5TH GENERATION (2015) SEISMIC HAZARD MODEL FOR SOUTHWEST BRITISH COLUMBIA.

Garry ROGERS
Geological Survey of Canada, Natural Resources Canada, Sidney, BC Canada
grogers@NRCan.gc.ca

Stephen HALCHUK
Geological Survey of Canada, Natural Resources Canada, Ottawa, ON Canada
shalchuk@NRCan.gc.ca

John ADAMS
Geological Survey of Canada, Natural Resources Canada, Ottawa, ON Canada
jadams@NRC.gc.ca

Trevor ALLEN
Geological Survey of Canada, Natural Resources Canada, Sidney, BC Canada
tallen@NRCan.gc.ca

ABSTRACT: About 3.5 million people live in southwest British Columbia which includes the metropolitan areas of greater Vancouver and greater Victoria and significant infrastructure of national importance. The region is subjected to three sources of earthquake shaking: earthquakes that are in crust of the North American plate, deeper earthquakes beneath the Strait of Georgia that are within the subducted plate and giant megathrust earthquakes off the west coast of Vancouver Island. Depending on which part of the earthquake spectrum is of interest, one of these sources has the largest contribution to the seismic hazard at a particular site. Compared to NBCC2010 short period hazard has gone up slightly in Victoria and down slightly in Vancouver, while long period hazard has gone up in both locations. Deaggregation of the hazard shows that the deeper earthquakes within the subducted plate make the largest contribution to the short period hazard for much of the region and the contribution from the offshore subduction earthquakes dominates the longer period hazard throughout southwest BC.

.

1. Introduction

Southwest British Columbia is located in a subduction environment where oceanic tectonic plates slide beneath the North American continental plate (Fig. 1). This tectonic setting causes the region to be subjected to three sources of earthquake shaking: earthquakes that are in crust of the North American plate, deeper earthquakes beneath the Strait of Georgia and Puget Sound that are within the subducted plate, and giant megathrust earthquakes that occur off the west coast of Vancouver Island. Each of these earthquake sources contributes to the seismic hazard in different proportions depending on the location of the site and on the period of ground motion considered. All of the sources are capable of producing damaging earthquakes.

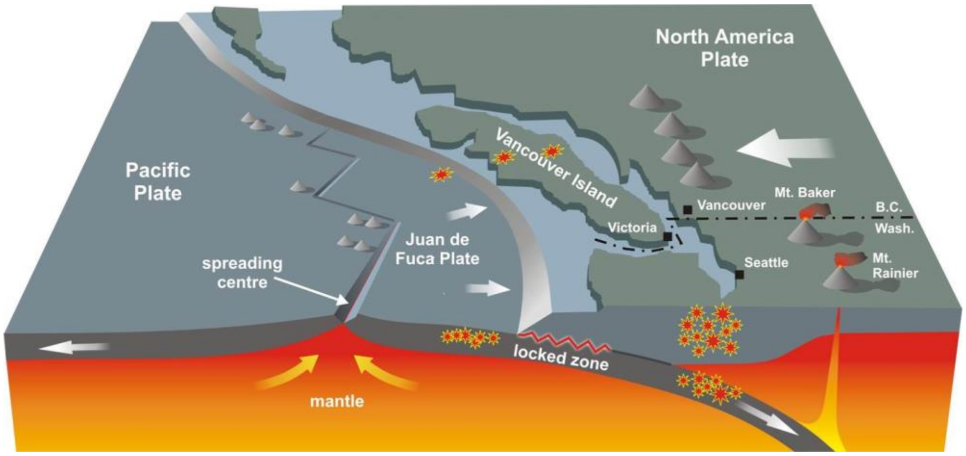

Fig. 1 – The tectonic setting of southwest British Columbia showing the three sources of earthquakes that contribute to seismic hazard: 1) earthquakes in the North American plate, 2) deeper earthquakes in the subducting Juan de Fuca plate and 3) large subduction earthquakes that occur where the two plates are currently locked in contact in the offshore region.

2. Crustal Earthquakes

Most of the small earthquakes than have been located in southwest BC are in the continental crust of the North American plate (Fig. 2). The main concentration of this shallow seismicity is in the Puget Sound region of Washington State and in the southernmost Strait of Georgia region in British Columbia. The east and west boundaries are both defined by a sharp drop off in seismicity rate. There is decrease in seismicity at about 47 degrees north which defines the southern boundary of the main seismicity concentration. The die-out of seismicity at the northern boundary is more diffuse. The boundary is definitely north of Victoria and south of Vancouver and a reasonable cut off is defined by a line that is approximately perpendicular to the outer coastline. The decrease in the north-south crustal deformation rate, as measured using Global Positioning System (GPS) data, matches the seismicity rate (Hyndman et al., 2003). The tectonic cause of this concentration of earthquakes is a coastal sliver of the North American crust in Oregon and Washington relentlessly moving north and meeting very resistant regions of older crust in Canada on Vancouver Island and the adjacent mainland. The deformation caused by this process is shown by analysis of GPS measurements to be confined between about 47 and 49 degrees north (Hyndman et al., 2003) and is evidenced by the ongoing small earthquake activity (Fig 2). Analysis of the focal mechanisms of these earthquakes shows they are consistent with a margin parallel (almost north-south) stress field (Balfour et al., 2011).

