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Assessing the Relative Threats from Canadian Volcanoes

Alexander M. Wilson and Melanie C. Kelman

1. INTRODUCTION

British Columbia (BC) and the Yukon Territory (YT) of western Canada lie within a zone of active tectonism and volcanism. As part of the Pacific “Ring of Fire”, the region has a rich and diverse history of Quaternary volcanism and dozens of potentially active volcanoes. No volcanic eruptions have occurred in living memory in Canada, however, and most volcanoes are located in remote areas with rugged mountainous terrain and sparse human populations (Hickson and Edwards, 2001). Furthermore, many Canadian volcanoes have atypical forms as a result of high erosion rates (due to intense glaciation and rapid Cordilleran uplift) and infrequent eruptions (Hickson, 1994). These factors, combined, have created the false perception that Canada’s volcanoes are extinct (Stasiuk et al., 2003).

Volcanoes cause a variety of destructive phenomena. They may discharge superheated pyroclastic density currents (PDCs) that travel downslope at hundreds of metres per second, destroying large areas of forest and infrastructure and endangering people (Francis and Baker, 1977; Crandell and Hoblitt, 1986; Neri et al., 2015). Globally, PDCs are responsible for 33% of historic volcano fatalities (Auker et al., 2013). Lahars (volcanic debris flows) may inundate low-lying land areas, destroying property and infrastructure, often many tens of kilometres downstream of the source (e.g. Nevado del Ruiz, 1985 [Mileti, 1991]). Lahars have caused 17% of historic volcano fatalities (Auker et al., 2013). Volcanoes often comprise highly fractured, weak lithologies, leading to frequent landslides, even in the absence of eruptive activity. Where significant water is available (as liquid water, ice, or snow), landslides may lead to formation of lahars (Siebert, 1992; Mothes and Vallance, 2015). Explosions, either phreatomagmatic (resulting from interaction of magma and water) or phreatic (steam explosions without new magma), may be highly destructive (Morrissey et al., 2000). Large explosive eruptions can eject ash plumes high into the atmosphere, disrupting local and global climates and causing downwind ash fall (e.g. Hansen et al., 1992; Kelly and Jones, 1996; Baldini et al., 2015; Wilson et al., 2015). Airborne volcanic ash plumes are a major hazard for aviation (e.g. the 2010 eruption of Eyjafjallajökull, Iceland [Gudmundsson et al., 2008, 2012]). They pose a hazard to power transmission, water treatment, and other infrastructure; can cause roofs to collapse; can impact agriculture; and can cause health hazards (Baxter, 1990). Many volcanic eruptions produce highly destructive lava flows (e.g. the Lower Puna eruption in Hawaii [Liu et al., 2018]). In most cases, lava flows move slowly enough that people can evacuate; however, the damage to property and infrastructure is likely to be considerable (Harris, 2015). Volcanic gas emissions may harm people, animals, and vegetation, and sulphur dioxide may contribute to formation of acid rain and affect climate (Self and Rampino, 1988). Finally, earthquakes associated with magmatism may, in rare cases, cause major damage; however, they are important as a volcanic unrest monitoring tool.

The volcanoes of western Canada have a history of highly destructive activity. Low viscosity basaltic lavas erupted from Tseax cone in 220 BP caused ~2000 fatalities to the Nisga'a First Nation (Sutherland Brown, 1969; Higgins, 2009) (Figure 1A). Pumiceous tephra dispersed throughout western Canada is evidence for a major Plinian (Volcanic Explosivity Index [VEI] 4) eruption at Mt. Meager, BC in 2360 BP (Read, 1990; Clague et al., 1995; Leonard, 1995;

Andrews et al. 2014) (Figure 1B). The lahar and outburst flood associated with this eruption can be traced at least 65 km downstream (Stasiuk et al., 1996; Hickson et al., 1999; Andrews et al., 2014). Primary block and ash deposits situated in and around the town of Squamish, BC were emplaced by pyroclastic density currents during eruptions of Mt. Garibaldi at 11 700 BP (Friele and Clague, 2009a; Wilson and Russell, 2018) (Figure 1C). More recently, in 2010, structural weakening due to hydrothermal alteration and high pore water pressures due to melting of ice and snow caused a 53 million m^3 volcanic debris flow at Mt. Meager (Roberti et al., 2017b) (Figure 1D). The debris flow dammed Meager Creek for ~19 hours and prompted evacuation orders for some residents of the lower Lillooet River valley.

Figure 1. Photographs showing evidence of Holocene volcanic events in Canada. A) Slabby pāhoehoe surface of the Aiyansh lava flow, a basaltic lava erupted from Tseax cone in 220 BP. Person circled for scale. Photograph by A.M. Wilson. NRCan photo 2021-220. B) Proximal

rhyodacite pumice fallout deposited during the 2360 BP Plinian eruption at Mt. Meager. Photograph by A.M. Wilson. NRCan photo 2021-221. C) Primary dacite block and ash deposits exposed in a suburb of Squamish, BC. These deposits are the product of pyroclastic density currents from dome/lava collapse at Mt. Garibaldi in 11 700 BP. Photograph by A.M. Wilson. NRCan photo 2021-222. D) Aerial image showing extent of the August 6, 2010 Capricorn Creek landslide at Mt. Meager (courtesy of Tim Gage). The slide removed 53 million m^3 of material and dammed Meager Creek for ~19 hours (Guthrie et al., 2012; Roberti et al., 2017a; Roberti, 2018).

Canada has ~348 Pleistocene or younger volcanic vents, ~54 of which have been active in the Holocene (Hickson, 1994; Hickson and Edwards, 2001; Stasiuk et al., 2003). Based on counts of known Holocene events, the annual probability of any volcanic eruption in Canada is 1/200, while the annual probability of a major explosive eruption is 1/3333 (Stasiuk et al., 2003). Many Canadians live and work within close proximity of dormant volcanoes that have the potential to impart devastating effects on human life, infrastructure, and the economy. Even volcanic unrest that did not lead to an eruption would likely have serious economic consequences due to the costs of monitoring and emergency response and impacts to businesses (Tilling, 1989). Although the accumulated scientific evidence shows the likelihood of a Canadian volcanic eruption is comparable to that of a megathrust earthquake (Hyndman and Rogers, 2010), knowledge and monitoring at Canadian volcanoes are minimal.

Unlike many geohazards (e.g. earthquakes, landslides, floods, and tsunamis), volcanoes typically show a period of unrest prior to eruption. Volcanic unrest signals are caused by magmatic intrusions into the crust, which deform and fracture rocks and interact with groundwater and hydrothermal systems. Many of these signals can be tracked from the Earth's surface and therefore offer a tool for forecasting potential eruptions. Almost all known eruptions have been preceded by anomalous seismic activity, typically occurring as swarms of hundreds or thousands of small magnitude events clustered closely in space and time. High-frequency, volcano-tectonic (VT) seismicity is a common precursor to eruptions, and shallow VT seismicity 2–30 km from the eventual vent is usually the earliest sign that a long-dormant volcano is about to erupt (Roman and Power, 2011; Chouet and Matoza, 2013; White and McCausland, 2016; Zobin, 2016).

Another important sign of volcanic unrest is ground surface deformation, most commonly on the scale of millimetres to centimetres. This deformation results from volume increases due to magmatic intrusion or to pressurization of hydrothermal systems, slope instabilities, or fault movements (e.g. Dvorak and Dzurisin, 1997; Newhall and Hoblitt, 2002).

