GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7893

Fifth Generation Seismic Hazard Model for Canada: Grid values of mean hazard to be used with the 2015 National Building Code of Canada

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ABSTRACT

Canada's 5th Generation seismic hazard model is the basis for the seismic design provisions in the 2015 National Building Code of Canada. The 2015 code uses mean ground motion on firm soil sites for a probability of exceedance of 2% in 50 years, with the ground motion being described by seismic hazard values for eight parameters: spectral acceleration at 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 second periods, peak acceleration and peak velocity. We tabulate values of the eight parameters and for three additional spectral periods (0.05, 0.1 and 0.3 seconds) for more than 200,000 grid points over Canadian territory and surrounding areas. Values at eight probability levels are provided. The spectral parameters will allow the construction of approximate uniform hazard spectra and hazard curves for every locality in Canada, and hence provide necessary information for earthquake-resistant design.

INTRODUCTION

The Geological Survey of Canada (GSC) has produced a new seismic hazard model (Halchuk et al., 2014; Adams et al., 2015a; Adams et al., 2015b) to provide seismic hazard values for the 2015 National Building Code of Canada. Adams et al. (2015b) will cover the development of (and rationale for) this 5th generation hazard model and give the seismic hazard results for selected cities and localities across Canada. It thus will document the final version of the body of work that formed the basis for the Standing Committee on Earthquake Design's (SCED) final recommendations for the seismic design provisions in the 2015 edition of the National Building Code of Canada (NBCC).

The present open file is being issued to place on record and make available seismic hazard values for a grid of more than 200,000 grid points over the Canadian territory and surrounding areas, computed using the final methods and model used for the 2015 National Building Code of Canada. It supplements Adams et al. (2015b), which gives values just for the localities listed in the NBCC table "Design Data for Selected Localities in Canada". The primary values given in this report represent mean ground motion on firm soil sites (V_{S30} = 450 m/s) for a probability of exceedance of 2% in 50 years (0.000404 per annum), for the eight ground motion parameters (5% damped spectral acceleration at 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 second periods, plus peak ground acceleration and peak ground velocity) used by NBCC2015. Values for three additional periods (0.05, 0.1, and 0.3 seconds) are also tabulated. The spectral parameters will allow the construction of approximate uniform hazard spectra (Fig. 1) for every place in Canada, and hence providing necessary information for earthquake-resistant design.

In addition values are calculated for eight probabilities (see Table 1), allowing the construction of hazard curves (e.g. Fig. 2) for each parameter for every place in Canada.

This open file follows on from the equivalent NBCC2005 grid values presented in GSC Open File 5813 (Halchuk and Adams, 2008), which should be referred to for the prior history of the methodology and parameters of the grid. Sample solution lines are given in Table 1, together with a detailed explanation of the format.

METHOD

The present method for calculating seismic hazard builds upon the work of Adams and Halchuk, 2003) which established the fourth generation of seismic hazard maps for Canada. We apply the same Cornell-McGuire methodology (e.g., McGuire, 1993) using a customized version of the FRISK88 hazard code (FRISK88 is a proprietary software product of Risk Engineering Inc.) that we call GSCFRISK. This and other new-generation codes allow explicit inclusion of uncertainty, so the new Canadian model includes the effects of uncertainty. The choice of mean ground motions for NBCC2015 was accepted by SCED, and is discussed in Adams et al. (2015b).

Ground Motion Models

The different physical properties of the crust in eastern and western Canada and the different nature of the earthquake sources in southwestern Canada required the use of separate ground motion models (Adams et al., 2015), also termed Ground Motion Prediction Equations (GMPEs). Atkinson and Adams (2013) discuss the rationale for the seven GMPEs required:
- Eastern and stable craton earthquakes
- Western crustal earthquakes (for areal and fault sources)
- Cascadia inslab earthquakes (for two different depths)
- Cascadia and other western subduction interface earthquakes
- Pacific oceanic crust offshore earthquakes

Reference Ground Condition for Canada

For the preparation of national hazard maps it is essential to present seismic hazard levels on the same ground condition. NBCC2015 has adopted "Site Class C", defined by a 450 m/s time-averaged shear wave velocity in the uppermost 30 m (V_{S30}), as the Canada-wide reference ground condition. The GMPEs we use were all originally determined for the B/C boundary at V_{S30}=760 m/s. They have been modified to give NBCC Site Class C by adding the logarithmic value of appropriate period-dependent amplification factors (Adams et al., 2015b).

Computational aspects

The GSC modified a commercial software program (FRISK88, a proprietary product of Risk Engineering, Inc.) into GSCFRISK to compute hazard and its uncertainty for the 4th Generation maps. The input models are published in Halchuk et al. (2014).

Grid chosen

A grid of points with 10-km spacing was constructed to generate the seismic hazard values for NBCC2005 (Halchuk and Adams, 2008). The same grid was used for this Open File, supplemented by finer grids in the vicinity of modelled active faults in western Canada and the Charlevoix, Quebec, seismic zone. The spacing in the vicinity (within 10 km) of the faults is approximately 2 km and approximately 7 km in the Charlevoix region. The finer spacing was chosen to ensure smooth contouring in these areas of high hazard gradients. The grid has a total of 206,366 points.

Accuracy and precision in this report

The numbers in this report are as correct as humanly possible. The main files represent computer manipulation of the direct output from the computer model, and are definitive.

Seismic hazard values should be reported to two significant figures (in our view, an appropriate level of precision). However we have retained four places after the decimal in Table 1 for two reasons: (i) The reported precision confirms these values as direct numerical output, and (ii) for

interpolation of values for sites between grid points it is advisable that no imprecision be introduced through rounding errors.

Cautions

Distal grid points, i.e. those beyond Canadian territory, are likely to be inaccurate because they extend towards regions where the 5th Generation source zones represent an incomplete account of the seismicity that is contributing ground motions. Thus these distal grid values should be used with extreme caution. The accompanying file canada_2015grid_released.txt contains the latitude and longitude coordinates of boundary of the region for which hazard values were calculated, while canada_2015grid_border.txt contains the coordinates of the Canadian border (the region for which seismic hazard values are considered valid).

The model does not include stable oceanic crust sources that lie farther offshore than higher-activity sources such as ACM, ECM and HGT, because such oceanic sources would not change the onshore hazard for NBCC. Thus the hazard for distal points <u>within</u> Canadian territory but offshore of such sources are underestimated. This is most obvious for the region of the Arctic Ocean north of ~80°-85° N that extends to the North Pole, and where the hazard values drop below the stable craton values onshore.

Grid points in United States of America territory should not be used for seismic hazard design. Values from the USGS website (http://earthquake.usgs.gov/hazards) should be used instead.

RESULTS

Tabulated Values

For each parameter [Sa(0.05), Sa(0.1), Sa(0.2), Sa(0.3), Sa(0.5), Sa(1.0), Sa(2.0), Sa(5.0), Sa(10.0), PGA and PGV], a separate file tabulates the mean, firm ground NBCC Site Class C seismic hazard values at eight different probabilities ranging from 1/50 to 1/2475 years. A sample part of one of these ASCII flatfiles is provided in Table 1. The top of each column in the grid file is labelled with the parameter and annual probability (equivalent probabilities in 50 years and return periods are listed in Table 2). The region gridded extends beyond the borders of Canada, mainly to ensure smooth contouring at the border (but see the Cautions section above).

Maps

Figures 3 to 13 give coloured maps of each of the spectral and peak values for Canada as a whole. The maps show the level of seismic hazard and an indication of the direction and steepness of the hazard gradient, important insights that are hard to gain from the tabulated values. Note that the colour scale is adjusted from map to map in order to show national variations in a sensible way. Figure 14 provides additional detailed contour maps of Sa(0.2) hazard for four regions. It is not intended that values be read off these maps (hence their small scale). Instead, values in the appropriate electronic table file(s) should be used. Hazard depicted on these maps has been extended into the offshore but is limited to Canadian onshore and

offshore territory. Grid values for regions outside of Canadian territory are given in the electronic tables to ensure smooth contouring near the border, but the caveats noted in the Caution section apply.

GeoTIFF Files

For the first time, the GSC is providing the national seismic hazard maps in Geographic Information Systems (GIS)-enabled geoTIFF files. GeoTIFF is a metadata standard which allows georeferencing information to be embedded within a TIFF file (Mahammad and Ramakrishnan, 2015). The benefit of the geoTIFF format is that the maps can be recoloured and reprojected easily in various GIS software packages.

The geoTIFF files (each with a single-band) are generated by parsing the tabulated values for the various ground-motion periods and exceedance probabilities. For each period and probability, these values are interpolated across a uniform grid spacing of 0.05º (approximately 3.6 km at 50ºN) using a 2-dimensional (smoothed) cubic-spline interpolation (SciPy.org). Interpolated values outside of the region covered by the tabulated grid are assigned to NaN or "no data" values and should be masked when using the geoTIFF files for plotting purposes. The interpolated grid values were subsequently converted to the geoTIFF format using the Python GDAL/OGR API (https://pcjericks.github.io/py-gdalogr-cookbook/). Note that the interpolation to 0.05º grid spacing may slightly smooth hazard values near crustal faults in the Yukon Territory, where the hazard is calculated at a grid spacing of 2 km. Note that the grid values in the tabulated gird files are definitive (i.e. individually calculated from the hazard model) whereas the geoTIFFs are derivative (i.e. derived by interpolation of the definitive results). Therefore if there is a difference, the grid values should be used.