As the oceanic plate descends beneath the North America Plate it absorbs heat from the interior of the earth and prevents some of this heat from reaching the surface. This produces a region of anomalously low heat flow near the edge of the continental plate that is characteristics of subduction zones around the world. The net effect of this is to make the brittle region, where temperatures are cold enough to support earthquakes, thicker in the coastal regions. It is about 30km thick (Fig. 1) compared to the interior of British Columbia or California where the seismogenic thickness is about 20km. This means that larger earthquakes are possible in the coastal region for the same fault length.

Although the seismicity dies out to the north of the main concentration it does not disappear. There are some scattered earthquakes in the mountainous region north of Vancouver and a very persistent source of very shallow events between Vancouver and Nanaimo in the middle of the Strait of Georgia (Cassidy et al., 2000) noticeable in Fig. 2. The central region of Vancouver Island, which is almost aseismic today, was the location of the largest known on-land earthquake in Canada (M=7.3) on June 23 1946 (Rogers and Hasegawa, 1978; Cassidy et al. 2010). The current low seismicity and the very low strain rate measurements in the region using GPS (Mazzotti et al., 2011) support a conclusion that an event of this size is very rare in central Vancouver Island.

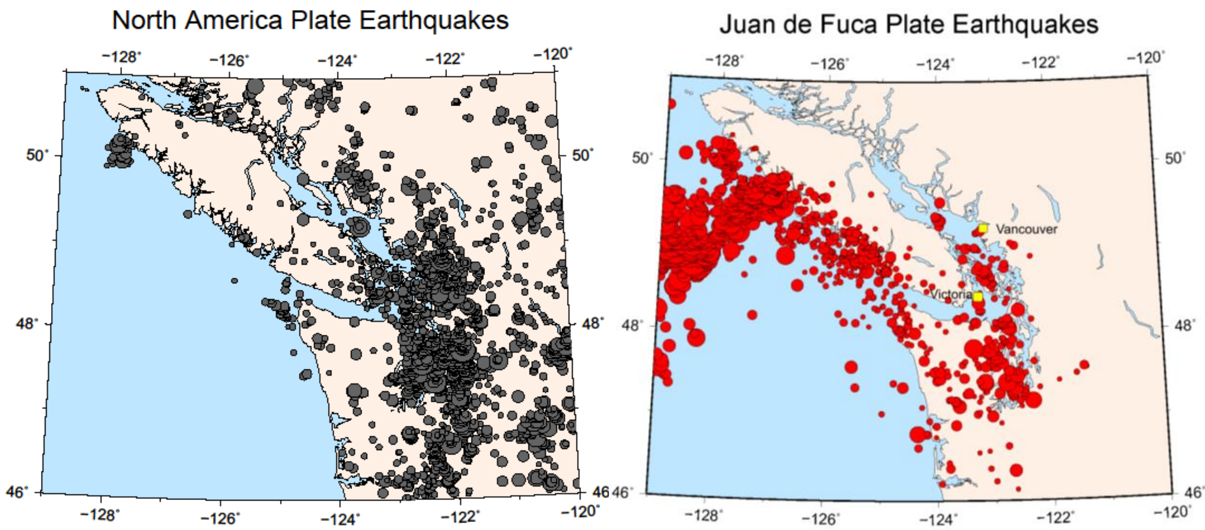

Fig. 2 – A fifteen year sample of earthquakes. Circle size is scaled to magnitude from 1.5 ≤ M ≤ 5.0. North America Plate earthquakes are within about 30km of the surface. Juan de Fuca Plate earthquakes are within 10km of the surface in the deep ocean, but earthquakes beneath Georgia Strait and Puget Sound (see Fig. 3 for location names) are in the 40km to 60km depth range.

3. Subcrustal Earthquakes

As the oceanic Juan de Fuca plate descends beneath Vancouver Island it is subjected to increased heat and pressure. There is a concentration of seismicity beneath the outer coast of Vancouver Island as the plate begins to dip beneath the North American Plate, then a hiatus beneath much of Vancouver Island and then another concentration to the east beneath the lowland region of Georgia Strait and Puget Sound. It is this second band of seismicity that is of most concern. It occurs at depths between about 40 km and 70 km and is confined to a layer about 10 km thick. This is the depth range where the increased temperature and pressure causes dehydration and phase changes in the oceanic crust converting it to denser material and where the dip of the Juan de Fuca plate steepens from 12 - 18 degrees to about 30 degrees as it changes from positively to negatively buoyant in the Earth's asthenosphere. The focal mechanisms of the larger earthquakes are consistent with them being caused by bending stress.