Volcanic gas emissions also provide important information about the state of magma in the subsurface: gases are a driving force of many volcanic eruptions, and different gases behave differently depending on the pressure, temperature, and composition of intruded magma. Low solubility gases such as carbon dioxide (CO_2) and hydrogen sulphide (H_2S) are typically released early from deep intrusions. Magma ascent may be indicated by the early release of these relatively insoluble gases, followed by release of more soluble gases such as sulphur dioxide (SO_2) (Giggenbach, 1996; Newhall and Hoblitt, 2002).

While unrest timescales vary from days to years, both between volcanoes and between discrete eruptions of a single volcano (e.g. Scott et al., 2008; Castro and Dingwell, 2009; Smith and Kilburn, 2010), these detectable phenomena offer the opportunity to recognise an impending eruption early enough to take appropriate mitigating actions such as evacuations or airspace closures (e.g. Ewert et al., 2005; Sparks et al., 2012). To minimize the impacts of volcanic hazards, it is crucial that all volcanoes are evaluated in terms of their eruptive and non-eruptive hazard potential and monitored at a level commensurate with the threat. Without long term continuous monitoring, pre-eruptive unrest may not be detected in time to prevent a disaster (Newhall and Hoblitt, 2002; Ewert et al., 2005). Furthermore, without detailed volcanic hazard mapping and assessment prior to unrest, it will be challenging to identify the areas of greatest risk and rationally prioritize scientific activities such as type and distribution of unrest monitoring or emergency management activities such as road closures or evacuations. A period of unrest, particularly at a long-dormant volcano, is likely to be a rapidly changing situation requiring coordination between scientific and government organizations or departments that may not ordinarily work closely together. It may be difficult or impossible to deploy monitoring equipment, interpret data, prepare hazard maps, and forecast the outcome of unrest effectively during a rapidly escalating crisis at a minimally studied volcano, particularly if unrest has not been detected at an early stage.

Volcanic threat is the qualitative risk that a volcano may pose to people and property. It is a combination of the hazards (i.e. destructive phenomena associated with a volcano) and exposure (i.e. people, infrastructure, and property at risk). Volcanic threat is distinguished from risk, which can be quantified (e.g. in lives lost, cost of property) but requires an estimate of a hazard event's probability (Fournier d'Albe, 1979; Newhall and Hoblitt, 2002), which may not be possible where information about a volcano is very limited. Our study has two primary goals: i) identify high-threat volcanoes by evaluating associated hazards and exposure, and, ii) quantify knowledge and monitoring gaps to establish a clear priority list for assigning future resources (e.g. scientific research, hazard exposure modelling, and monitoring).

First, we compile a database of 348 Pleistocene or younger Canadian volcanic vents (Table A1 in the Appendix). Our database includes the location of each vent, the type of volcanic feature, the primary rock composition and a summary of existing geochronological information. Using these data, we systematically lump the vents into 28 volcanoes (i.e. volcanic groups, complexes, or fields) (Figure 2), each of which we evaluate in terms of its overall volcanic threat. Our threat ranking utilizes a well-established method for scoring volcanic hazards and exposure developed by the United States Geological Survey (USGS) as part of a National Volcano Early Warning System (NVEWS) (Ewert et al., 2005; Ewert, 2007; Ewert et al., 2018). We compare our ranked volcanoes to similarly scored volcanoes in the United States (US) and discuss the recommended level of monitoring for each Canadian edifice. Finally, we include a semi-quantitative analysis of geologic uncertainty for each volcano and demonstrate how the acute lack of scientific knowledge surrounding Canadian volcanism contributes to conservative (i.e. minimized) overall threat scores.

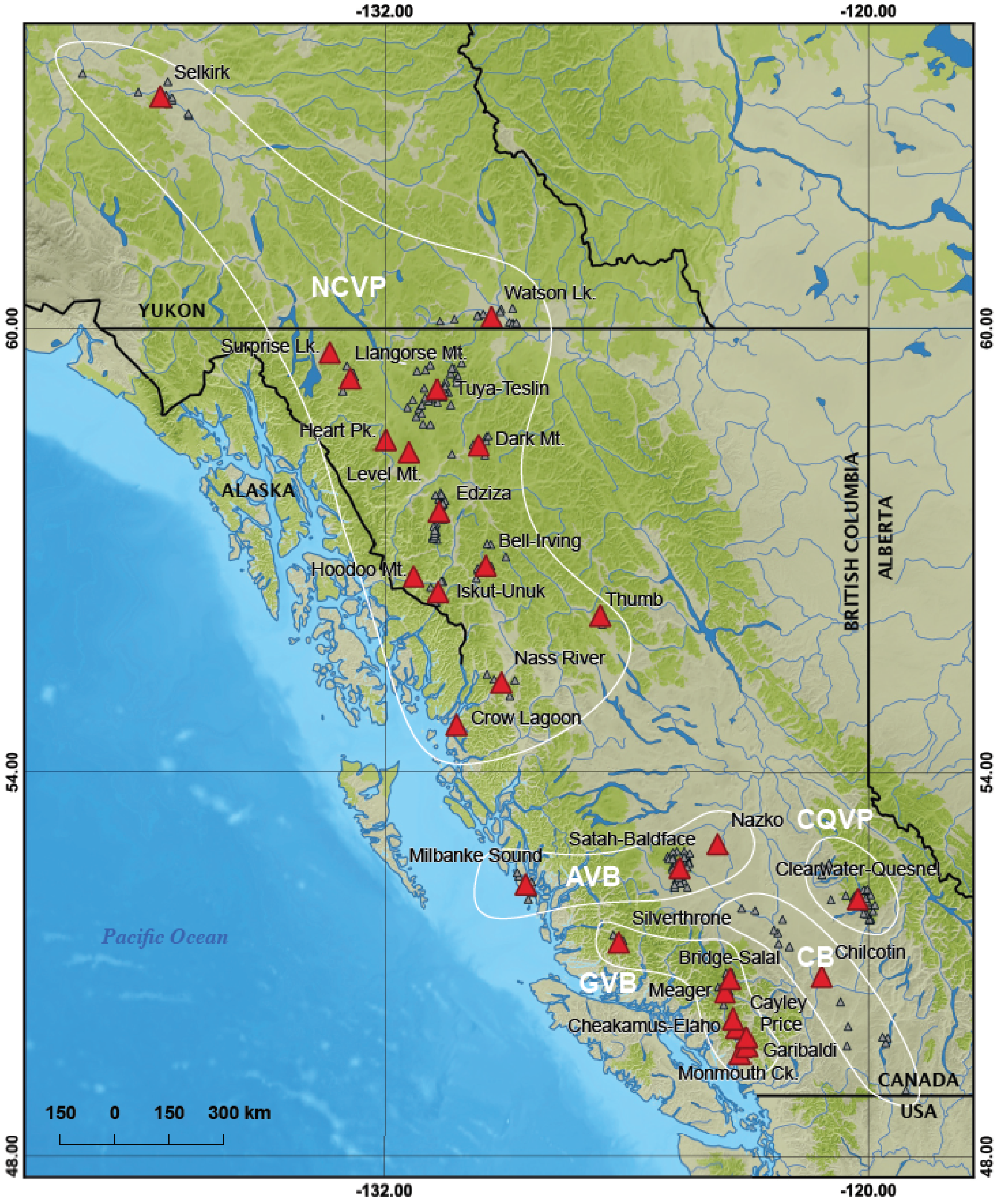


Figure 2. Map showing location of Canadian vents (small grey triangles), lumped volcanoes used for this study (large red triangles) and volcanic belt/province divisions. GVB – Garibaldi volcanic belt; CG – Chilcotin group; AVB – Anahim volcanic belt; CQVP – Clearwater-Quesnel volcanic province; NCVP – Northern Cordilleran volcanic province.

