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Modelling the Contribution of Possible Active Fault Sources to the Seismic Hazard in Vancouver, British Columbia

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ABSTRACT

Moderate to strong ($M_W \geq 5.0$) crustal earthquakes are scarce in the seismic record of southern British Columbia. However, recent trenching of the Leech River Fault has revealed multiple surface-rupturing events during the Holocene. This, and similar work in Washington State, calls attention to the possibility of other faults in the area, which may contribute to the seismic hazard of Metropolitan Vancouver. The Coast Mountains, north of Vancouver, have been cut by a multitude of faults throughout their complex deformational history. Based on an analysis of seismicity, terrain, and previous literature, eight potential seismic hazard sources (PSHSs) were selected from the southern Coast Mountains. These PSHSs were integrated into the Vancouver Island-Coast Mountains (VICM) area source of Canada's 6th Generation seismic hazard model. We performed probabilistic hazard calculations of PGA, SA(0.1), SA(1.0), and SA(10) using the OpenQuake Engine. Occurrence rates were set to a conservative value of 1 earthquake every 11.7kyrs, to represent one Holocene event per fault. Magnitude scaling relations for the PSHSs indicate magnitudes ranging from $M_W7.0$ to $M_W7.9$. Hazard curves for a point in Vancouver, with V_{S30} = 360 m/s, show that the Britannia Shear Zone ($M_W7.4$) contributes the most hazard, possibly due to its proximity to Vancouver, except at SA(10) where the Fraser River Fault ($M_W7.9$) is most dominant. The addition of the PSHSs to the VICM model increases the 50-year probability of exceedance by up to 15% for PGA, 13% for SA(0.1), 28% for SA(1.0), and 85% for SA(10.0). These findings suggest that the contribution of PSHSs to the hazard in Vancouver is significant and will further increase if they are found to have ruptured multiple times during the Holocene. The study shows that comprehensive investigations of the Coast Mountain faults, despite their apparent tectonic quiescence, are necessary to accurately assess the hazard in southern British Columbia.

Keywords: Vancouver, potentially active faults, probabilistic seismic hazard, Coast Mountains, OpenQuake Engine

INTRODUCTION

The 5th Generation seismic hazard model for Canada included three main earthquake sources for southern British Columbia: crustal earthquakes in the North American Plate, subcrustal earthquakes in the subducted Juan de Fuca Plate slab, and megathrust earthquakes along the Cascadia subduction zone [1]. Since then, several studies have found evidence indicating recent fault rupture along another seismic source in the region, the Leech River Valley – Devil's Mountain Fault system, which has been added to Canada's 6th Generation seismic hazard model (CanadaSHM6) [2]. The addition of this fault system increases the peak ground acceleration (PGA) in the nearby city of Victoria by 9% at a 2475 year return period [3]. This discovery has brought attention to other potentially active faults (PAFs) in the region and their contribution to the seismic hazard in the area. There are no faults identified to be active within the southern Coast Mountains and the Lower Mainland, but there are many candidates for investigation. The Coast Mountains are cut by a multitude of faults due to their complex tectonic history [4-6]. While these faults are currently considered to be inactive, we know that faults can remain as zones of weakness in the crust which may reactivate under the present-day stress regime [7]. Moderately sized earthquakes have been known to occur within the British Columbia mainland [8] and large crustal earthquakes during the Holocene have been inferred from subsidence patterns from Victoria to Vancouver based on marsh and bog sediments [9].

Seismic hazard analysis is rarely straightforward when applied to potentially active faults [10]. While there are ways to investigate fault paleoseismicity (e.g., trenching), such methods may be costly in terms of time, resources, and labor. When there are many potentially active faults in an area, there arises a need to prioritize the allocation of resources to the investigation of faults with the greatest potential to cause damage. In this study, I compared the seismic hazard contribution of PAFs in the southern Coast Mountains and Lower Mainland with the hazard of the corresponding area source (i.e., the *Vancouver Island Coast Mountains* area source) as calculated in CanadaSHM6.