The majority of the deeper earthquakes occur between about 47 and 49 degrees north, straddling the change in orientation of the outer coastline from north-south in the United States to northwest-southeast in Canada. The three largest earthquakes in 1949, 1965 and 2001, all about magnitude (Mw) 6.8, have occurred near the south end of this concentration. This band of seismicity would be expected to die out to the north because the age of the plate, as it begins to subduct, is younger and this results in it being hotter and seismogenically thinner at depth. The northernmost substantial concentration of deep earthquakes is in the central Strait of Georgia just north of Nanaimo (Fig. 2).

4. Offshore Megathrust Earthquakes

Giant megathrust earthquakes occur off the west coast of Vancouver Island. It takes considerable time for strain to build up to a level to cause these giant earthquakes. Paleoseismic evidence indicates that in the last 10,000 years the mean recurrence time has been about 500 years with variation from about 200 years to about 1000 years between events (Goldfinger et al., 2012). The last great earthquake was on January 26, 1700. Today there are almost no earthquakes on the interface between the two plates. That indicates the two tectonic plates are stuck together, storing strain for the next great earthquake. Measurements using GPS can document this ongoing buildup of strain (e.g. Mazzzotti et al., 2011) and fit with models of a locked region that is offshore (Fig.3).

Down-dip of the locked zone there is a region of stick-slip behavior, called Episodic Tremor and Slip or ETS (Rogers and Dragert, 2003) before increasing temperature further down-dip suggests the plate interface at that depth will yield in continuous aseismic slip. The ETS region can only accumulate strain for, on average, about 15 months before it fails in a “slow” earthquake that takes place over several weeks and releases a very low level of seismic energy, below the level that can be felt.

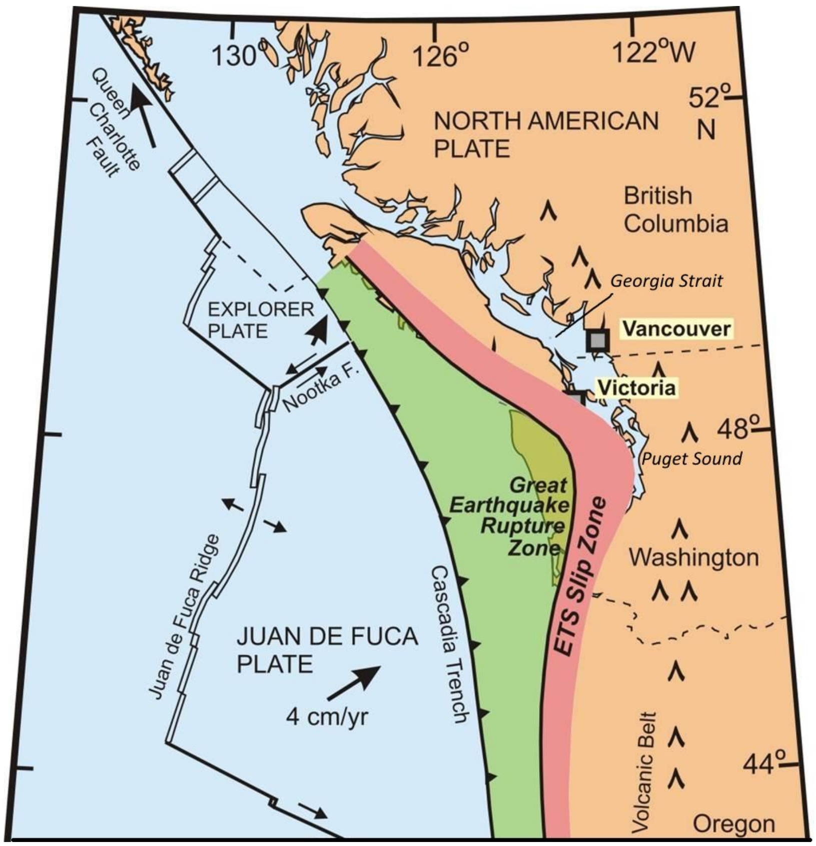

Fig. 3 – Expected rupture zone of great megathrust earthquakes (in green) that is currently stuck and accumulating strain. The pink area is the approximate region of stick-slip behavior called Episodic Tremor and Slip (ETS).

A key element in determining the hazard from subduction zone earthquakes is the closest approach of the region that will rupture in the future releasing seismic energy. It is located approximately under the outer coast of Vancouver Island (Fig.3). The location is determined by deformation modelling to match of GPS observations, thermal modelling to match observed heat flow and the expected temperature and properties the rocks at the depths where the plates are in contact, and more recently the mapping of the ETS region.

Such observations have shown Explorer Plate region off Northern Vancouver Island (Fig. 3), immediately north of the Juan de Fuca Plate, is also locked and accumulating strain. The region north of that is also under compression and may also be capable of large thrust earthquakes (see Allen et al., 2015), but there is no subducted plate detected there (Cassidy et al. 1998).