2. CANADIAN VOLCANISM

2.1. Pleistocene to Recent Canadian volcanic eruptions

Pleistocene to Recent volcanism in western Canada occurs in 5 volcanic belts (Figure 2). In the south, the Garibaldi volcanic belt (GVB) is the northern extension of the US Cascade volcanic arc. The GVB experiences dominantly calc-alkaline volcanism with both large stratovolcanoes (e.g. Mt. Meager) and smaller basaltic to felsic monogenetic centres (Mathews, 1958; Green et al., 1988; Wilson and Russell, 2018). In the BC interior, the Miocene to Recent calc-alkaline Chilcotin group basalts (CB) form a medium-sized large igneous province: a volcanic plateau that is >50,000 km^2 (Bevier, 1983; Mathews, 1989; Souther, 1991). In eastern BC, the Clearwater-Quesnel volcanic province (CQVP) is a collection of monogenetic alkaline basaltic volcanoes erupted from ~3.5 Ma to 400 BP (Hickson, 1986; Metcalfe, 1987; Hickson et al., 1995; Hickson and Vigouroux, 2014). The cause of CQVP volcanism is a topic of ongoing debate; however, it is likely the result of asthenospheric upwelling due to extensional crustal displacement along the Nootka Fault (Madsen et al., 2006). The Anahim volcanic belt (AVB) trends easterly across central BC from just north of Vancouver Island to near Quesnel, BC (Figure 2). Alkaline basaltic AVB volcanism is interpreted to result from the North American plate sliding westward over a long-lived mantle hotspot (Kuehn, 2014; Kuehn et al., 2015). Nazko cone (erupted 7300 BP) is the most easterly and youngest AVB volcano (Souther et al., 1987). The Northern Cordilleran volcanic province (NCVP) incorporates a broad group of alkaline basaltic to felsic, Miocene to Holocene eruptive centers distributed across northern BC and the central YT (Edwards and Russell, 1999). This volcanism is caused by trans-tensional extension of the North American plate in response to the Pacific plate sliding northward along the Queen Charlotte Fault. The NCVP is the most volcanically active region of Canada and has many recent eruptive centers, including Tseax cone (220 BP [Sutherland Brown, 1969]), Lava Fork (150 BP [Hauksdóttir, 1992]), and Mt. Edziza (at least 29 Holocene eruptions [Souther, 1992]). We do not include volcanoes associated with the Canadian portion of the Wrangell volcanic belt (Rabbit Mountain and Felsite Creek) in our Pleistocene database as these volcanoes are Late Miocene (Souther, 1991).

2.2. Canadian volcano lumping criteria

Distinguishing the number of "volcanoes" in Canada is not an unambiguous process. A large volcanic complex may contain multiple discrete vents and overlapping deposits, and isolated edifices may be reported as part of a larger volcanic field or not included in many geologic investigations. Our database of Pleistocene volcanoes includes 348 vents (Table A1 in the Appendix). For the purpose of this study, we consider the upper Pleistocene limit to be 1.8 million years BP (Gradstein and Ogg, 2004) and the Holocene to represent the period following deglaciation of the last Cordilleran Ice Sheet in western Canada (i.e. from 11 000 BP to the present) (Clague and James, 2002; Clague and Ward, 2011). We use these time intervals because the vast majority of volcanology research in Canada was conducted prior to the 2004 geologic timescale revision and a number of edifices have estimated Pleistocene or Holocene ages only. In addition, one primary means for estimating the age of a Holocene eruption in western Canada is by the lack of indicators for post-eruptive glacial overriding. Deglaciation of the last Cordilleran Ice Sheet was essentially complete by ~11 000 BP (Clague and Ward, 2011), thus we consider all postglacial (i.e. Holocene) vents to have an age of 11 000 years or less.

It would be impractical to evaluate volcanic threat for every Canadian vent, and thus, we systematically lump the deposits into 28 groups which we refer to as "volcanoes" (Table 1). The groupings are broad and amalgamate closely related volcanic fields (e.g. the Satah, Baldface

Mountain, and Itcha Range volcanic fields are combined due to their proximity in space and similarities in age), and combine complex stratovolcanoes with peripheral monogenetic edifices (e.g. Mt. Edziza includes the central complex stratovolcano and peripheral monogenetic centers such as Eve Cone and Pillow Ridge). Broadly lumping the volcanoes has four key advantages: i) the lumped volcanoes provide a simple and approachable means to communicate our results with a non-scientific community, ii) lumping minimizes bias towards well studied volcanoes by maximizing the amount of available data for all volcanic groups, iii) if seismic unrest were to occur at any of the volcanoes, it would be difficult to locate very small events and thus clarify the spatial distribution of unrest, given the coarse resolution of Canada's current (regional) seismic network, and iv) because VT seismicity up to 30 km from the eventual vent is typically the earliest sign of unrest at a long-dormant volcano (White and McCausland, 2016), in terms of evaluating unrest in order to produce short-term activity forecasts, it is necessary to consider each volcanic complex or field as one system. Table 1 reports the type, age, and location of the 28 Canadian volcanoes. The locations are calculated as the average of the contributing vent locations.

Table 1. List of 28 volcanoes in Canada including volcanic belt, type, location, recent activity, and references.