The geodetic reference system used is WGS84.

GeoTIFF files at three exceedance probabilities (2%, 5% and 10% in 50-year exceedance) have been generated. Figure 15 provides an example of the application of the 2% in 50-year 2015 hazard values at *Sa*(0.2 s) for the greater Vancouver region.

If users are plotting the hazard values at national scale, the authors recommend similar colour palette discretization to those used in Figures 3 to 13 (i.e. not using a linearly discretized palette) given the spatial variability of calculated hazard values across Canada.

DISCUSSION

Seismic hazard values for all points in Canada can be obtained from the definitive grid values in this report by interpolation. Halchuk and Adams (2008) contains details on the interpolation method used. The interpolation will generally be very good, especially in regions of low hazard gradient. The gradient can be found by inspection of neighboring data points or in a more general way from Figures 3 - 14. Tests in Halchuk and Adams, 2008 indicated that for the "seismically active" part of Canada (the region with hazard values above the stable craton level, comprising approximately 60% of the 206,000+ points), interpolated results differ from the

directly calculated results by less than 2%, 19 times out of 20. The 2015 interpolation will be better than this, because the underlying model is fully probabilistic[a].

We include probabilities as high as 1/50 years. The 1/50 and 1/75 year seismic hazard estimates, from the model (and even the 1/100 estimates in low-seismicity regions) might significantly underestimate the actual weak-shaking values as the model deliberately does not include contributions from earthquakes with magnitudes smaller than M_W 4.8; such smaller earthquakes make a significant contribution to the weak shaking at these higher probabilities[b].

We do not include values for probabilities lower than 2%/50 years. The determination of 1/5,000 or 1/10,000 year (0.0002 or 0.0001 per annum) seismic hazard is normally required only for special facilities such as nuclear power plants or dams which have a large consequence if they were to fail. These low probabilities are beyond the scope of the current National Building Code of Canada (NBCC), which is intended to be used for standard structures at a probability of 1/2475 years (0.000404 p.a.). Extrapolation of the hazard model to lower probability results is mathematically possible, but represents an uncertain extrapolation of the model, and may be unreliable due to (for example) the crudeness of the seismic source zones used in the national model.

Having said that, we give some guidance for screening purposes. The user can determine the seismic hazard at the 10%/50 year and 2%/50 year probabilities for any point in Canada from the grid tables. One can then plot these two sets of values on a log-log scale and extrapolate them out to the 1/10,000 year return period, with the understanding that the GSC cannot vouch for the validity of these extrapolated values at a particular site. For most sites in Canada, these extrapolated 1/10,000 year values will be slightly conservative compared to the precise 1/10,000 year values calculated directly from the 5th generation model (though precise, the values may be inaccurate). These values can be used as a screening tool to determine if a site-specific seismic hazard assessment is warranted.

If the project requires it (because of the consequences of failure), a site specific hazard assessment developed by consulting engineers would be required to determine the 1/10,000 year hazard. The engineers would have to perform detailed investigations of the local earthquakes and nearby earthquake sources and/or faults in order to better determine the very low probability hazard for the site.

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[a] The interpolations in the 2005 model are not as precise because the larger deviations arose when the values of adjacent grid points came from different seismicity models within the 2005 "Robust" model, with a consequent abrupt change in seismic hazard gradient.

[b] However, such smaller earthquakes are not considered of engineering significance as their duration of shaking is generally too short to cause damage.

SUMMARY

This Open File gives the final seismic hazard results used by the 2015 edition of the National Building Code of Canada. Three additional spectral parameters are tabulated to provide extended detail on the shape of the uniform hazard spectra. The spectral parameter values in this open file will permit site-specific uniform hazard spectra and site-specific hazard curves to be constructed for each place in Canada, and hence allow improved earthquake-resistant design.

ACKNOWLEDGEMENTS

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Adams, J., Halchuk, S., Allen, T.I., Rogers, G.C., 2015a. Canada's 5th Generation seismic hazard model as prepared for the 2015 National Building Code of Canada. *Proceedings, 11th Canadian Conference on Earthquake Engineering*, 21–24 July 2015, Victoria, Canada, Paper 93775, 10p. *Downloadable from the Earthquakes Canada website.*

Adams, J., Halchuk, S., Allen, T.I., Rogers, G.C., 2015b. Fifth Generation seismic hazard model and values for the 2015 National Building Code of Canada. Geological Survey of Canada Open File xxxx (in preparation).

Atkinson, G., and Adams, J., 2013. Ground motion prediction equations for application to the 2015 national seismic hazard maps of Canada, Can. J. Civil Eng. 40**,** 988–998. *Downloadable from the Earthquakes Canada website.*

Halchuk, S; Adams, J., 2008. Fourth generation seismic hazard maps of Canada: Maps and grid values to be used with the 2005 National Building Code of Canada; Geological Survey of

Canada, Open File 5813, 2008; 32 pages; 1 CD-ROM, doi:10.4095/225402. *Downloadable from the Earthquakes Canada website.*

Halchuk, S., Allen, T.I., Adams, J., and Rogers, G.C., 2014. Fifth Generation Seismic Hazard Model Input Files as Proposed to Produce Values for the 2015 National Building Code of Canada; Geological Survey of Canada, Open File 7576. doi:10.4095/293907. *Downloadable from the Earthquakes Canada website.*

Mahammad, S. S., and R. Ramakrishnan (2015). *GeoTIFF - A standard image file format for GIS applications*, Retrieved 10 August 2015, from http://www.gisdevelopment.net/-technology/ip/mi03117pf.htm.

Wessel, P., and W. H. F. Smith, 1991. Free software helps map and display data, Eos Trans, AGU, v. 72, p. 441.

TABLES AND FIGURES

Table 1 – Sample format of the electronic supplement files containing seismic hazard values for the 10 km grid across Canada. An explanation of the columns is given in the Results section. Line 1 (which wraps in this display) identifies the ground motion parameter that is calculated. Line 2 contains the latitude and longitude column labels, followed by the probabilities (expressed in terms of *per annum* values). Line 3 and subsequent lines give the latitude and longitude values, followed by the mean, soil Class C seismic hazard values. The values are in units of g (9.81 m/s^2) for spectral & peak acceleration, and in units of m/s for peak velocity. The "Point No." is a reference for the grid point number. Grid points should be in the same order as the 4th Generation grid (Halchuk and Adams, 2008).

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2015 GSC 5th Generation mean seismic hazard values. Sa(0.2 s) on Soil Class C (Vs30 = 450 m/s) for
probabilities of 1/50 - 1/2475 years. Values expressed in terms of g (9.81 m/s^2)

Latitude Longitude0.0200   0.01375  0.0100   0.00445  0.0021   0.0010   0.0005   0.000404  Point No.

60.000  -140.000  0.2979   0.3603   0.4227   0.6164   0.8518   1.1492   1.4889   1.6039   pt.     1

59.999  -139.821  0.2623   0.3169   0.3682   0.5285   0.7222   0.9632   1.2421   1.3417   pt.     2

59.997  -139.642  0.2477   0.3031   0.3555   0.5203   0.7151   0.9446   1.1991   1.2876   pt.     3