5. 2015 Seismic Hazard

Seismic hazard (Fig. 4) decreases away from the coast. Short period hazard is strongly influenced by the distance from the concentrations of deep and shallow earthquakes shown in Figure 2. The dominant influence for the long period hazard is the distance from the subduction zone (Fig. 3). Compared to the 4th generation hazard model used in NBC2010, in the 5th generation hazard model short period hazard has gone up slightly in Victoria and down slightly in Vancouver while long period hazard has gone up in both locations (Adams et al., 2015). This is due to new ground motion prediction equations (Atkinson and Adams, 2013), refinements to seismicity and subduction sources, and probabilistic, rather than deterministic, treatment of the subduction sources.

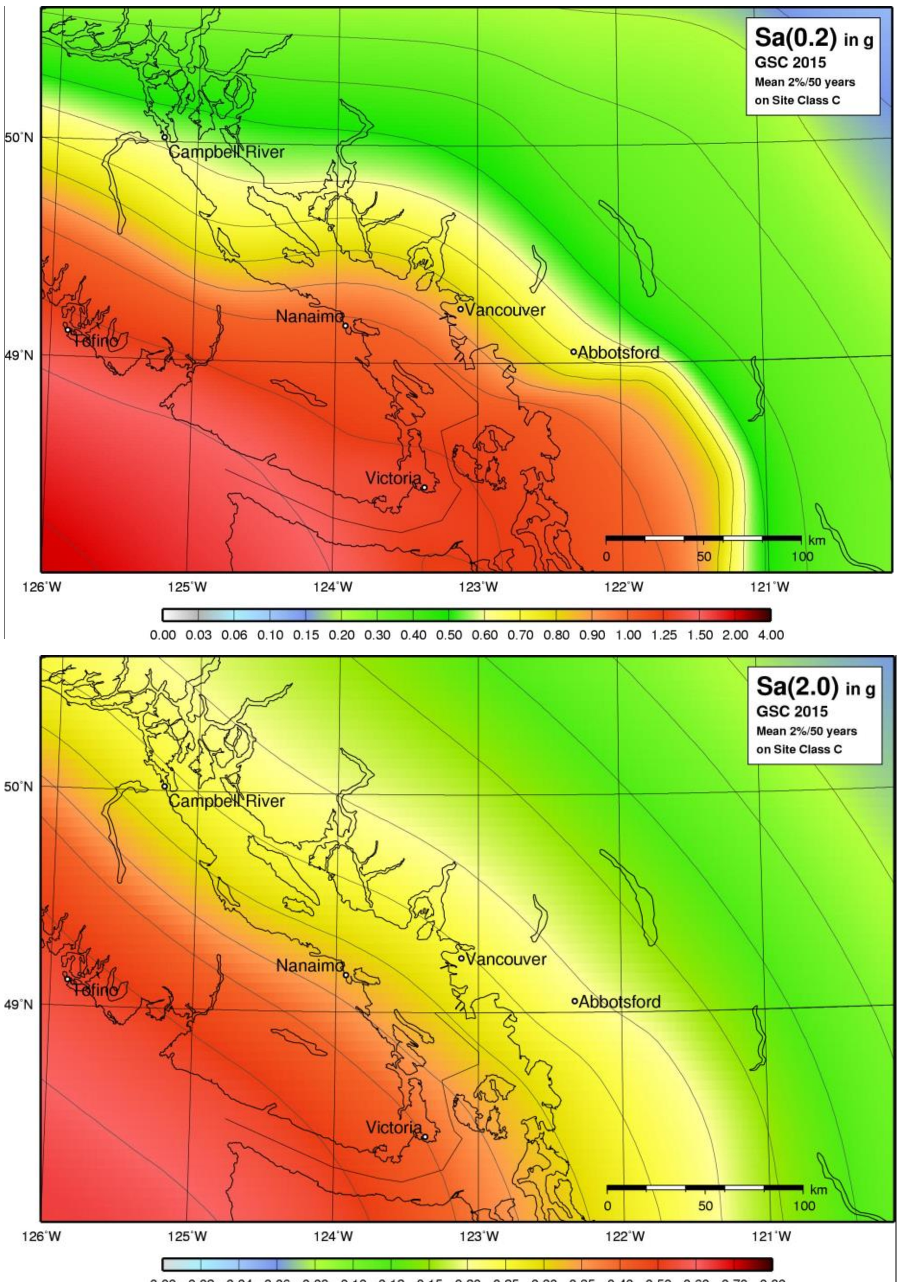

Fig. 4 - Short period (0.2) and long period (2.0) seismic hazard for southwest British Columbia.

6. Deaggregation of Seismic Hazard

Deaggregation of seismic hazard is a service provided by the Geological Survey of Canada (GSC).