Volcano	Belt	Type	Location		Recent Activity (ka)	Reference
			Latitude	Logitude		
Milbanke Sound	AVB	Small volcano	52.3181111	-128.509889	14.5-12.5, 12.3	Baer (1973); Wood and Kienle (1992); Bednarski and Hamilton (2019)
Nazko Cone	AVB	Small volcano	52.9277778	-123.734722	7.2	Souther (1987); Hickson (2009)
Satah-Baldface	AVB	Shield volcano	52.5681461	-124.677065	1770, 1430, 910, 800	Charland et al. (1993); Cassidy et al. (2011); Kuehn (2014); Kuehn et al. (2015)
Chilcotin Basalts	CB	Lava flows	50.9085370	-121.164356	180, 170	Bevier (1983); Mathews (1989); Dohaney (2009); Sluggett (2003)
Clearwater-Quesnel	CQVP	Small volcano	52.1071581	-120.262169	174, 0.4	Hickson (1986); Hickson (1989)
Mt. Silverthrone	GVB	Stratovolcano	51.4308333	-126.194306	472, 12.2	Blake (1986); Green et al. (1988)
Mt. Meager	GVB	Stratovolcano	50.6480388	-123.553842	75, 17, 2.360	Read (1977); Green et al. (1988); Read (1990); Hickson et al. (1999)
Mt. Cayley	GVB	Stratovolcano	50.1116091	-123.267651	219, 49.1, <12	Green et al. (1988); Kelman (2005); Wilson and Russell (2018)
Monmouth Creek-Watts Poi	GVB	Small volcano	49.6713889	-123.203611	21.9	Bye et al. (2000); Wilson et al. (2016); Wilson and Russell (2018)
Mt. Garibaldi	GVB	Stratovolcano	49.8264975	-122.997265	11.7, 9.3	Mathews (1952); Wilson and Russell (2018)
Mt. Price	GVB	Stratovolcano	49.9522587	-123.023494	300, 13	Mathews (1948, 1958); Green et al. (1988); Wilson and Russell (2018)
Cheakamus-Elaho	GVB	Lava flows	50.2432500	-123.349500	<34	Mathews (1958); Green et al. (1988); Wilson and Russell (2018)
Bridge River-Salal Creek	GVB	Small volcano	50.8623741	-123.422433	589, 408	Lawrence et al. (1984); Roddick and Souther (1987); Wilson and Russell (2018)
Tuya-Teslin	NCVP	Small volcano	59.2352554	-130.715470	961, 140, <10	Watson and Mathews (1944); Edwards et al. (2011); Russell et al. (2013)
Dark Mt.	NCVP	Small volcano	58.5140741	-129.675772	Pleistocene	Gabrielse (1998)
Level Mt.	NCVP	Stratovolcano	58.4246528	-131.414097	Pleistocene	Hamilton and Scarfe (1977); Wood and Kienle (1992)
Heart Peaks	NCVP	Stratovolcano	58.5846065	-131.989444	Pleistocene	Casey and Scarfe (1978); Casey (1980)
Watson Lake	NCVP	Lava flows	60.1407407	-129.359028	230.0	Klassen (1987); Colpron et al. (2016)
Nass River	NCVP	Small volcano	55.3009722	-129.112431	175, 0.625, 0.22	Sutherland Brown (1969); Evenchick and Mustard (1996); Haggart et al. (1998)
Surprise Lake	NCVP	Small volcano	59.7001389	-133.354931	Holocene	Clague (1991); Edwards et al. (1992); Edwards et al. (1996); Edwards and Bye (2003)
Llangorse Mt.	NCVP	Small volcano	59.3731468	-132.850660	Pleistocene	Edwards et al. (2003); Harder et al. (2003); Harder and Russell (2006)
Mt. Edziza	NCVP	Stratovolcano	57.6455679	-130.663469	6, <6, 1.34	Souther (1992)
Iskut-Unuk	NCVP	Small volcano	56.5604861	-130.687736	33, 8.73, 2.555, 0.35, 0.15	Stasiuk and Russell (1990); Hauksdóttir (1992); Hauksdóttir et al. (1994).
Hoodo Mt.	NCVP	Stratovolcano	56.7719444	-131.296389	9.0	Edwards et al. (2002); Edwards and Russell (2002)
The Thumb	NCVP	Small volcano	56.2337698	-126.654127	Pleistocene	Wood and Kienle (1992)
Fort Selkirk	NCVP	Lava flows	62.7738889	-137.620750	Holocene	Nelson et al. (2009); Jackson et al. (2012)
Crow Lagoon	NCVP	Small volcano	54.7000000	-130.230000	140.0	Souther and Weiland (1993).
Bell-Irving	NCVP	Small volcano	56.9165451	-129.501493	430.0	Edwards et al. (2006)

3. SYSTEM FOR RANKING VOLCANIC THREAT

We use the NVEWS threat assessment system to evaluate the 28 volcanoes in terms of 12 hazard factors (e.g. volcano type, eruption recurrence interval, history of pyroclastic density currents, etc.) and 9 exposure factors (ground-based population, airport proximity, previous fatalities, etc.). The scores from each factor are added within the two categories and then the categories are multiplied to produce an overall threat score (Ewert et al., 2005; Ewert, 2007). Selected factors are also subtotaled to give a hazard score, exposure score, and an aviation threat score (Ewert et al., 2018). The hazard and exposure factors are designed to be general enough to be applied easily to most volcanoes yet include sufficient detail such that the absence of data for one or two factors will not inordinately bias the overall results (Ewert et al., 2005). The NVEWS threat assessment is not a formal risk assessment of Canadian volcanoes. A risk assessment would require probabilistic hazard analyses for each edifice and evaluation of the vulnerability of people and property to determine potential losses. Given our lack of knowledge of Canadian eruption histories and hazards, a formal risk assessment is beyond the scope of this analysis.

Variants of the NVEWS system have been used to evaluate threat for volcanoes in Europe (Kinvig et al., 2010), New Zealand (Miller, 2011) and Central and South America (Lara et al., 2005; Palma et al., 2008). Thus, applying this system directly to Canadian volcanoes produces numerical rankings that may be easily compared with similarly ranked volcanoes internationally. Data and methods used for our threat analysis are discussed below and a summary of the evaluation factors used is given in Table 2 (modified from Ewert et al., 2018). For a detailed discussion of the development of the threat ranking system and rationale behind each scoring factor, we refer the reader to Ewert (2007) and Ewert et al. (2005, 2018).

Table 2. Hazard and exposure factors contributing to threat ranking of Canadian volcanoes (modified from Ewert et al., 2018).

Hazard Factors	**Score**
Volcano type	
If volcano type is cinder cone, basaltic field, small shield, or fissure vents	0
If volcano type is stratocone, lava domes, complex volcano, maar or caldera	1
Maximum volcano explosivity index (VEI)	
If maximum known VEI≤2	0
If maximum known VEI=3 or 4	1
If maximum known VEI=5 or 6	2
If maximum known VEI≥7	3
If no maximum VEI known and if volcano type=0	0
If no maximum VEI known but volcano type=1	1
If no known Holocene[*] eruptions and the volcano is not a silicic caldera system	0
Explosive activity in past 5000 years	
If major explosive activity (VEI≥4) within past 5,000 years	1
Eruption recurrence	
If eruption interval is 1–100 years	4
If eruption interval is 101–1000 years	3
If eruption interval is 1001 to 5500 years	2
If eruption interval is 5501–11 000 years	1
If no known Holocene eruptions	0
Holocene pyroclastic flows?	
If yes	1
Holocene lava flows?	
If Holocene lava flows have traveled beyond the immediate eruption site or flanks and reached currently populated areas	1
Holocene lahars?	
If Holocene lahars or volcanic debris flows have traveled beyond the flanks and reached currently populated	1
Sector collapse potential?	
If the volcano has produced a sector collapse in Quaternary-Holocene time and has re-built its edifice, or, has high relief, steep flanks and demonstrated or inferred alteration	1
Primary lahar source?	
If volcano has a source of permanent water/ice on edifice, water volume >10^6 m^3	1
Historical Unrest Factors	
Observed seismic unrest	
Since the last eruption, in the absence of eruptive activity, has there been seismic activity within 20 km of the volcanic edifice? If yes, score as indicated	1
Has seismic of the volcano monitoring with the regional Canadian seismic network been insufficient to detect small magnitude swarms or local earthquakes since the 1980's? If yes, score as indicated	0.5
Observed ground deformation	
Since the last eruption, in the absence of eruptive activity, inflation, slope creep or other evidence of magma injection or signifcant mass wasting event? If yes, score as indicated	1
Observed fumarolic or magmatic degassing	
Since the last eruption, in the absence of eruptive activity, either heat source or magmatic gases? If yes, score as indicated	1
Exposure Factors	
Ground-based population (log$_{10}$)	
Calculated with JRC Global Human Settlement population layer (Schiavina et al., 2019). Estimated annual visitor statistics and seasonal workers for volcanoes near Sea to Sky highway (Whistler and Squamish, BC) are added to the ground-based population. Population outside the 30 km radius are included within the extent of Holocene flow deposits or reasonable inundation modeling of flowage processes. This includes preliminary lahar hazard modelling for Mt. Meager, Mt. Garibaldi and Mt. Cayley.	
Historical fatalities?	
If yes, and a permanent population is still present	1
Historical evacuations?	
If yes, and a permanent population is still present	1
Local aviation exposure	
If any type of volcano is within 50 km of an airport with scheduled passenger service it receives a score of 1; if a type 1 volcano is within 300 km of an airport with scheduled passenger service it receives a score of 1; if a type 1 volcano is within 300 km of a major international airport it receives a score of 2.	
Regional aviation exposure	
Applied only to type 1 volcanoes and those type 0 volcanoes that have produced explosive eruptions (Nazko Cone, Nass River (Tseax), Crow Lagoon volcano, Iskut-Unuk cones). The score is based on the log$_{10}$ of approximate daily passenger air traffic transiting within 300 km of each volcano.	
Power infrastructure	
Is there power infrastructure (for example, power generation/transmission/distribution for electricity, oil, or gas) within flowage hazard zones, or in an area frequently downwind of the volcano and close enough to considered at some risk? If yes, score as indicated	1
Transportation infrastructure	
Is there transportation infrastructure (for example, port facilities, rail lines, major roads) within flowage hazard zones, or in an area frequently downwind of the volcano and close enough to be considered at some risk? If yes, score as indicated	1
Major development or sensitive areas	
Are there major developments or sensitive areas threatened (for example, national or provincial park facilities, significant cultural sites, mine operations, developed tourist/recreation facilities, or other manufacturing? If yes, score as indicated	1
Could an eruption restrict access to a community?	
Community affected has 1 road in/out	2
Community affected has 2 roads in/out	1
Community affected has >2 roads in/out	0