This study aimed to determine the baseline contribution of a range of tectonic structures to the seismic hazard in Vancouver, in order to quantify their impact and determine whether further study is justified. It was guided by the following sub-objectives: 1) identify a short-list of PAFs as well as unverified lineaments, collectively called potential seismic hazard sources (PSHSs) in this study, which may contribute significant seismic hazard; and 2) calculate and compare hazard curves for these PSHSs.

SEISMOTECTONICS OF THE STUDY AREA

Southern British Columbia is an amalgamation of magmatic arcs, sedimentary basins, and accreted terranes from multiple collisional events off the west coast through the last 170 million years [4]. One of the last major collisional events was between the Insular Superterrane and the Intermontane Superterrane [6]. The subduction of the oceanic crust between the two superterranes resulted in the formation of the Coast Plutonic Complex (Figure 1) during the Middle Jurassic to Middle Cretaceous [6]. This complex currently manifests itself on the surface as the Coast Mountains north of Vancouver. Through its long and complex deformational history, the Coast Mountains have been dissected by dominantly NW-striking faults that have experienced compressional, extensional, and most recently translational slip. Geologic evidence suggests that the last motions along these faults are dextral strike-slip on steep faults [6].

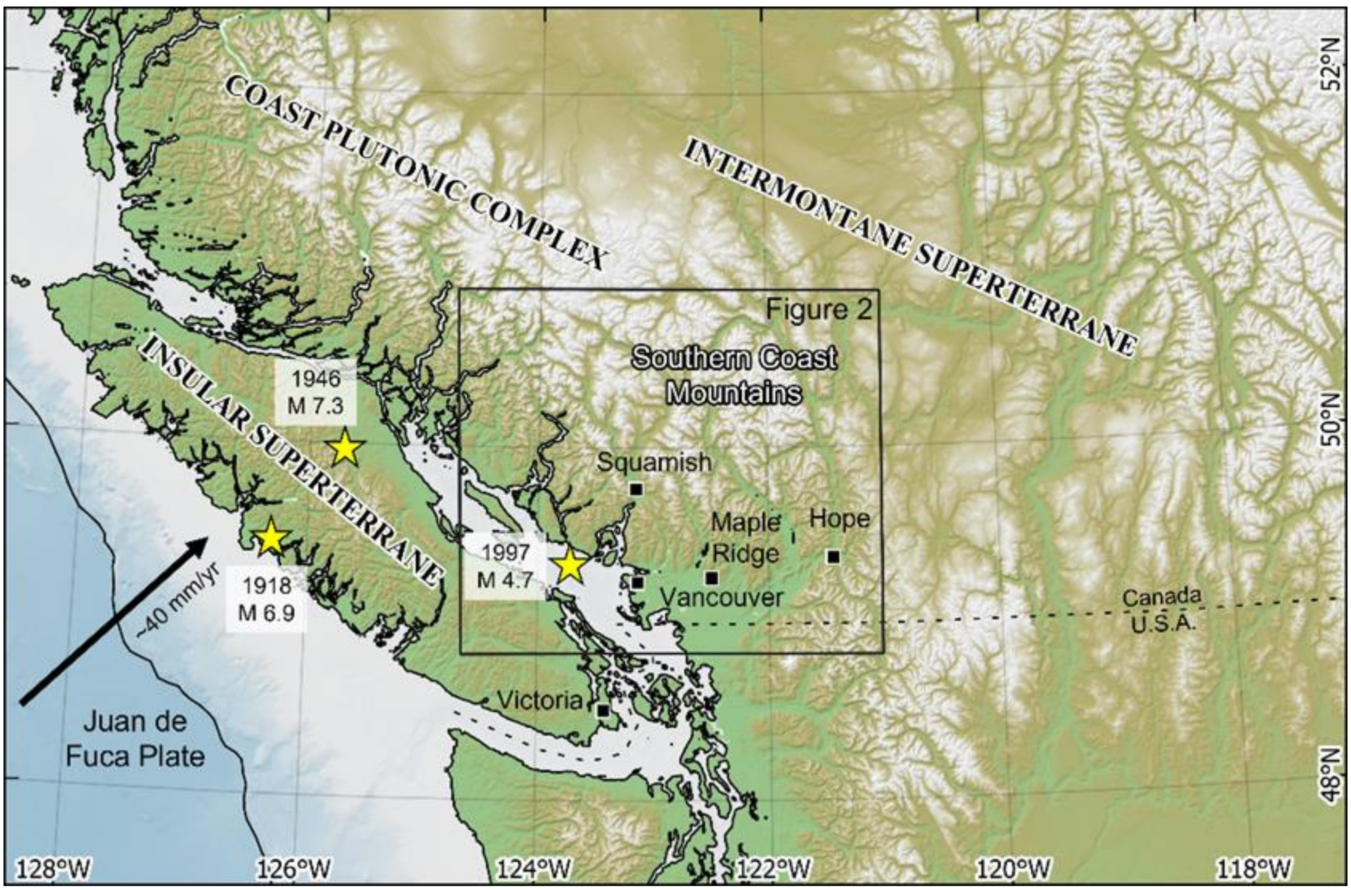

Figure 1. Location map showing the major tectonic units comprising southern British Columbia. Notable earthquakes are shown as yellow stars and population centers are represented by black squares. The methods were applied to the area enclosed by the rectangle labelled as Figure 2.

In the present day, the subduction of the Juan de Fuca Plate beneath the North American Plate along the Cascadia Subduction Zone dominates the tectonic regime of southern British Columbia and serves as the largest seismic hazard source for communities along the west coast. Additionally, the oblique nature of the subduction south of the Juan de Fuca Strait causes the forearc to move northwards, as shown by GPS data [11]. This motion is thought to be accommodated by faulting between the Olympic Mountains and the Leech River Fault [12]. However, earthquakes have been known to occur further north, such as the 1946 Vancouver Island Earthquake [13] and 1997 Georgia Strait Earthquake [14] (Figure 1).