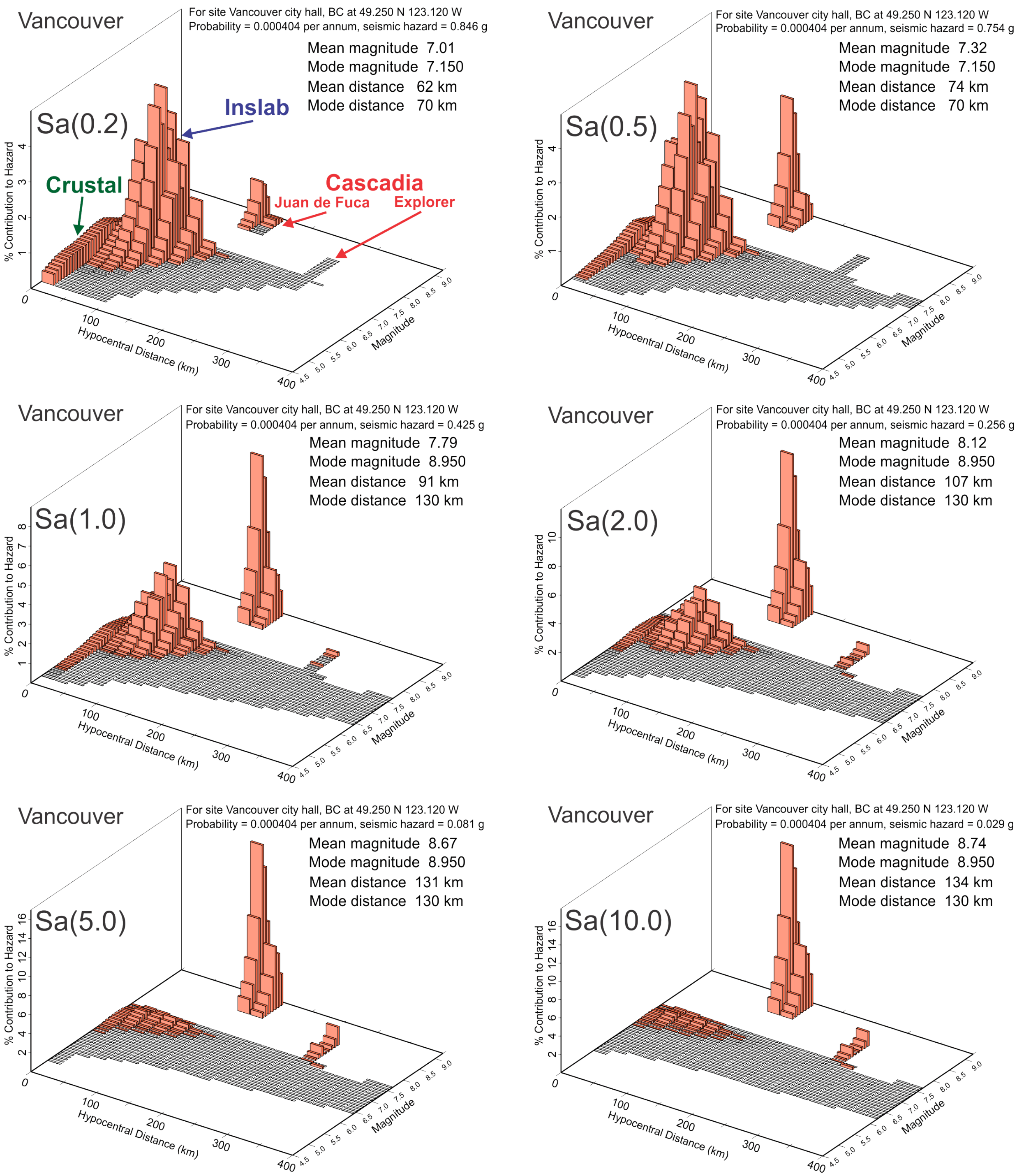

Fig. 5 – Deaggregation of seismic hazard for Vancouver. Contributions from various earthquake sources are indicated in the top left example for Sa(0.2s). The different contributions from these sources can be tracked for the periods proposed for 2015 NBCC. Note the vertical scale changes.

Deaggregation of seismic hazard breaks down the hazard into the relative contributions from various sources. This is useful for assessing the size and distance of the most likely earthquakes to affect a site. Once the 2015 edition of the National Building Code of Canada (NBCC2015) is finalized, the GSC will provide deaggregations for the 5th generation hazard model for for fundamental periods 0.2, 0.5, 1.0, 2.0, 5.0, and 10.0 seconds, as well as for PGA and PGV.

In examining the deaggregated hazard for Vancouver (Fig. 5) it can be seen that the subcrustal, or inslab, earthquakes in the subducted Juan de Fuca plate (Fig. 2) are the largest contributions to the hazard for the shorter periods of 0.2s and 0.5s. Contributions from shallow crustal earthquakes in the North American plate (Fig. 2) and from subduction earthquakes (Fig. 3) are significant but lower. However, as longer periods are considered, the subduction earthquakes become the dominant source ofhazard, primarily from the Juan de Fuca segment of the Cascadia subduction zone (Fig 3.), but there are also lower levels of hazard contributed from the Explorer segment.