[*] *Holocene is considered to represent the period from 11 000 BP to present day.*

3.1. Hazard factors and scoring

Data contributing to hazard factor calculations are compiled from a range of geological literature (Tables A1 and A2 in the Appendix). Our threat ranking uses 12 of the original 15 NVEWS hazard factors of Ewert et al. (2005). We do not evaluate the "Explosive eruption activity (VEI ≥ 3) in the past 500 years", the "Holocene tsunamis", or the "Holocene phreatic explosive activity" factors, as they do not apply to any Canadian volcanoes. We provide a detailed overview of the factors used and our modifications to the NVEWS threat ranking below.

3.1.1. Volcano type (scored as 0 or 1)

Volcano type gives a basic description of how dangerous a volcano is likely to be. *Type 0* volcanoes tend to be less explosive and include cinder cones, tephra mounds, tuyas, basaltic lava fields, and basaltic shield volcanoes. *Type 1* volcanoes include more explosive stratovolcanoes, lava domes, and calderas. This factor is used to score several other important factors (e.g. maximum VEI, regional aviation exposure) and is assigned based on the main volcanic feature in each of the 28 lumped volcanoes (e.g. Mt. Edziza, a stratovolcano within a surrounding basaltic lava and cinder cone field, is assigned a score of 1). *Type 1* volcanoes include Mt. Silverthrone, Mt. Garibaldi, Mt. Cayley, Mt. Price, Mt. Meager, Mt. Edziza, Hoodoo Mountain, Level Mountain, and Heart Peaks.

3.1.2. Maximum volcanic explosivity index (VEI) (scored from 0 to 3)

The volcanic explosivity index (VEI) is a relative measure of the explosiveness of volcanic eruptions, ranging from 0 to 8, wherein every interval above VEI 2 represents a tenfold increase in the volume of ejecta; it is widely used to report and compare the magnitude of explosive eruptions (Newhall and Self, 1982). For this threat ranking, volcanoes with Holocene VEI 3–4 eruptions receive a score of 1, VEI 5–6 eruptions receive a score of 2, and VEI 7–8 eruptions are given a score of 3. *Type 1* volcanoes without reported eruption magnitudes receive a score of 1. Conversely, *type 0* volcanoes receive a score of 0. Mt. Meager is the only Canadian volcano with a Holocene eruption for which a VEI has been assigned (VEI 4), for the large explosive eruption in 2360 BP (Clague et al., 1995; Leonard, 1995; Andrews et al., 2014), so it receives a score of 1.

3.1.3. Explosive eruptive activity (VEI 4/5) in the past 5000 years (scored as 0 or 1)

The explosive activity factor is designed to emphasise particularly active, large explosive volcanic systems (Ewert et al., 2005). The 2360 BP eruption of Mt. Meager is the only VEI 4 or 5 eruption known to have occurred in Canada in the past 5000 years (Andrews et al., 2014). Mt. Meager is given a score of 1 for this category and all other volcanoes are scored as 0.

3.1.4. Eruption recurrence (scored from 0 to 3)

The eruption recurrence factor is designed to capture the average time interval between volcanic events. Many apparently young Canadian eruption events are not dated quantitatively. Instead, a Holocene age is inferred based on the absence of post-eruptive glacial overriding indicators (e.g. Souther, 1992; Kelman, 2005; Simpson et al., 2006a). In western Canada, deglaciation of the Cordilleran Ice Sheet was complete by ~11 000 BP (Clague and James, 2002). Correspondingly, many inferred "Holocene" vents may be up to ~11 000 years old. For the purpose of this study, we calculate the eruption recurrence interval by dividing 11 000 by the number of demonstrable Holocene eruption events (Table 2). Mt. Edziza scores the highest in this category with an eruption recurrence interval of 379 years and a score of 3. Other notable volcanoes include Mt. Garibaldi, Mt. Silverthrone, the Clearwater-Quesnel volcanic province, Nass River group, Iskut-

Unuk River Cones, and Fort Selkirk volcanic field, each of which has produced at least 2 Holocene eruptions and receives a score of 2.

3.1.5. Holocene pyroclastic flows, lahars and lava flows (scored as 0 or 1)

These three factors are designed to account for lethal and destructive pyroclastic flows, lahars, and lava flows (Ewert et al., 2005, 2018). If a volcano has produced pyroclastic flows during the Holocene, the volcano is assigned a score of 1. For the lahar and lava flow factors, a positive score is only assigned if the lava flows or lahars have travelled beyond the immediate eruption vicinity and inundated currently populated areas. We include all lahar and debris flow events emanating from volcanic structures, including those events generated by non-eruptive mass wasting. Mt. Garibaldi is scored positively for all three categories: the pyroclastic flow factor is assigned to account for primary pyroclastic density current deposits situated in and around the town of Squamish BC (11 700 ± 475 BP [Friele and Clague, 2009a; Wilson and Russell, 2018]), a positive lava flow factor is assigned for the Ring Creek lava (a 17 km long dacite lava flow that abuts the current Squamish town site, dated at 9360 ± 160 BP [Brooks and Friele 1992]), and a positive lahar factor is assigned to account for the complex history of volcanic debris flow deposits situated in the Cheekye drainage (i.e. emitting from the western flank of Mt. Garibaldi [Friele et al., 1999; Friele and Clague, 2009a, b]). Mt. Meager is scored positively for the pyroclastic flow category to reflect pyroclastic flows associated with the 2360 BP eruption (Read, 1990; Hickson et al., 1999). Both Mt. Cayley and Mt. Meager receive a positive lahar score for their records of large debris flows in volcanic materials, in Turbid Creek on the southwest side of Mt. Cayley (Brooks and Hickin, 1991; Evans and Brooks, 1991), and in the Lillooet River valley southeast of Mt. Meager (Friele et al., 2005, 2008). The Nass River group receives a positive lava flow score, accounting for the basaltic lava flow emitted from Tseax cone in 220 BP (Sutherland Brown, 1969). We do not score for the Holocene dacite lava flows that originated at Mt. Price (the Rubble and Culliton Creek flows [Green et al., 1988; Wilson and Russell, 2018]) due to the absence of permanent populations within their inundation zones.