METHODOLOGY

Selection and Characterization of Potential Seismic Hazard Sources

PSHSs (Table 1) were selected from a list of faults mentioned in the literature as well as visual identification of lineaments, observed from a 30-m SRTM digital elevation model, that align with seismicity [15]. Note that anthropogenic and unknown events of the REST Catalog were not considered. To simplify the analysis, faults that are of similar length and location were represented by a single fault. The Yalakom Fault system was particularly affected by this simplification. Since the Yalakom Fault itself is known to be cut by younger faults such as the Red Mountain Fault [16], the Marshall Creek Fault was selected to represent the system. For each fault, surface length was calculated using QGIS 3.16. Fault properties such as dip angle, maximum depth, and fault type (normal, reverse, strike-slip) were collated from available references, such as the seismic sections [6] and focal mechanism solutions [17]. For each fault, the characteristic earthquake magnitude was calculated assuming full fault rupture using well-established empirical equations [18] to stay consistent with the available scaling relations of the OpenQuake Engine. The PSHSs and their characteristics have not been verified through fieldwork or geodetic methods at this time.

Seismic Hazard Calculations

The classical hazard calculations were executed by modifying the OpenQuake model files for the trial CanadaSHM6 (accessed from https://github.com/OpenDRR/CanadaSHM6). The following lists the modifications that were made to the West Canada model:

1. Hazard calculations were performed for only one site, with coordinates 49.26°N 123.25°W, which correspond to the Earth and Ocean Sciences Main building at the University of British Columbia's Vancouver campus.
2. Since only one site was considered, the calculations were only performed for the V_{S30} at that site, which was set to 360 m/s [19].
3. Since all the PSHSs are located within the *Vancouver Island Coast Mountains* (VICM) area source zone of the CanadaSHM6, all other sources (source groups, area sources, simple fault sources) were discarded to produce a fair comparison and to simplify calculations.