…

…

…
```

Table 2 – Equivalent probabilities. Seismic hazard values are provided for the following annual probabilities in the electronic supplement files. Equivalent probabilities in 50 years and return periods are given.

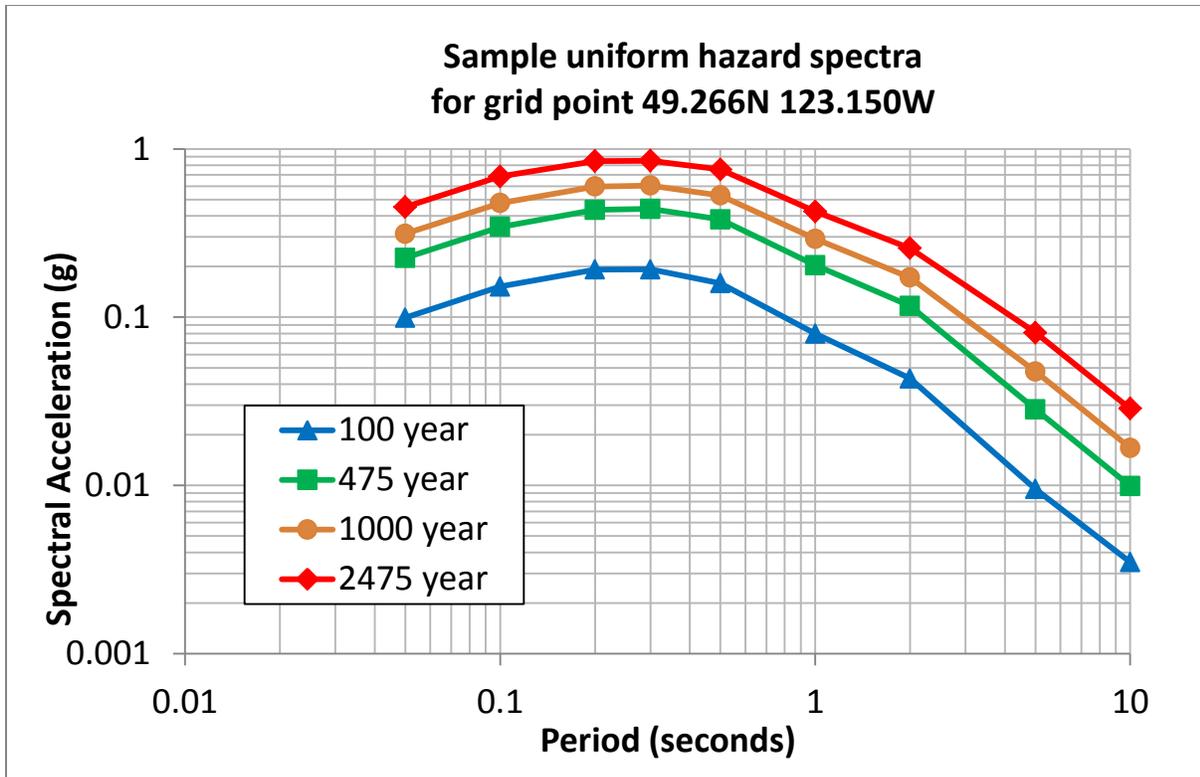| Annual probability	Probability (%) in 50 years	Return period (years)
0.02	63.6	50
0.01375	50.0	73
0.01	40.0	100
0.00445	20.0	225
0.0021	10.0	475
0.001	5.0	1000
0.0005	2.5	2000
0.000404	2.0	2475

Figure 1. Sample uniform hazard spectra at 4 different return periods derived from grid point values.