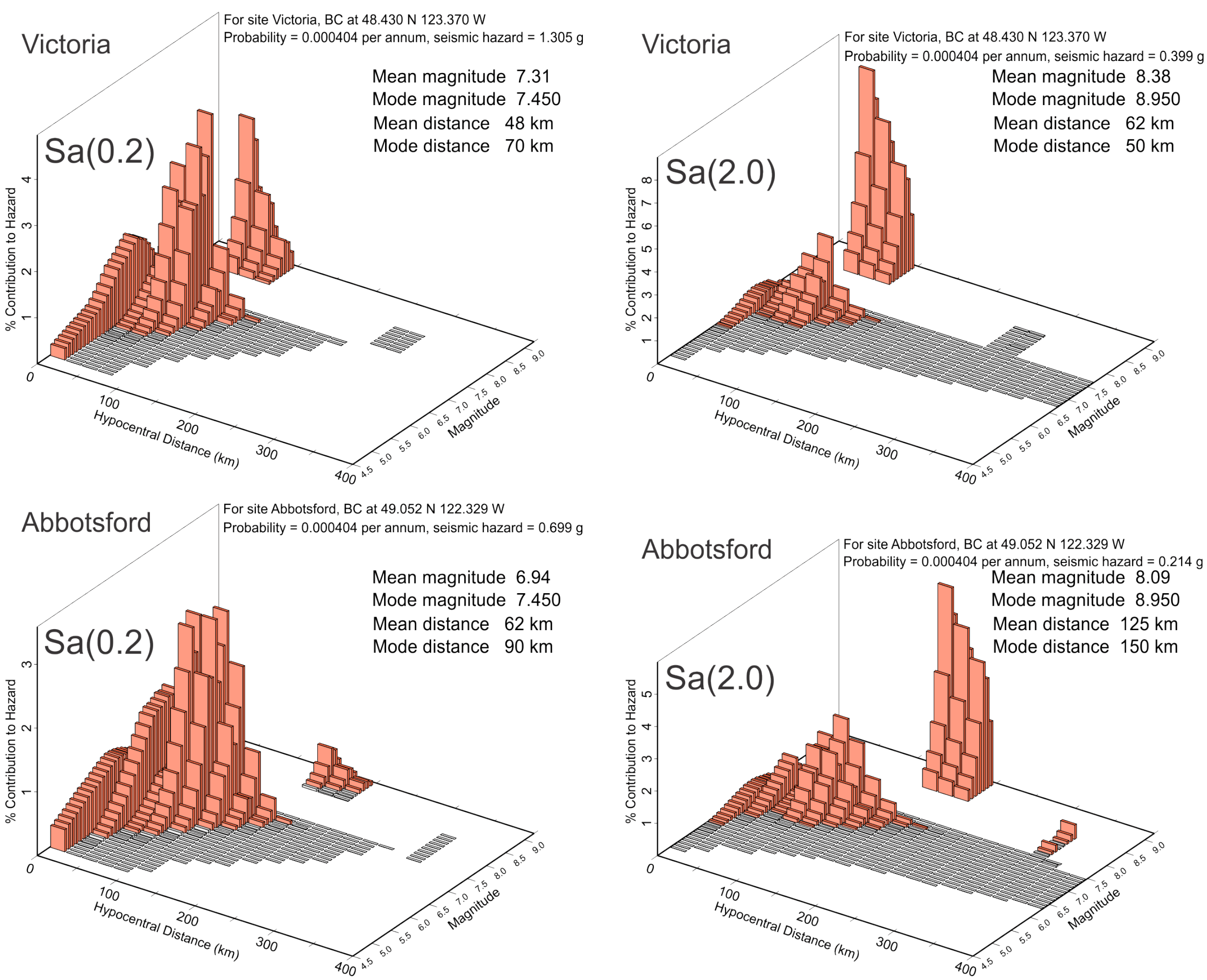

Fig. 6 - Deaggregation of seismic hazard for Victoria and Abbotsford (see Fig. 4 for locations). Sources of hazard are labeled in the top left of Fig. 5. Note changes on vertical scales.

In Figure 6 the effect on hazard in an east-west direction across southwest BC can be seen by examining deaggregation of representative short period (Sa(0.2)) and long period hazard (Sa(2.0)) for Victoria and Abbotsford (Fig. 4) and comparing them with the Vancouver values (Fig. 5). Victoria and Abbotsford are similar to Vancouver in that the subcrustal earthquakes are the dominate contribution to the short period hazard and the subduction earthquakes are the dominant contribution to the long period hazard. Victoria has a greater contribution from both the crustal earthquakes (Fig. 2) and the subduction earthquakes (Fig. 3) because it is closer to both of those sources than Vancouver and Abbotsford. The crustal source has a larger contribution to the hazard for Abbotsford than Vancouver because it is a bit farther south and closer to the greater concentration of shallow earthquakes to the south.