3.1.6. Sector collapse potential (scored as 0 or 1)

Sector collapse is a major hazard at many Canadian volcanoes (Friele et al., 2008; Jakob et al., 2013). Volcanoes were scored positively if they have more than ~1000 m of vertical relief, have active fumaroles, have large areas of altered rock, or host permanent accumulations of snow and ice. Positively scored volcanoes include Mt. Silverthrone, Mt. Garibaldi, Mt. Cayley, Mt. Price, Mt. Meager, Mt. Edziza, and Hoodoo Mountain.

3.1.7. Primary lahar source (scored as 0 or 1)

Many Canadian volcanoes occur in mountainous terrain with year-round accumulations of ice and snow that could provide a source of water for lahars or debris flows during seasonal melting or volcanic heating. Volcanoes were scored positively if they host a permanent snow/ice accumulation of $>10^6$ m^3. These volcanoes include Mt. Silverthrone, Mt. Garibaldi, Mt. Cayley, Mt. Price, Mt. Meager, Mt. Edziza, and Hoodoo Mountain. It should be noted that the Holocene Rubble Creek lava flow, which originated at Mt. Price and forms the cliff known as "The Barrier", has a history of landslides and poses a risk of landslides that may affect Highway 99 or inhabited areas further downstream; this risk is not encompassed by this threat ranking, as the "Sector collapse potential" and "Primary lahar source" factors do not apply, but it merits future consideration in evaluations of hazards related to Canadian volcanoes (Mathews, 1952a; Moore, 1976; Moore and Mathews, 1978; Green et al., 1988; Hickson, 1994).

3.2. Historical Unrest Factors

Historic or current volcanic unrest provides a reliable indicator of latent or active magmatism (e.g. Ewert et al., 2005; Sparks et al., 2012; Fujii and Yamasato, 2015). Indicators for unrest include fumaroles or hot springs, local seismicity, or active ground deformation (Ewert et al., 2005, 2018). Due to the lack of dedicated volcano monitoring in Canada, the number of volcanoes scoring positively for these factors is low.

3.2.1. Observed seismic unrest (scored as 0 or 1)

The current seismic network in Canada was set up to monitor tectonic earthquakes. Most stations are not located within close proximity of any volcanoes. Since 1980, however, this regional seismic network has recorded small magnitude, shallow crustal seismicity within close proximity of 10 volcanoes, including the Clearwater-Quesnel volcanic province, Mt. Silverthrone, Mt. Meager, Mt. Cayley, Mt. Garibaldi, Mt. Price, Mt. Edziza, the Iskut-Unuk River Cones, Hoodoo Mountain, and Crow Lagoon (Stasiuk et al., 2003). Because these earthquakes are not demonstrably magmatic, we assign these volcanoes a score of 0.5 (according to the procedure of Ewert et al., 2018). Clearly magmatic seismicity occurred at Nazko cone in 2007, when a swarm of M<3 earthquakes, most at 25-31 km depth, was detected by a temporary seismic array; the sequence was interpreted as resulting from a magma injection into the lower crust (Cassidy et al., 2011). Nazko cone is assigned a score of 1.

3.2.2. Observed ground deformation (scored as 0 or 1)

Canada does not conduct regular volcano deformation monitoring using ground-based global positioning systems (GPS), tiltmeters, or remote sensing, although an InSAR monitoring plan is currently being developed. Despite this, a remote sensing study at Mt. Meager, using

Interferometric Synthetic Aperture Radar (InSAR), Light Detection and Ranging (LIDAR), Structure from Motion photogrammetry, analysis of glacier loss, and site-specific field mapping, identified 27 large (>500 000 m^2) unstable slopes (Roberti et al., 2017b; Roberti, 2018).The ground deformations detected included, during a 24 day period in the summer of 2016, displacements of up to 34 mm on the east flank of Job Creek and up to 36 mm on the east flank of Devastation Creek valley; a collapse of either of these two slopes could potentially produce a landslide of 100 million to 1 billion m^3 (Roberti, 2018). We assign a score of 1 to Mt. Meager for ground deformation.

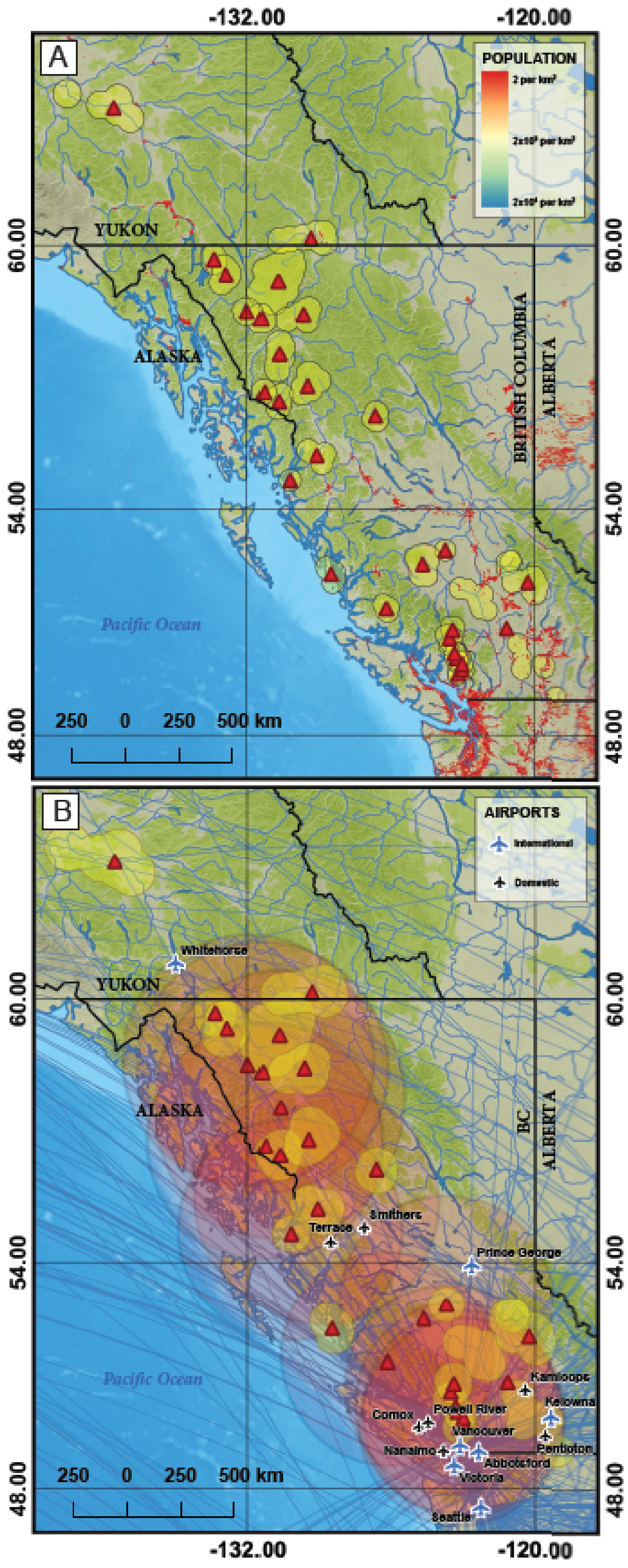
3.2.3. Observed fumarolic or magmatic degassing (scored as 0 or 1)

Thermal features such as hot springs or fumaroles are indicators of an active magmatic system (Sparks et al., 2012). A score of 1 is assigned to Mt. Meager, due to the presence of multiple fumaroles and hot springs (Lewis and Souther, 1978; Venugopal et al., 2017), and to Mt. Cayley, which has four hot water seeps with temperatures of up to 40ºC (Souther, 1980).