All other parameters and logic trees were maintained. The PSHSs were modelled as simple faults. Due to the lack of data on the paleoseismicity of the PSHSs, earthquake occurrence rates were assumed to rupture once within the Holocene (11.7 ka), because this is the minimum criteria for a fault to be considered 'active'. Thus, the incremental magnitude frequency distribution for each PSHS was set to contain a single bin, with a frequency equal to 8.547008e-05, and upper and lower magnitude limits corresponding to the error limits of the empirical scaling relations [18]. Hazard calculations were made for 1) only the VICM area source, 2) each of the PSHSs, 3) all the PSHSs combined, and 4) the VICM area source with all the PSHSs. To simplify the analysis, only PGA, SA(0.1), SA(1.0), and SA(10.0) were graphed and compared.

RESULTS AND DISCUSSION

Potential Seismic Hazard Sources

Eight PSHSs were included in this study (Table 1; Figure 2). Their surface lengths range from 42 km to 309 km. Correspondingly, their characteristic earthquake magnitudes are estimated to range from M_W 7.0 to M_W 7.9. The longest and farthest fault from the study site is the Fraser Fault (sometimes referred to as the Fraser River Fault) and it is at least 130 km away from the study site. The northern termination of the fault is 300 km away, beyond the extent of Figure 2. The PSHSs are evenly spaced across the Coast Mountains and the Lower Mainland. They are mostly NW-striking, except for the NE-striking Vedder Fault and the proposed Alouette Lake Fault. The latter is a lineament that aligns well with earthquake epicenters [15] and focal mechanism solutions [20] that indicate sinistral faulting along a steep NE-trending plane. All other PSHSs are established faults with no known recent activity.

Table 1. Potential seismic hazard sources and their parameters used to build OpenQuake source models.

Name	Length (km)	Dip angle (°)	Type	M_W	Min. M_W	Max. M_W	Bin Center	Bin Width	Depth (km)	Dip direction	Reference/s
Fraser (River) Fault	309	82	dextral	7.95	7.62	8.28	7.95	0.7	15	SW	[6], [16], [21]
Marshall Creek Fault	96	31	normal	7.48	6.62	8.33	7.48	1.7	15	SW	[6], [16], [21]
Owl Creek Fault	88	27	reverse	7.37	6.84	7.90	7.37	1.1	10	NE	[6], [21]
Harrison Lake Fault	99	60	reverse	7.43	6.90	7.97	7.43	1.1	15	NE	[6], [21-22]
Ashlu Creek Fault	89	51	reverse	7.38	6.85	7.91	7.38	1.1	10	NE	[6], [21]
Alouette Lake Fault	52	90	sinistral	7.08	6.81	7.35	7.08	0.5	15	--	[15], [20]
Britannia Shear Zone	48	40	strike-slip	7.04	6.78	7.31	7.04	0.5	16	SW	[6]
Vedder Fault	42	80	normal	7.00	6.24	7.76	7.00	1.5	15	NW	[6]

Hazard Curves

Figure 3 and Figure 4 show the calculated hazard curves for PGA, SA(0.1), SA(1.0), and SA(10). The hazard curves for the individual PSHSs have maximum probabilities of exceedance (PoE) in 50 years equal to 0.43%. The PoE decreases with higher ground motion values. For PGA, the decrease in PoE starts at around 0.015 g and higher. The combined hazard curve for all PSHSs (referred to herein as the PSHS hazard curve) has a maximum PoE of 3.4%, which is equivalent to multiplying the individual maximum PoEs by the number of PSHSs (8). Caution then should be taken when comparing the PSHS hazard curve with the hazard curve for the VICM model (referred to herein as the VICM hazard curve), as will be done in the following paragraph, because simply adding more PSHSs to the model will increase the PoE of the PSHS hazard curve, despite the fact that in reality the number of faults does not determine the seismic hazard.

The black line in Figure 3 and Figure 4 shows the VICM hazard curve, and the dashed yellow line shows the hazard curve that combines the VICM with all the PSHSs (referred to herein as the VICMPSHS hazard curve). Figure 3 and Figure 4 illustrate that the difference between the VICM and VICMPSHS hazard curves is mostly negligible. The largest difference between them is for the SA(10) hazard curves: at 0.017 g the VICMPSHS PoE is about 85% greater than the VICM PoE.