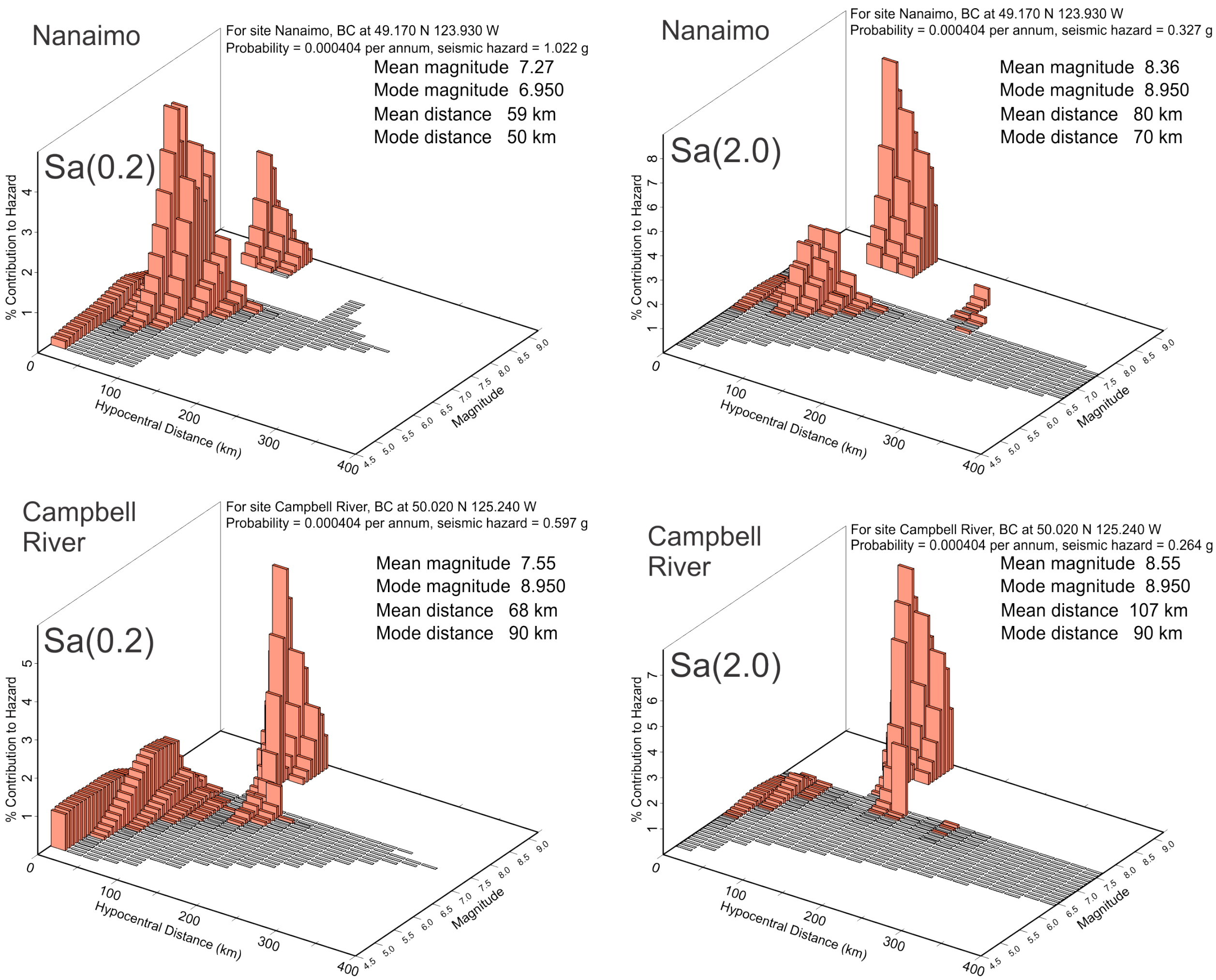

Fig. 7 - Deaggregation of seismic hazard for Nanaimo and Campbell River (see Fig. 4 for locations). Sources of hazard are labeled in the top left of Fig. 5. Note changes on vertical scales.

The variation in hazard in a northwest-southeast direction is shown in (Fig. 7) as deaggregation plots for Nanaimo and Campbell River can be compared with those for Vancouver (Fig. 5) and Victoria (Fig. 6). The Nanaimo plots for both Sa(0.2) and Sa(2.0) are similar to Vancouver for contributions from crustal and subcrustal earthquakes because both cities are about same distance from those sources to the south. The contributions from the subduction earthquakes are higher for Nanaimo for both Sa(0.2) and Sa(2.0) because it is closer to the subduction source. For Campbell River the contributions from the concentrations of crustal and subcrustal are lower because it is father from the sources to south, but there is still a noticeable contribution from the larger subcrustal earthquakes. Because these contributions are lower, the contribution from the Juan de Fuca segment of the subduction zone is thus proportionally larger. There is also a noticeable contribution from the Explorer segment of the subduction zone. The deaggregation for Tofino (Fig. 4) on the west coast of Vancouver Island is not shown, but it is dominated by the subduction zone contribution at all frequencies.

