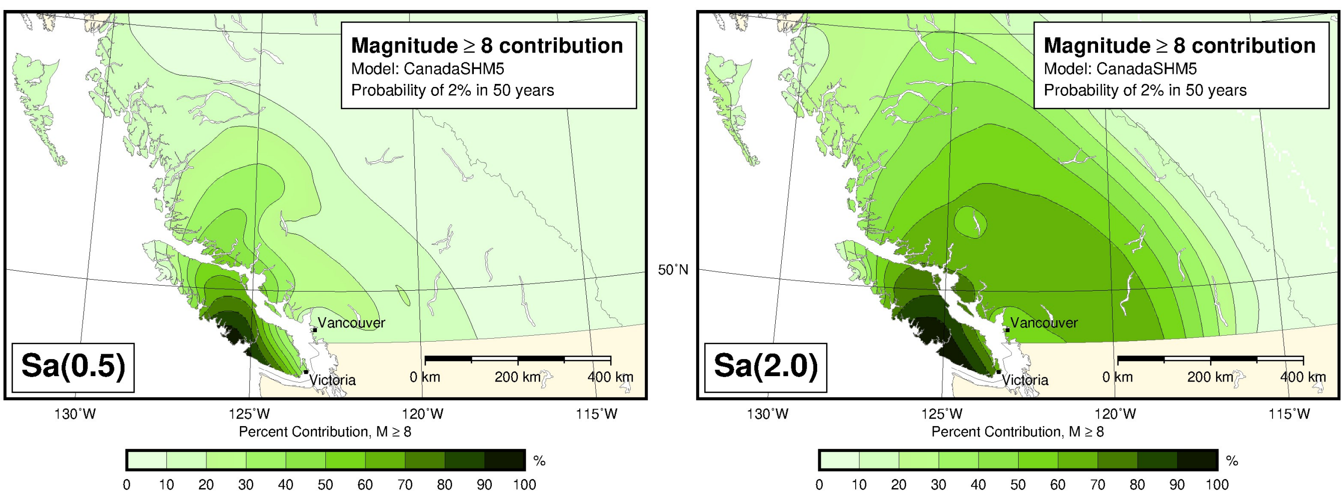

Figure 12. Percent contribution of magnitude 8 or greater earthquakes to the 2% in 50 year Sa(0.5) and Sa(2.0) hazard in southwestern Canada.

DISCUSSION

Summary statistics of deaggregations, like mean and/or modal magnitudes and distances, are useful as simplified characterizations of complicated 2-dimensional distributions. However, in some case this simplification is fraught with potential errors. A more reliable and precise approach would be to use the full deaggregation distribution or some further-quantized version which better approximates the true distribution of events. One option may be to use coarser bins such that the analyses are not overly cumbersome or by incorporating additional statistical measures such as the mean and some percentiles. Regardless, one should not use summary statistics when the shape of the distribution is unknown. For this reason, we introduced a methodology to identify deaggregations that are not well-represented by summary statistics because the underlying distribution is multimodal. The source of multimodality is generally the underlying seismic source model, where the characteristics of significant earthquakes can be very different in different source regions (i.e., large offshore interface events, inslab events and crustal events in southwestern Canada).

In this work we chose to use topographic prominence as the basis for identifying deaggregations that have some degree of multimodality. Determining whether a distribution is unimodal or multimodal is often somewhat subjective, and it is a challenging topic. There are many ways to assess the modality of a distribution (e.g., clustering, dip-tests; [7]) which were not tested in this work. However, peak prominence was found to be a simple and robust measure for our dataset. We have chosen a cut-off value of 0.4 as the threshold above which a deaggregation is suspected to be sufficiently multimodal that a summary statistic such as the mean or mode may be unreliable. Choosing a single threshold across all of Canada is an approximation and may be overly- or under-conservative for some locations.

Moreover, it's important to note that while unimodal distributions may have an "appropriate" mean or modal value, the question of whether a single event is adequately representative of the total distribution depends on the shape of the distribution. For instance, a modal and mean value may be well defined for a very broad (i.e., flat) unimodal deagreggation, but a specific scenario designed around a summary statistic may account for only a very small portion of the total probability. Future work will focus on expanding the algorithm to detect other cases such as the one described above in which the summary statistical values may be inappropriate.

Deaggregations show the contributions from events that were considered in the hazard assessment. As such, they will be influenced by the choice of the minimum considered magnitude (Mmin). A more complete analysis of Mmin is provided in [8]. In short, for some cities (in particular, in lower hazard regions in central and eastern Canada), there could be significant contributions from events below Mmin for higher probability hazard. These events are excluded from the hazard assessment through the engineering decision that they are unlikely to cause significant damage.

CONCLUSIONS

Deaggregations of the NBCC 2015 seismic hazard were performed for more than 30,000 points across all of Canada; this paper provides a preliminary look at this large database. We presented maps of mean and modal magnitudes and distance for various ground motion parameters across Canada. As mean and modal "summary" parameters are not representative for locations that are not unimodal, and in order to properly interpret these values, we performed an assessment of the degree of multimodality using peak prominence analysis of the 2D deaggregation distributions across all of Canada. Using this metric, we were able to flag regions in which we do not expect the use of deaggregation summary statistics alone to be appropriate (e.g., parts of southwestern and southeastern Canada). The maps presented in this work can be used to infer the dominant sources of hazard for engineering or geotechnical analyses and for emergency management planning. The full database of deaggregations will be published in an Open File in late 2023.

ACKNOWLEDGMENTS

The deaggregation and percentile version of GSCFRISK, the hazard calculation engine for the 5th Generation seismic hazard model for Canada, is a legacy of Frank Anglin (1935-2016). All of the maps in this paper were created with the indispensable GMT software package [9]. NRCan contribution number 20230064.

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