Before interpreting the results, the effects of the limitations and intended use of the study must first be discussed. In this study, the PSHSs are assumed to each have an earthquake occurrence rate of one every 11.7 kyrs (8.547008e-05 earthquakes/yr), such that the calculated hazards are assumed to be the baseline hazards if the faults are active. Therefore, if the results show high hazard contributions from a PSHS, then it can be interpreted that investigating that PSHS for Holocene activity is worthwhile because we are ensured that it will be hazardous if it is active. However, if the results show low hazard contributions from a PSHS, it does not necessarily mean that the PSHS can be ruled out from being a seismic hazard source, because if the PSHS is active and it has a higher earthquake occurrence rate than assumed, then it will contribute a higher hazard than modeled.

The results show that the combined baseline seismic hazard contributions of the PSHSs are negligible when compared to the hazard that is already modeled from the VICM area source. Unless future studies reveal that the PSHSs can generate large earthquakes more than once every 12,000 years, the VICM area source model of the CanadaSHM6 should be sufficient for long-term seismic hazard forecasting and preparedness, especially for short period structures. However, the VICM area source may be underrepresenting the seismic hazard for long period structures, such as the high-rise buildings in Vancouver. Furthermore, the ground shaking in localities proximal to the PSHSs will be far greater than those calculated in this study.

Similar analyses are currently being performed for these localities, which include but are not limited to, Squamish, Maple Ridge, and Hope.