7. Conclusions

In the densely populated regions of southwest British Columbia earthquake hazard comes from three sources, crustal earthquakes within the North American tectonic plate, deeper subcrustal earthquakes within the subducting slabs of the Juan de Fuca and Explorer oceanic plates and large infrequent offshore megathrust earthquakes on the Juan de Fuca and Explorer segments of the Cascadia subduction zone. Deaggregation of the seismic hazard shows that the main contributions to hazard for short periods vary throughout the region but for longer periods the Juan de Fuca segment of the Cascadia subduction zone is the dominant contribution to the hazard.

8. Acknowledgements

We would like to thank Taimi Mulder for assistance with Figure 2. The data for that figure is a combination of solutions from the Geological Survey of Canada and the Pacific Northwest Seismic Network. Some of the figures were created with the GMT software package (Wessel and Smith, 1991).

9. References

ADAMS, J., HALCHUK, S., ALLEN, T.I., and ROGERS, G.C., 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, 11p.

ALLEN, T., ADAMS, J., HALCHUK, S. and ROGERS, G. New seismic hazard model for north-western Canada. *11th Canadian Conference on Earthquake Engineering*, 21–24 July 2015, Victoria, Canada, Paper 93781, 13p.

ATKINSON, G.M. and ADAMS, J. Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps, *Canadian Journal of Civil Engineering,* Vol. 40, 2013, pp. 988–998, doi: 10.1139/cjce-2012-0544.

BALFOUR, N.J., CASSIDY, J.F., DOSSO and MAZZOTTI, S. Mapping crustal stress and strain in southwest British Columbia. *Journal of Geophysical Research*, Vol.116, B03314, 2011, 11p. doi:1029/2010JB008003.

CASSIDY, J.F., ELLIS, R.M., KARAVAS., C. and ROGERS, G.C. The northern limit of the subducted Juan de Fuca plate system, *Journal of Geophysical Research*, Vol. 103, 1998, pp. 26,949-26,961.

CASSIDY, J.F., ROGERS, G.C. and WALDHAUSER, F., Characterization of active faulting beneath the Strait of Georgia, British Columbia, *Bulletin of the Seismological Society of America*, Vol. 90, 2000, pp. 1118-1199.

CASSIDY, J.F., ROGERS, G.C., LAMONTAGNE, M., HALCHUK, S. and ADAMS, J. Canada's earthquakes: the good, the bad, and the ugly, *Geoscience Canada*, Vol. 37, 2010, pp. 1-17.

GOLDFINGER, C., NELSON, C.H., MOREY, A.E., JOHNSON, J.R., PATTON, J., KARABANOV, E., GUTIERREZ-PASTOR, J., ERIKSSON, A.T., GRACIA, E., DUNHILL, G., ENKIN, R.J., DALLIMORE, A., AND VALLIER, T. Turbidite event history - Methods and implications for Holocene paleoseismicity of the Cascadia Subduction Zone. *U.S. Geological Survey Professional Paper*,1661–F, 2012, 170 p.

HYNDMAN, R.D., MAZZOTTI, S., WEICHERT, D., and ROGERS, G.C. Frequency of large crustal earthquakes in Puget Sound-southern Georgia Strait predicted from geodetic and geological deformation rates, *Journal of Geophysical Research*, Vol. 108, No. B1, 2003, 12p. doi:10.1029/201JB001710

HYNDMAN, R.D., and ROGERS, G.C., Great Earthquakes on Canada's West Coast: A Review, *Canadian Journal of Earth Sciences*, Vol. 47, 2010 pp. 801-820, doi10.1139/E10-011.

MAZZOTTI, S., LEONARD, L.J., CASSIDY, J.C., ROGERS, G.C. and HALCHUK, S., Seismic hazard in western Canada - from GPS strain rates versus earthquake catalogue, *Journal of Geophysical Research,* Vol. 116, B12310, 2011, 17p. doi:10.1029/2011JB008213.

ROGERS, G.C. and HASEGAWA. H.S., A second look at the British Columbia earthquake of 23 June, 1946, *Bulletin of the Seismological Society of America*, Vol. 68, 1978, pp. 653-676.

ROGERS, G. and DRAGERT, H., Episodic tremor and slip on the Cascadia subduction zone: the chatter of silent slip, *Science*, Vol. 300, 2003, pp. 1942-1943. doi:10.1126/science.1084783.

WESSEL, P., and SMITH, W. H. F., Free software helps map and display data, *Eos, Transactions of the American Geophysical Union,* Vol. 72, 1991, p. 441.