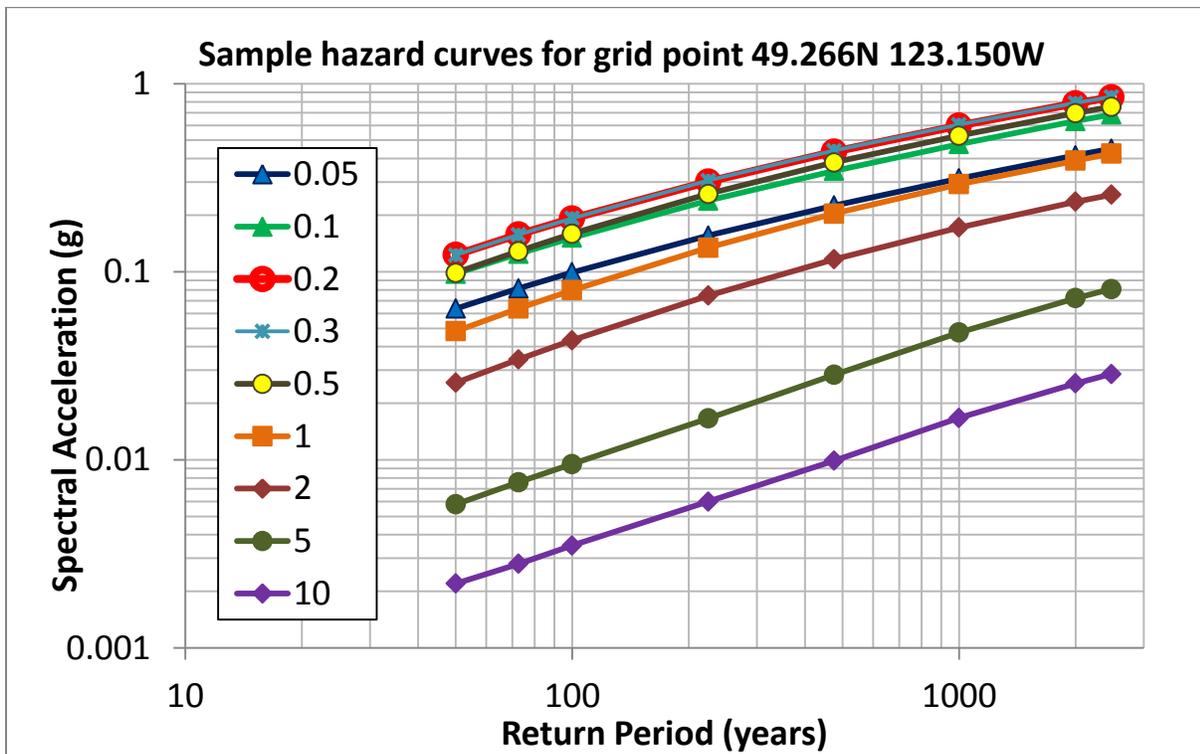

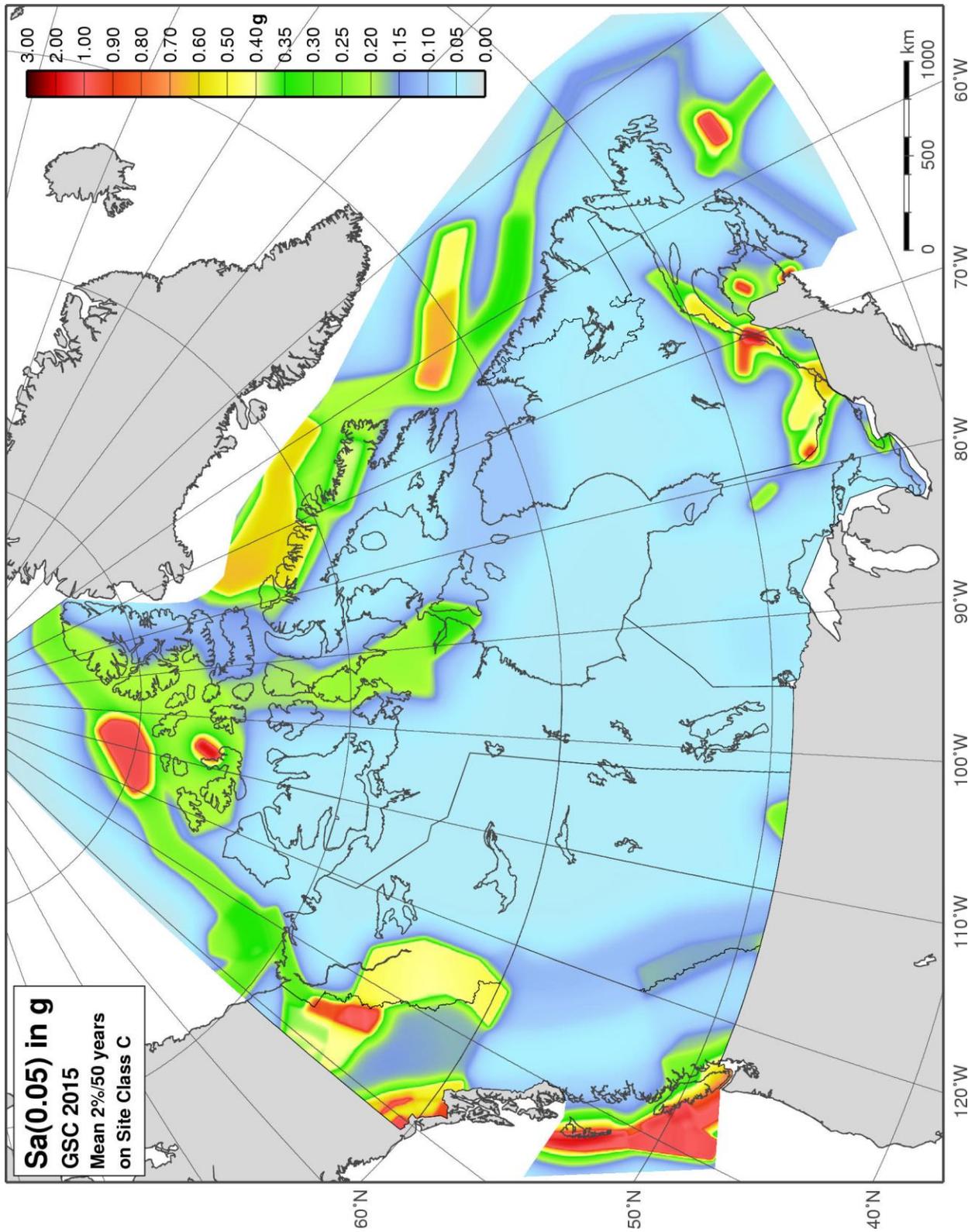Figure 2. Sample hazard curves of all spectral parameters for a given grid point.

Figure 3. Spectral Acceleration map for a period of 0.05 seconds for Canada. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, in g.
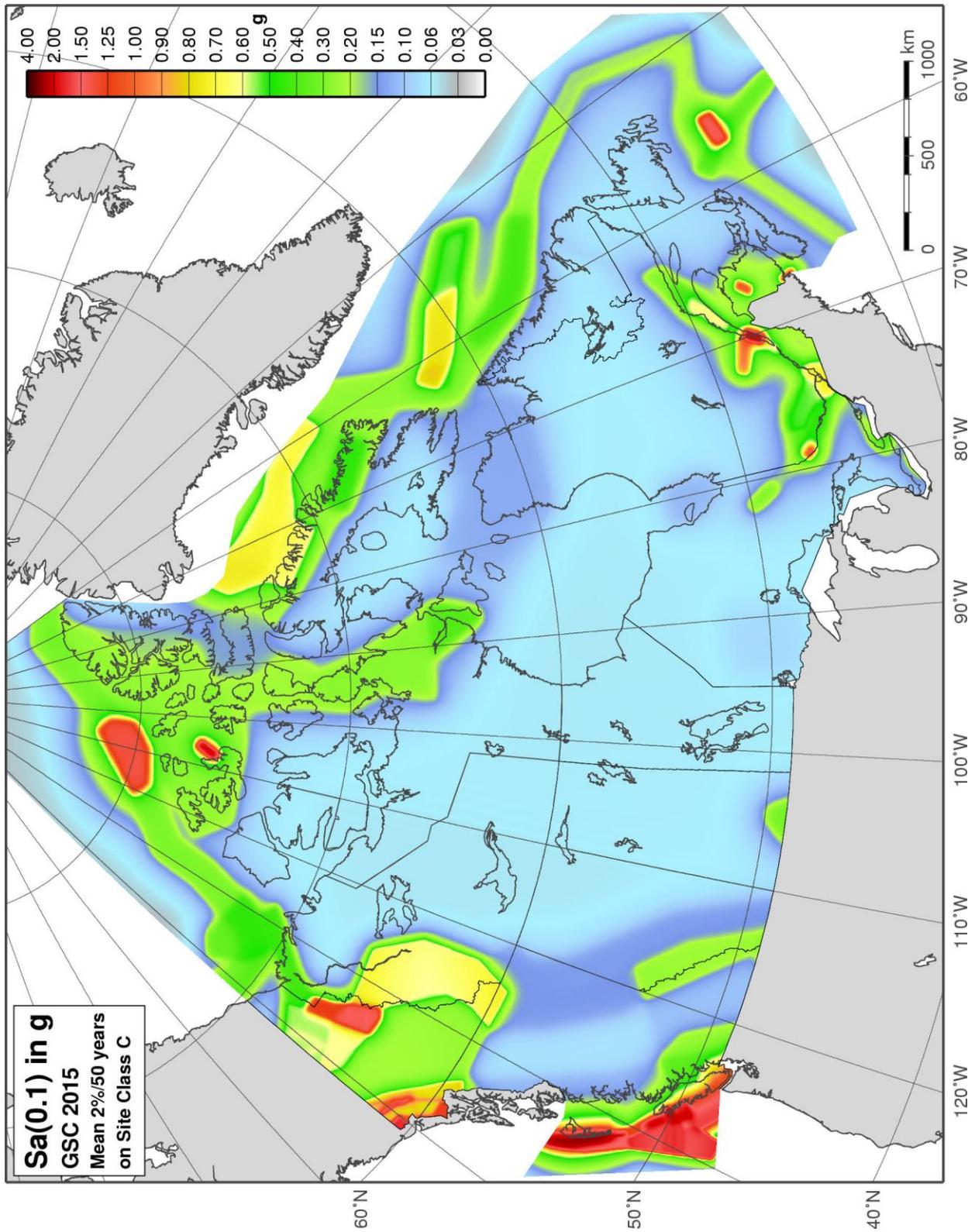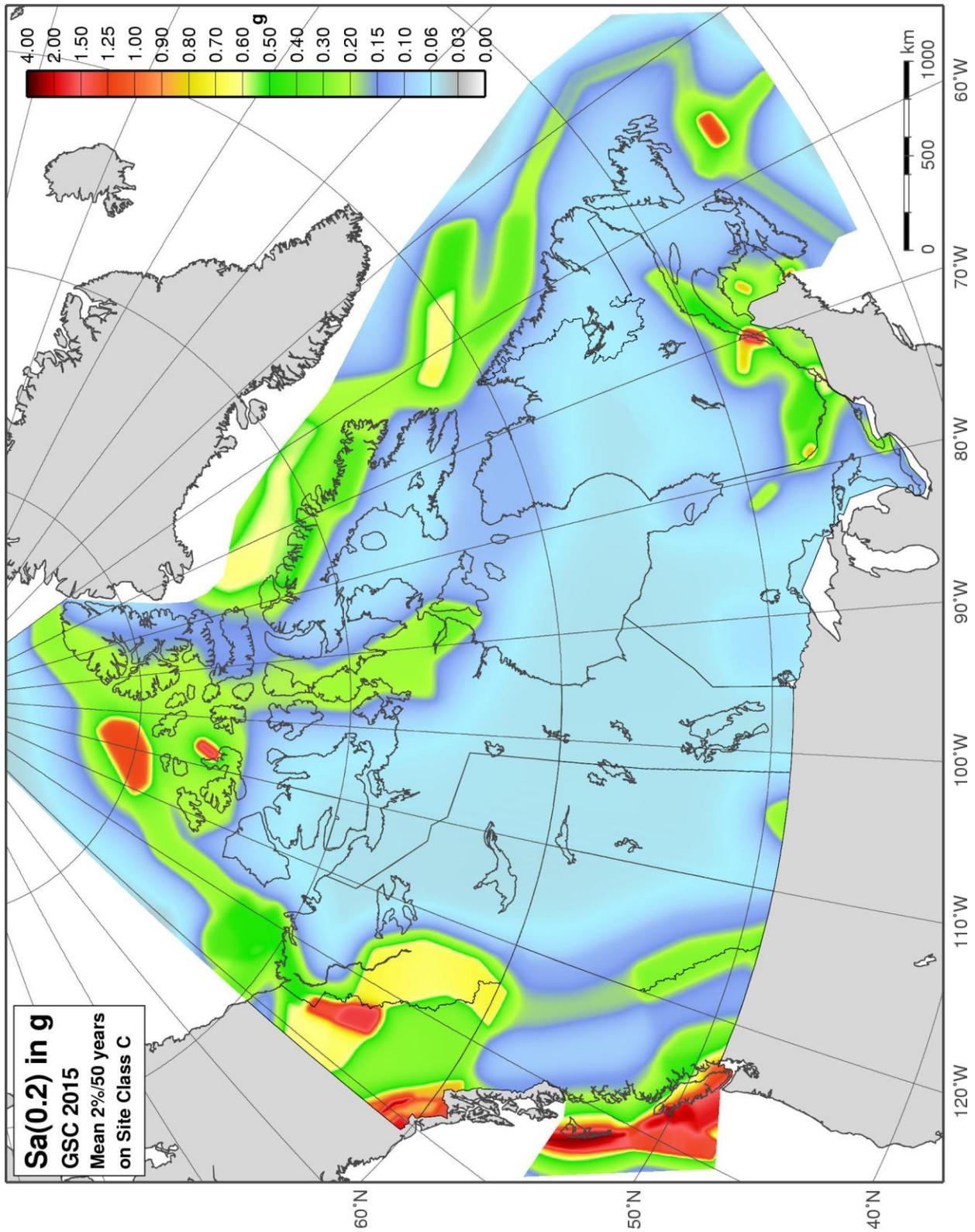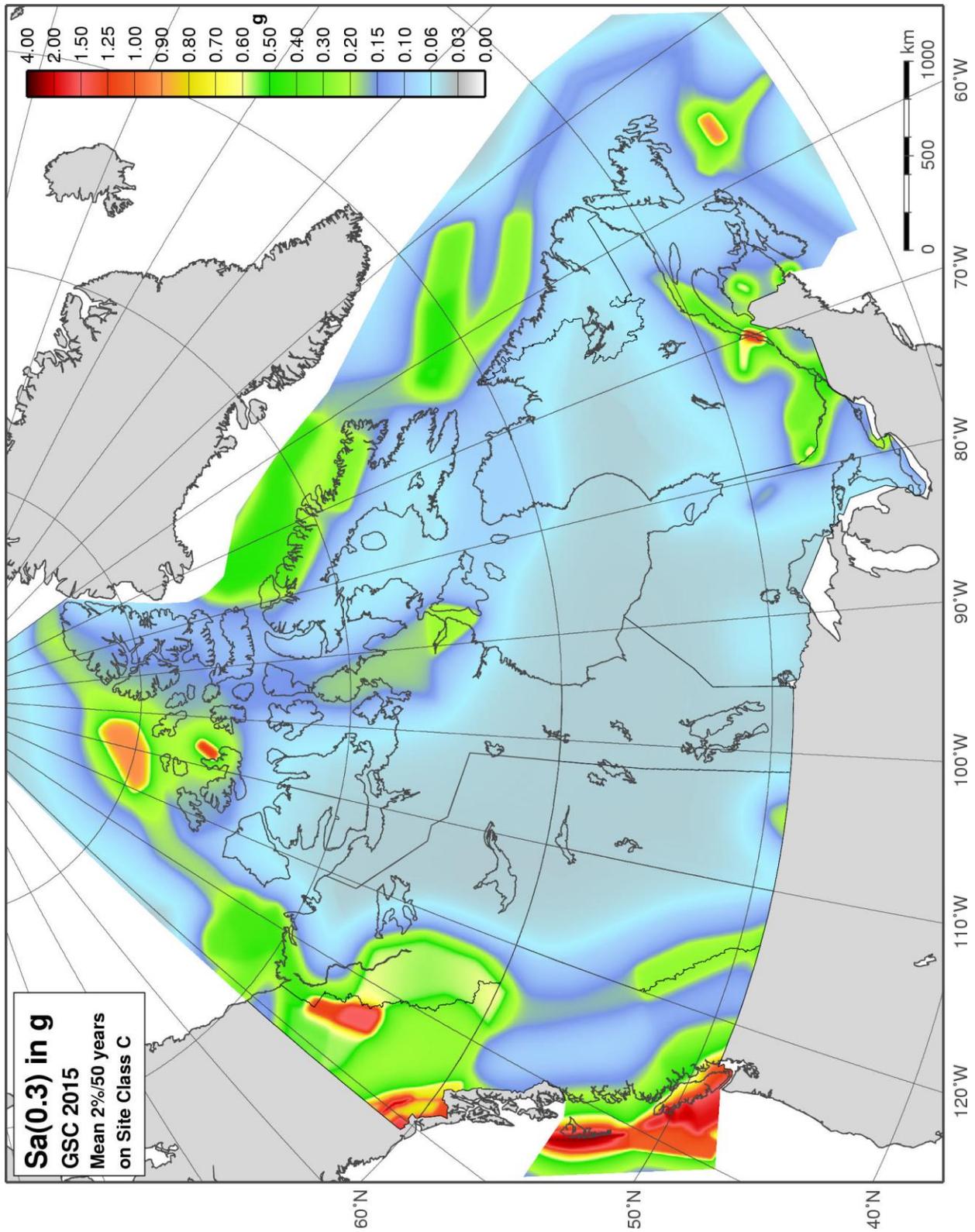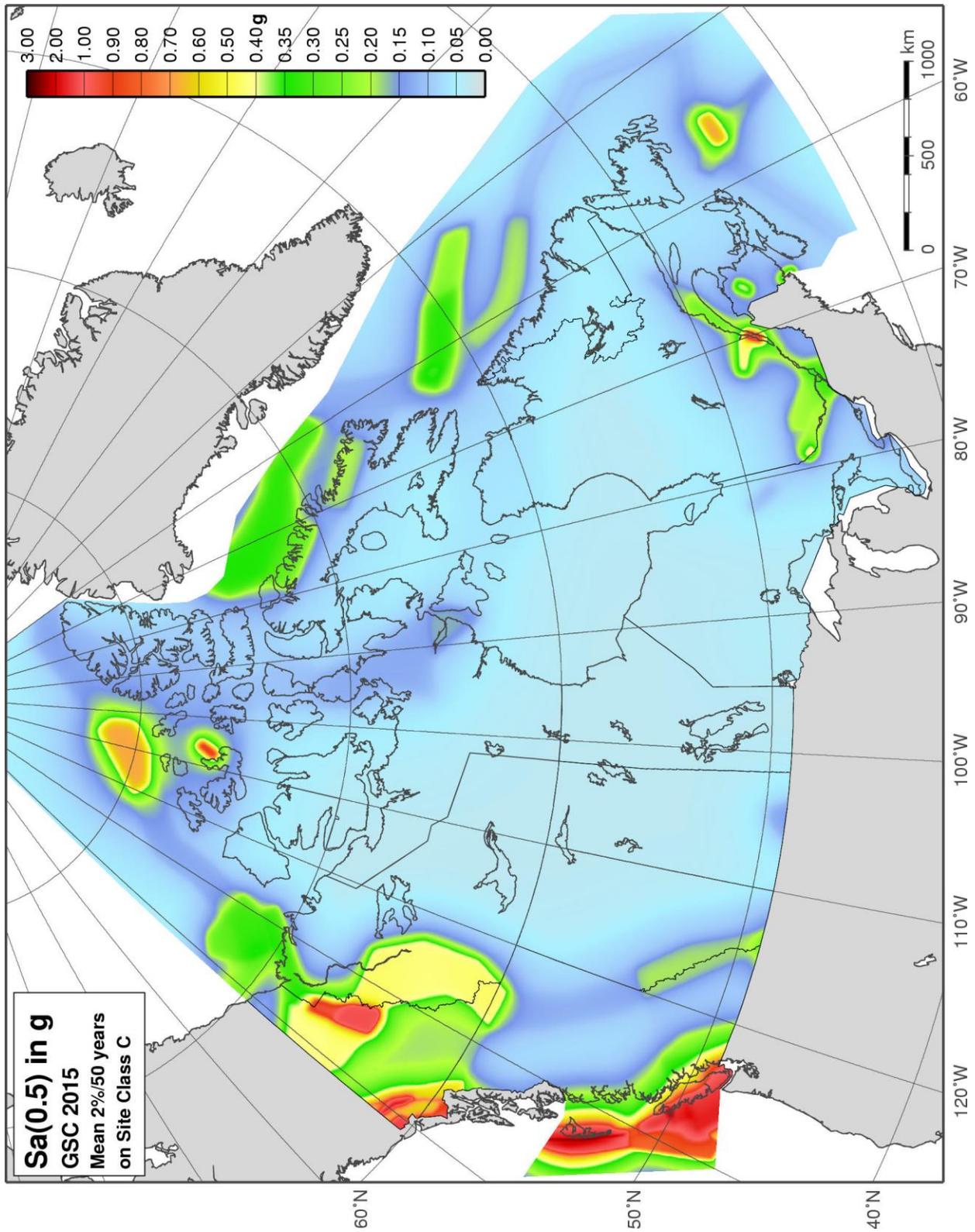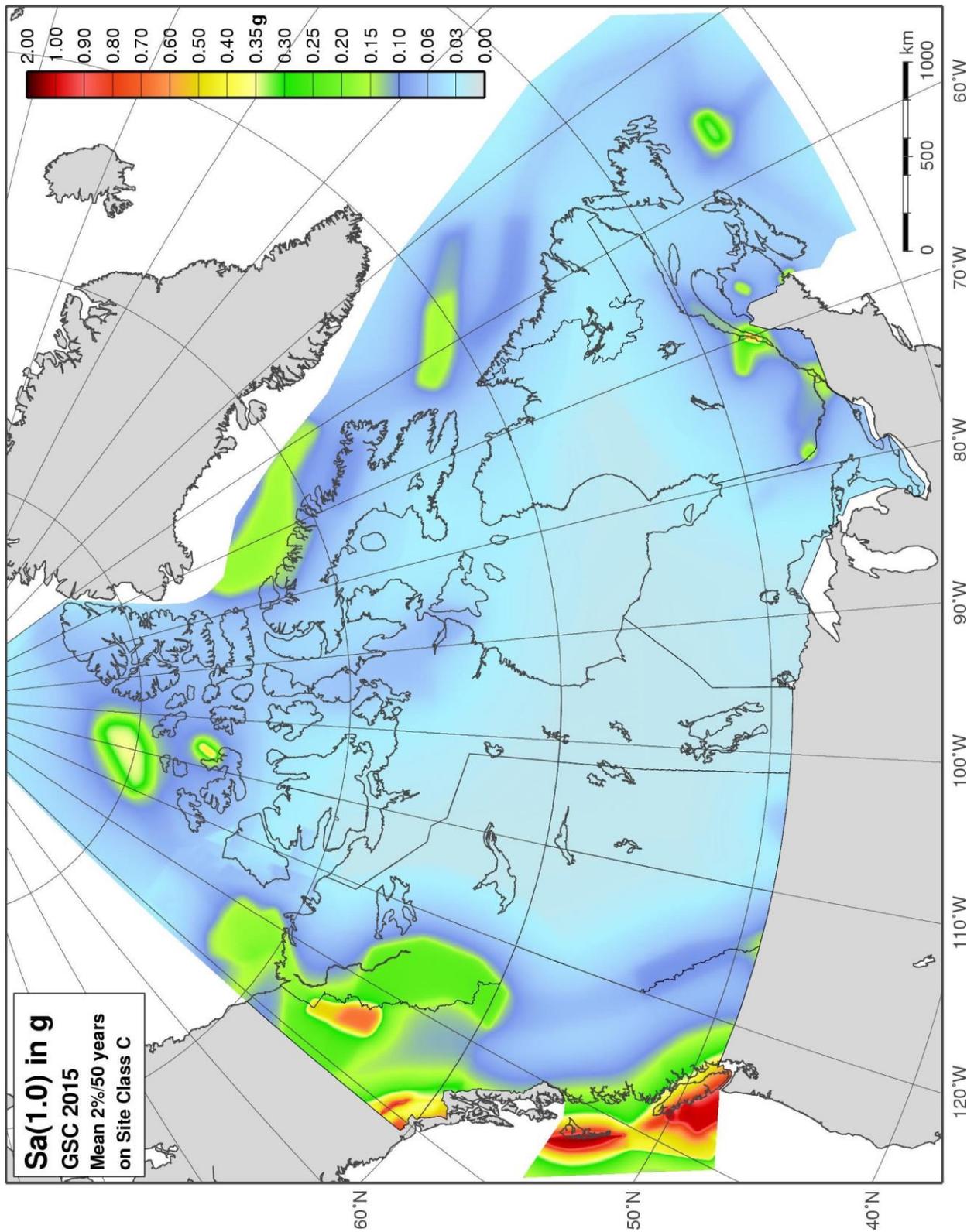
Figure 4. Spectral Acceleration map for a period of 0.1 seconds for Canada. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, in g.