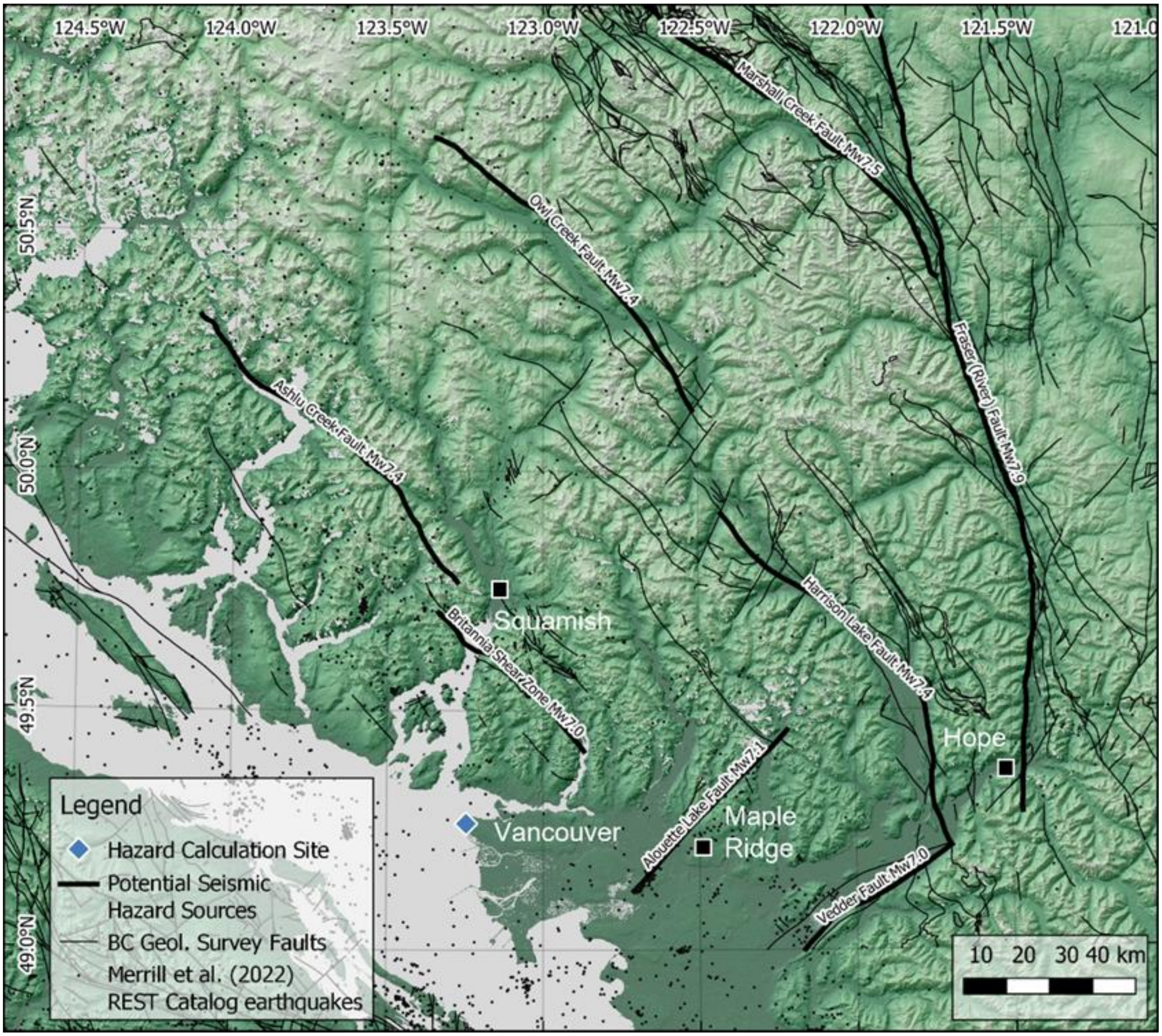

Figure 2. Potential seismic hazard sources and their estimated characteristic earthquake magnitude. The Fraser Fault extends beyond the extent of the figure.

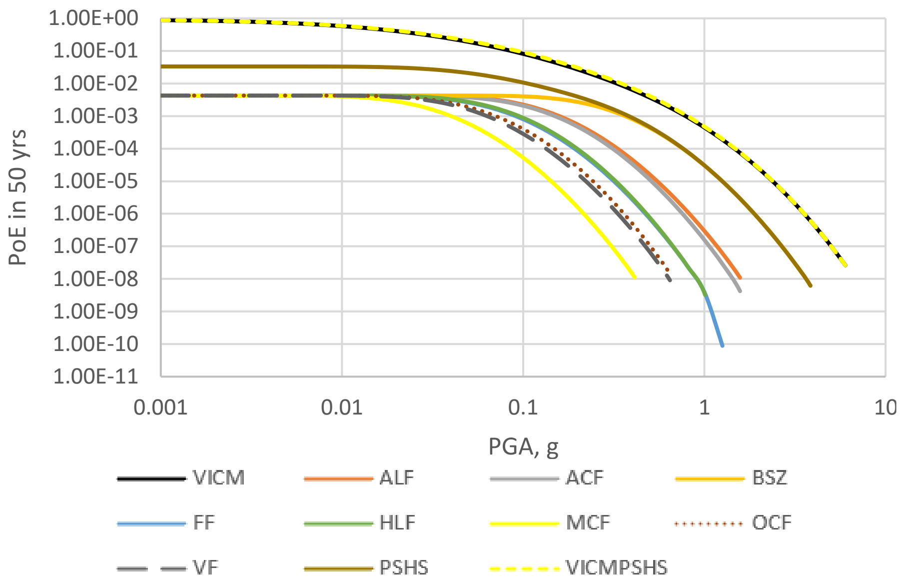

Figure 3. PGA hazard curve calculated for the study site, with V_{S30} = 360 m/s. VICM: Vancouver Island Coast Mountain area source, ALF: Alouette Lake Fault, ACF: Ashlu Creek Fault, BSZ: Britannia Shear Zone, FF: Fraser Fault, HLF: Harrison Lake Fault, MCF: Marshall Creek Fault, OCF: Owl Creek Fault, VF: Vedder Fault, PSHS: all potential seismic hazard sources, VICMPSHS: Vancouver Island Coast Mountain area source combined with all potential seismic hazard sources.