3.3. Exposure Factors

Assessing volcanic threat includes evaluating the potential populations and infrastructure (including aviation traffic) that may be at risk during an eruption. We implement the methodology of Ewert et al. (2005, 2018) and Ewert (2007), which identifies population and infrastructure within a 30 km radius of the volcano, and aviation infrastructure (i.e. airports) within 50 and 300 km radii (for *type 0* and *type 1* volcanoes, respectively). We also evaluate daily aviation traffic within 300 km radii zones of all *type 1* volcanoes. Because the 28 lumped volcanoes represent collections of vents, we construct 30, 50, and 300 km exposure zones around each of the 348 known vents (Tables A1 and A2 in Appendix) and merge the contributing zones

(Figure 3). While this raises the exposure footprint of several sparsely populated volcanic fields (e.g. the Chilcotin basalts), we suggest that it provides a more reasonable assessment of exposure, given the unpredictability of future vent locations at long-dormant volcanoes, particularly broad volcanic fields with many monogenetic vents.

-132.00
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A
POPULATION
2 per km^2
2x10^{3} per km^2
2x10^{4} per km^2
YUKON
ALASKA
BRITISH COLUMBIA
ALBERTA
Pacific Ocean
60.00
54.00
48.00
250 0 250 500 km
B
AIRPORTS
International
Domestic
Whitehorse
YUKON
ALASKA
BC
ALBERTA
Terrace
Smithers
Prince George
Pacific Ocean
Kamloops
Comox
Powell River
Kelowna
Vancouver
Penticton
Nanaimo
Abbotsford
Victoria
Seattle
60.00
54.00
48.00
250 0 250 500 km
-132.00
-120.00

Figure 3. Maps showing Geographic Information System (GIS) based method for calculating population and aviation exposure around volcanoes (red triangles). A) Canadian population within 30 km exposure zones (yellow circles). B) Airports and airline routes (blue lines) exposed within 50 km (yellow circles) and 300 km (red circles) exposure zones.

Debris flows and lahars commonly inundate areas that lie beyond 30 km from the source area at many volcanoes (e.g. Ewert et al., 2005; Wilson et al., 2014). For this reason, Ewert et al. (2005) suggest that the hazard zones for volcanoes with the potential for significant lahars and debris flows should be extended to include areas inundated by previous events or areas indicated by plausible modelling studies. For our study, geologic data and debris flow and lahar modelling suggest that inundation zones associated with flow events larger than 10^8 m^3 may extend downstream beyond 30 km at Mt. Meager, Mt. Cayley, and Mt. Garibaldi. At Mount Meager, at least six debris flows during the last 8000 years have inundated now-inhabited portions of the Lillooet River valley (Friele and Clague, 2004; Friele et al., 2005; Simpson et al., 2006b; Friele et al., 2008), and multiple mass wasting events at Mount Cayley were large enough to temporarily dam the Squamish River (Brooks and Hickin, 1991; Evans and Brooks, 1991). For this reason, in accordance with procedures used in Ewert et al. (2005), we extended the 30 km radii hazard zones to include runout zones for Mt. Meager (reaching the town of Pemberton and Lillooet Lake), Mt. Cayley (reaching the town of Squamish and Howe Sound), and Mt. Garibaldi (reaching the town of Squamish and upper Pitt Lake).

3.3.1. Ground-based population (Log$_{10}$ of exposed population) (scored from 0 to 5.42)

To estimate the human population potentially exposed to volcanic hazards, we use the Joint Research Centre Global Human Settlement layer (GHS) (Schiavina et al., 2019), a 1 km-resolution spatial dataset constructed using satellite-based imagery combined with 2015

Canadian census data. Population evaluations use the 30 km exposure footprints (discussed above), which encompass the likely inundation zones of most volcanic hazards (e.g. lava flows, lahars, and tephra fall [Ewert et al., 2005]). For Mt. Meager, Mt. Cayley, and Mt. Garibaldi, we include populations residing in the extended debris flow/lahar runout zones, as described above.

Seasonal visitors and workers comprise a large portion of the population exposed in the towns of Squamish and Whistler. In 2017, Whistler received three million tourists and hosted approximately 2000 seasonal workers (https://trade.whistler.com/about/stats). Access to Whistler is via the Sea to Sky Highway (Highway 99), thus, based on the annual number of tourists, we estimate that an additional 8200 people may be at risk in the Sea to Sky corridor each day. These 8200 additional people are added to the population for each of the volcanoes that occurs within 30 km of the Sea to Sky Highway (i.e. Mt. Cayley, Mt. Garibaldi, Mt. Price, and Monmouth Creek-Watts Point), and an additional 2000 people are added to volcanoes within 30 km of Whistler (i.e., Mt. Cayley, Mt. Garibaldi and Mt. Price) to account for seasonal workers. Following Ewert et al. (2005) we take the Log_{10} of the total population residing in each exposure zone and score the population factor accordingly (Table A3 in the Appendix).

Population factors for Canadian volcanoes range from 0 to 5.42. Remote volcanoes like Mt. Silverthrone, Hoodoo Mountain, and Heart Peaks score <0.85, reflecting permanent populations of fewer than ten people. The Chilcotin basalts score the highest (5.42), primarily due to the large land area covered and their proximity to several major cities (Kelowna and Kamloops). The scores for Mt. Garibaldi and Mt. Price are the second highest (4.61), reflecting the >40 000 people residing in Squamish and Whistler.

3.3.2. Historical evacuations and fatalities (scored as 0 or 1)

Because only a single eruption and several volcanic landslides are historically documented in Canada, the evacuation and fatalities factor applies to only two volcanic events. The 220 BP eruption at Tseax cone (part of the Nass River group) emitted a 32 km long basaltic lava flow, which dammed the Nass River and killed approximately 2000 people of the Nisga'a First Nation (Sutherland Brown, 1969; Le Moigne et al., 2020). Accordingly, the Nass River group receives a score of 1 for the fatalities factor. Similarly, the 2010 landslide at Mt. Meager, one of the largest landslides worldwide since 1945, caused a dam in Meager Creek for 19 hours. The event initiated an evacuation order for 1500 residents in the Lillooet River valley, due to debris flow and flood concerns (Guthrie et al., 2012). Mt. Meager is given a score of 1 for the evacuations factor.

3.3.3. Local aviation exposure (scored as 0 or 1)

The Local aviation exposure factor is designed to capture the effect of volcanic ash on local aviation. If a *type 0* volcano is within 50 km, or a *type 1* volcano is within 300 km of an airport with a scheduled passenger service, the volcano is given a score of 1. We include international airports in British Columbia, Yukon Territory, and Washington state (e.g. Vancouver International Airport and Seattle-Tacoma International Airport), as well as a number of smaller domestic Canadian airports that have scheduled passenger services (e.g. Smithers Regional Airport).