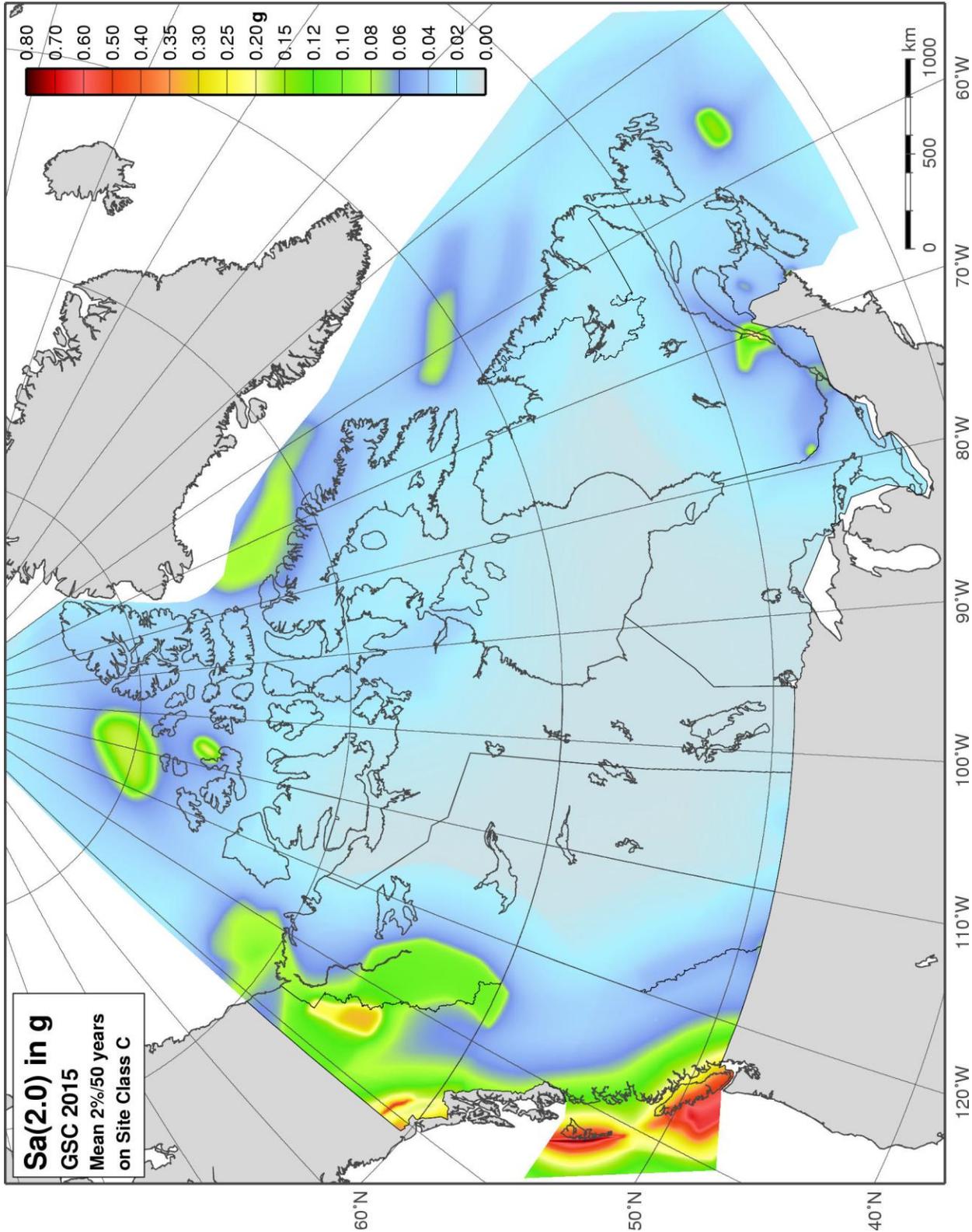
Figure 5. Spectral Acceleration map for a period of 0.2 seconds for Canada. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, in g.
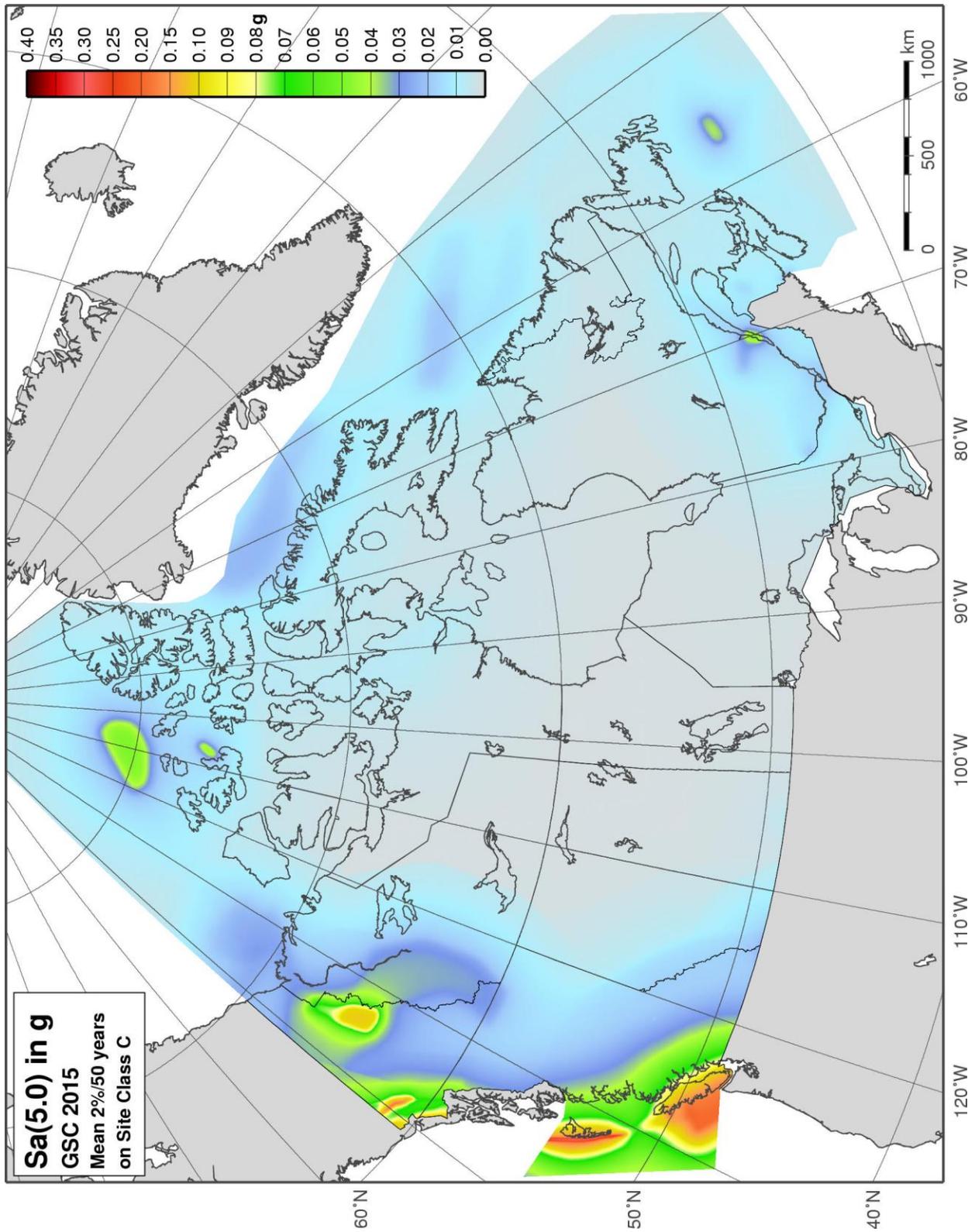
Figure 6. Spectral Acceleration map for a period of 0.3seconds for Canada. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, in g.

Figure 7. Spectral Acceleration map for a period of 0.5 seconds for Canada. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, in g.