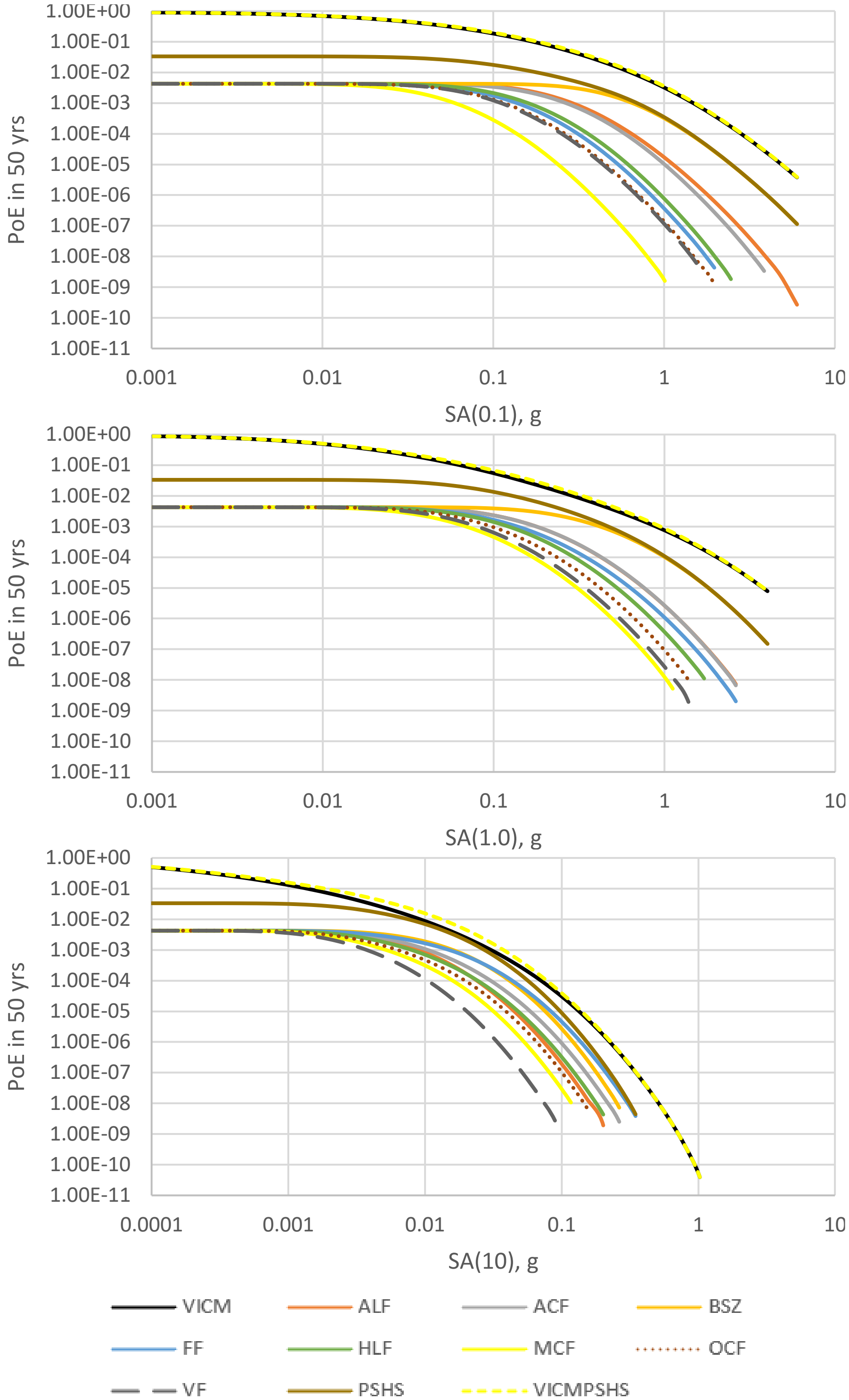

Figure 4. Hazard curves for SA(0.1), SA(1.0), and SA(10.0) calculated for the study site, with V_{S30} = 360 m/s.

CONCLUSIONS

Eight PSHSs were considered within the southern Coast Mountains and the Lower Mainland of British Columbia. If active, they are estimated to be able to generate M_W 7.0 to M_W 7.9 earthquakes, given their surface lengths. Fortunately, their baseline hazard contributions are sufficiently modelled by the VICM area source of the CanadaSHM6 for short period structures in

Vancouver. However, further investigations of their paleoseismicity and seismic activity are of importance for long period structures and for nearby localities.

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