Figure 8. Spectral Acceleration map for a period of 1.0 seconds for Canada. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, in g.
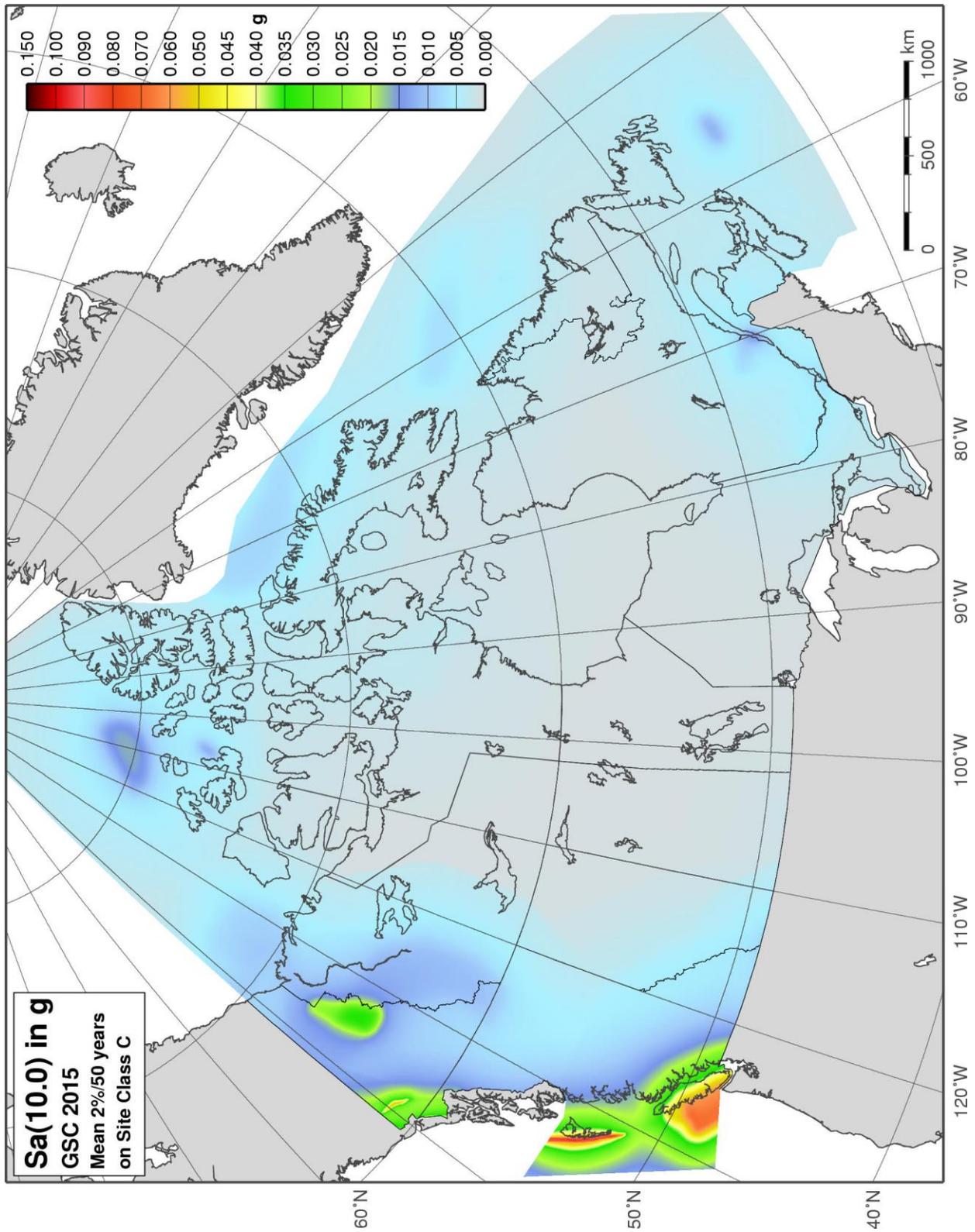
Figure 9. Spectral Acceleration map for a period of 2.0 seconds for Canada. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, in g.
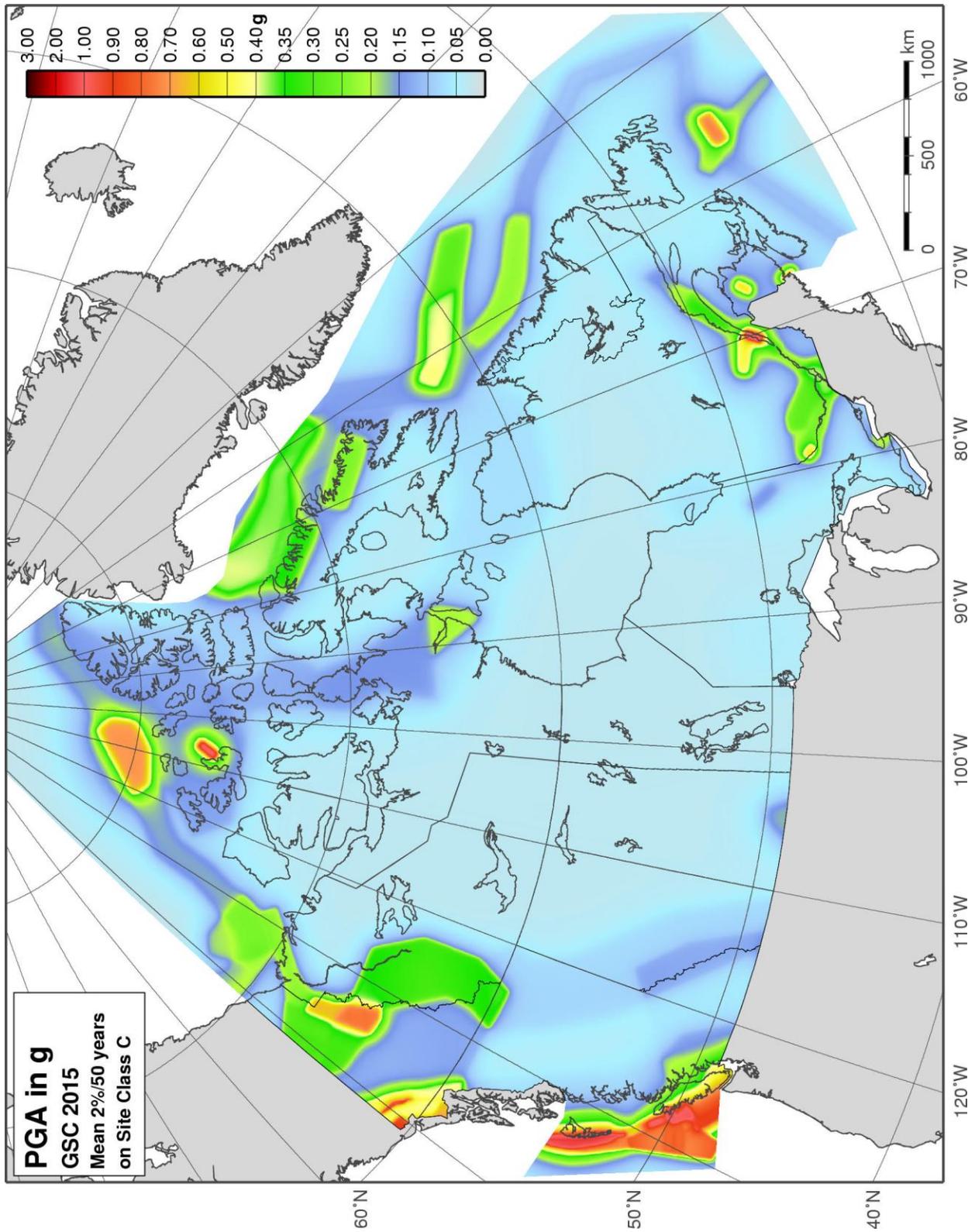
Figure 10. Spectral Acceleration map for a period of 5.0 seconds for Canada. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, in g.

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Figure 11. Spectral Acceleration map for a period of 10.0 seconds for Canada. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, in g.

Figure 12. Peak Acceleration map for Canada. Mean values of 5% damped peak acceleration for Site Class C and a probability of 2%/50 years, in g.
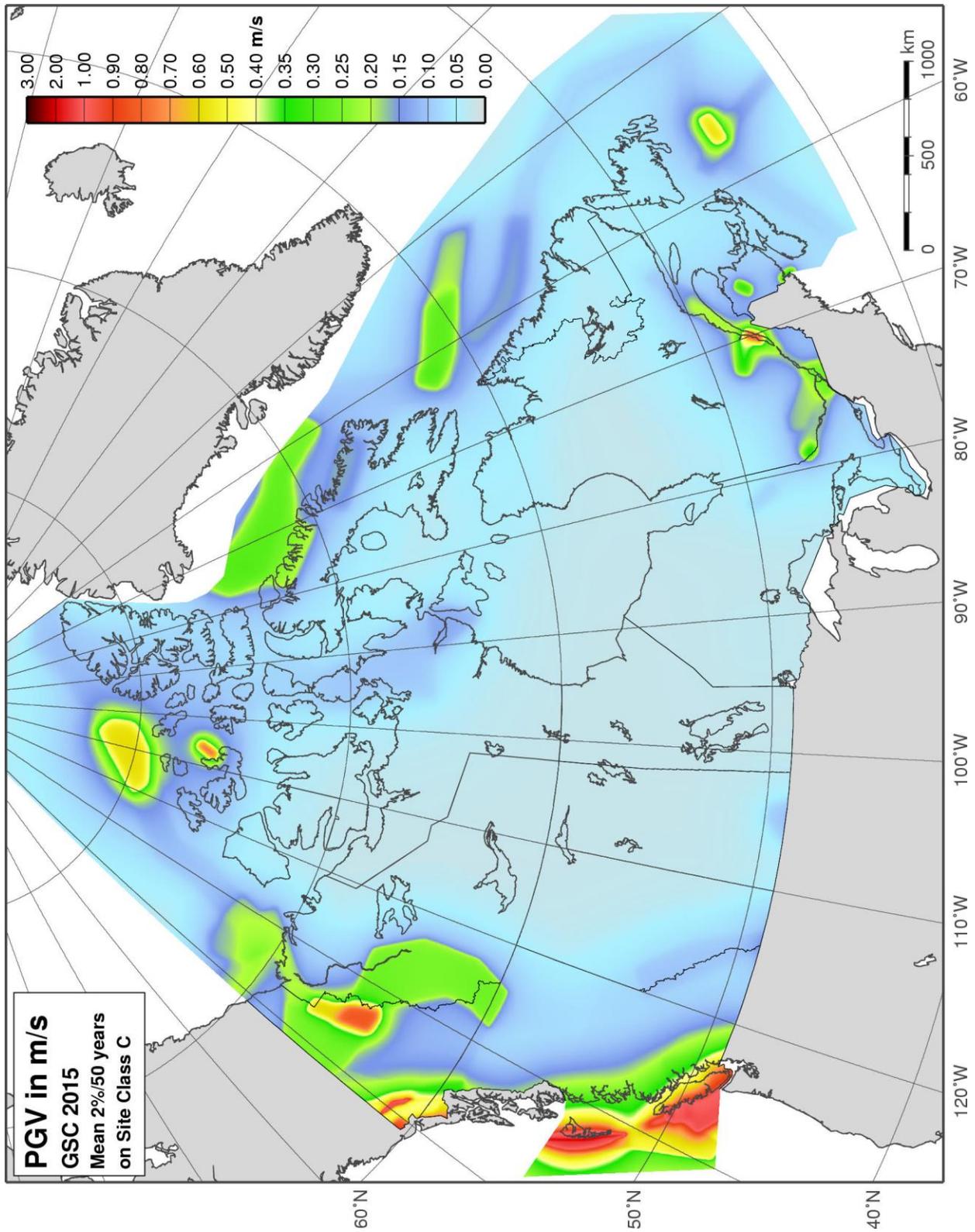
Figure 13. Peak Velocity map for Canada. Mean values of 5% damped peak velocity for Site Class C and a probability of 2%/50 years, in m/s.
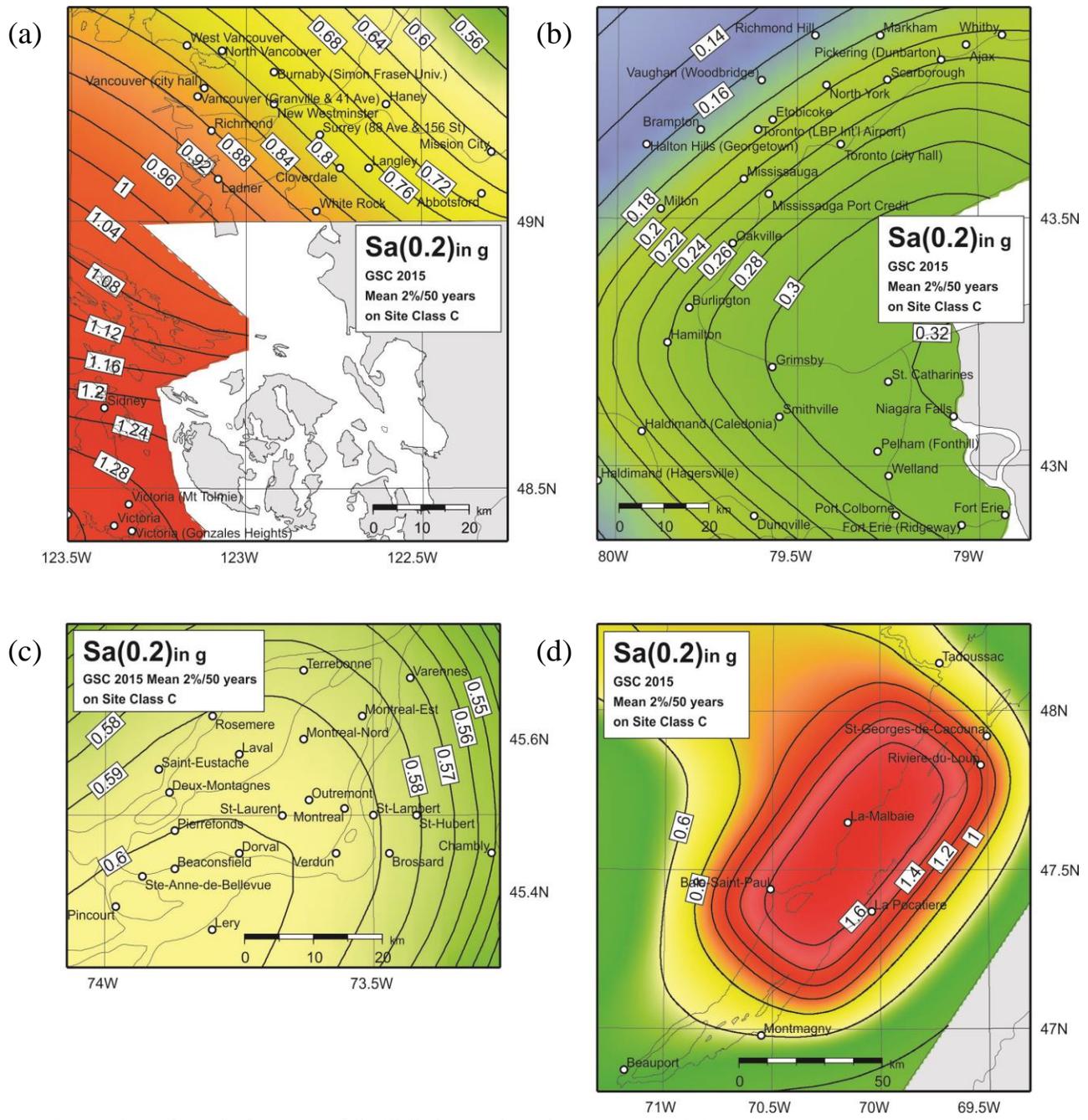
Figure 14. Detailed maps of Sa(0.2) hazard in the vicinity of (a) Vancouver-Victoria, (b) Toronto-Niagara, (c) Montreal and (d) Charlevoix (Quebec). Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years.
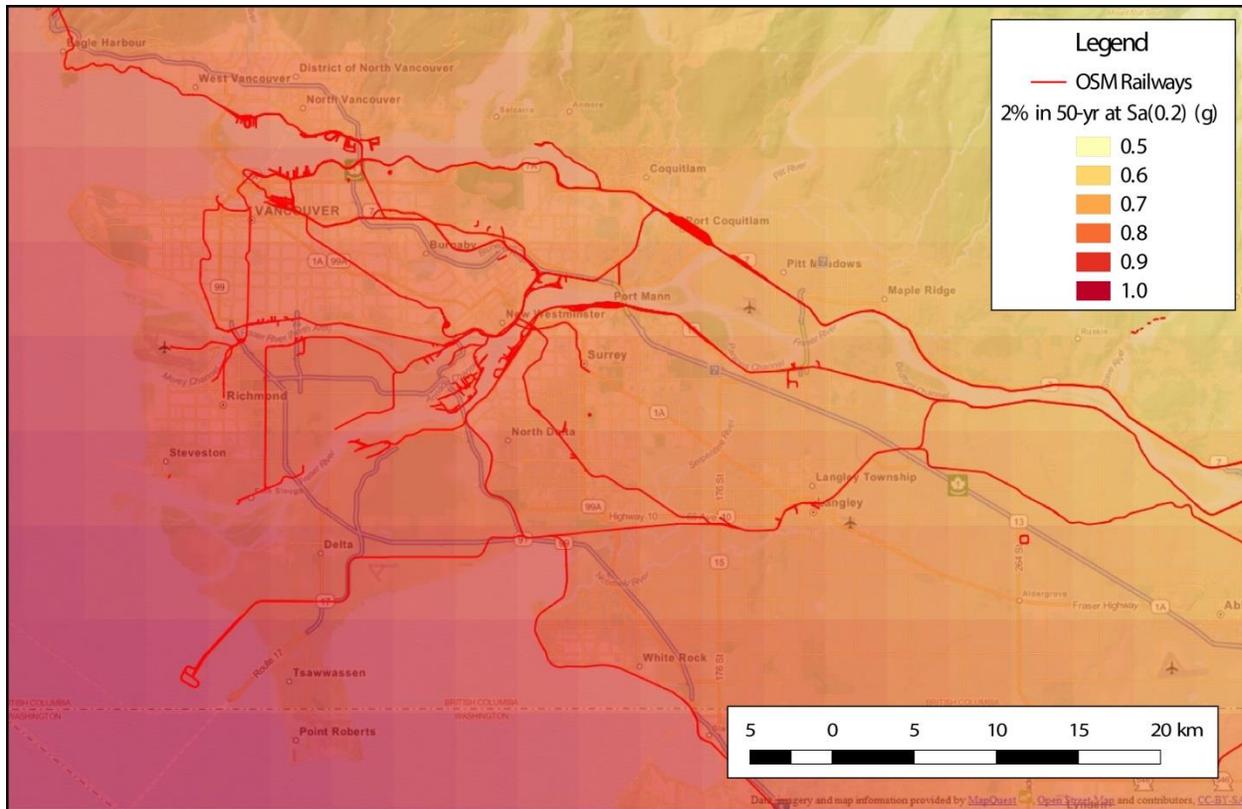
Figure 15. An example application of the geoTIFF files in a GIS framework. Map shows the mean 2% exceedance in 50-year hazard for Sa(0.2 s) for the greater Vancouver region. The geoTIFF is recoloured and reprojected to WGS 84/Pseudo Mercator in Quantum QIS (http://www.qgis.org). The hazard model superimposes an OpenStreetMap (OSM; https://www.openstreetmap.org) map layer and displays railway networks exported from OSM.