3.3.4. Regional aviation exposure (Log_{10} of daily passengers) (scored from 0 to 5.35)

The regional aviation exposure score is designed to quantify the daily number of passengers transiting the airspace above Canadian volcanoes. This factor is applied to *type 1* volcanoes and those *type 0* volcanoes with demonstrable Holocene pyroclastic activity. *Type 0* volcanoes included are Nazko cone (Souther et al., 1987), Nass River Group (Sutherland Brown, 1969) and the Crow Lagoon tephra source (Souther and Weiland, 1993). Ewert et al. (2018) used the Air Carrier Statistics (T100) databank (United States Department of Transportation, 2019) to estimate aviation routes and passenger numbers within United States airspace. Similar data for passengers transiting Canadian airspace are not readily available, however, annual enplaned and deplaned passenger data exist for the major Canadian airports. For Vancouver International Airport (YVR), these data are further divided into domestic, international, transborder (i.e. to the U.S.A.), and Asia-Pacific passenger segments (https://www.yvr.ca/en/about-yvr/facts-and-stats). To estimate daily passenger air traffic, we evaluate flight activity in three groups: i) flight routes that originate in Canada and terminate at Canadian airports (domestic), ii) flight routes that connect the Asia-Pacific region with western Canada (i.e. originating or terminating at YVR), and, iii) flight routes that transit Canadian airspace but do not land in Canada (e.g. a flight to Alaska or the Asia-Pacific from Washington state).

We calculate the regional aviation scores as follows. First, using the T100 aviation databank, we construct great circles (representing flight routes) connecting departure and destination airports. Routes that intersect 300 km volcano exposure footprints are extracted and the total average number of passengers transiting each exposure zone daily is summed. These data account for all transborder flight movements and domestic United States aviation movements. Second, we identify the airports that are within 300 km exposure zones of each volcano and add the average daily passenger count to the total for each volcano (Table A4 in the Appendix). Transborder passengers are removed, where possible, as these passengers are already accounted for in the T100 databank. Transborder passengers are not reported for all Canadian international airports (e.g. Victoria, Abbotsford, Prince George, and Kelowna), so these passengers represent a small overestimation of daily air traffic. Finally, Vancouver International Airport (YVR) serves a major air transit corridor over the western Canadian continental margin connecting Asia-Pacific with North America. To account for these passengers (originating or landing at YVR), we add the Asia-Pacific portion of YVR traffic to all volcanic edifices with 300 km exposure zones overlapping the western continental margin. We include Mt. Edziza, the Nass River Group, Crow Lagoon, Mt. Silverthrone, and Hoodoo Mountain. The highest-scoring volcanoes for the regional aviation exposure category are Mt. Meager (5.05), Mt. Cayley (5.35), Mt. Price (5.35), and Mt. Garibaldi (5.35). These scores reflect their close proximity and potential impact on aviation through YVR and Seattle-Tacoma airports (Table A4 in the Appendix).

3.3.5. Power, infrastructure, and major developments (scored as 0 or 1)

Volcanoes may destroy or affect transportation, power, or other critical infrastructure. To evaluate infrastructure exposure, we use a proprietary database compiled by Natural Resources Canada indicating the locations of major roads, railways, ferry and shipping routes, pipelines, active mines, other industry, and power generation or power dissemination structures. We also include proximity to ski resorts (e.g. Whistler-Blackcomb) and culturally sensitive areas (e.g. the Nisga'a Memorial Lava Bed Provincial Park). We use 30 km exposure footprints and score the power, infrastructure, and major development factors positively if the volcano hazard footprint overlaps with any infrastructure or sensitive area locations.

3.3.6. Isolation factor (scored from 0 to 2)

Ewert et al. (2005) include a *Volcanic Island* exposure factor that is designed to score for the difficulties of dealing with volcanic events on remote, populated islands (evacuation, aid delivery, etc.). No volcanoes in Canada form a significant portion of populated islands. However, due to the remoteness of western Canada, many populated areas may be effectively isolated during an eruption and experience similar difficulties in receiving aid or evacuating residents due to singular transportation routes, rugged terrain, or distance to the nearest population centre. To quantify this, we replace the *Volcanic Island* factor with a modified *Isolation* factor and evaluate ground-based community access (road infrastructure) within 30 km exposure footprints. If road access to a community could be restricted by a volcanic event (i.e. there is only one road in/out), the volcano is given a score of 2. If there are two access routes, the volcano is given a score of 1. If there are three or more access routes to the community, the volcano receives a score of 0. This factor is important for several remote western Canadian communities. For example, an eruption at Tseax cone (Nass River group) may significantly restrict access to several communities situated along British Columbia Highway 113 (Nisga'a Highway).

4. RESULTS

The threat assessment scores for each of the 28 volcanoes are given in Table 3. The details of how each volcano was scored, and source references used in the scoring, are given in Table A2 in the Appendix. We provide constituent component scores (aviation score, hazard score, and exposure score) and the overall threat score. In most cases, our ranking represents a minimum, as knowledge of past explosive activity, eruptive behaviour, and eruption recurrence for many Canadian volcanoes is low. Typically, detailed lithofacies studies uncover evidence for more eruption events, rather than fewer (e.g. Stasiuk et al., 2003; Van Daele et al., 2014). The distributions of overall threat scores and corresponding aviation threat scores are shown in Figure 4. The geographic distribution of classified volcanoes is shown in Figure 5 (northwestern

Canada) and Figure 6 (southwestern Canada). Overall threat scores range from 0 to 152.04 and show a broadly decreasing exponential distribution. Aviation scores range from 22.0 to 0 and follow a similar, decreasing exponential trend. For comparative purposes, our Canadian threat group classifications are kept consistent with Ewert (2007) and Ewert et al. (2018) and follow natural breaks in the overall threat rankings.

Table 3. Canadian volcanoes ranked and categorised according to NVEWS threat analysis including constituent hazard, exposure, unrest and aviation scores and geologic uncertainty score.

Rank	Volcano	Hazards Score	Exposure Score	Aviation Score	Unrest Score	Overall Threat Score	Category	Geologic Uncertainty
1	Mt. Meager	10.5	14.48	21.16	2.50	**152.04**	1	4
2	Mt. Garibaldi	9.5	15.9546	22.0454	0.50	**151.57**	1	8
3	Mt. Cayley	6.5	15.91	7.3483	1.50	**103.39**	2	7
4	Mt. Price	5.5	15.9548	14.6969	0.50	**87.75**	2	8
5	Mt. Edziza	7.5	10.77	17.22	0.50	**80.78**	2	6
6	Nass River	3	13.44	8.84	0.00	**40.31**	3	5
7	Mt. Silverthrone	6.5	5.59	14.22	0.50	**36.31**	3	10
8	Hoodo Mt.	5.5	4.40	8.81	0.50	**24.22**	4	7
9	Nazko Cone	2	9.28	3.95	1.00	**18.56**	4	2
10	Clearwater-Quesnel	2.5	6.72	0.00	0.50	**16.81**	4	6
11	Level Mt.	3	3.95	7.90	0.00	**11.85**	4	11
12	Heart Peaks	2	5.18	5.18	0.00	**10.36**	4	10
13	Surprise Lake	2	4.58	0.00	0.00	**9.17**	4	10
14	Milbanke Sound	1	7.19	0.00	0.00	**7.19**	4	8
15	Fort Selkirk	2	2.85	0.00	0.00	**5.69**	5	8
16	Iskut-Unuk	2.5	2.00	0.00	0.50	**5.00**	5	8
17	Crow Lagoon	0.5	8.24	0.00	0.50	**4.12**	5	8
18	Tuya-Teslin	1	2.69	0.00	0.00	**2.69**	5	8
19	Satah-Baldface	0	5.40	0.00	0.00	**0.00**	5	8
20	Chilcotin Basalts	0	9.42	0.00	0.00	**0.00**	5	7
21	Monmouth Creek-Watts Point	0	9.47	0.00	0.00	**0.00**	5	7
22	Cheakamus-Elaho	0	8.35	0.00	0.00	**0.00**	5	8
23	Bridge River-Salal Creek	0	2.45	0.00	0.00	**0.00**	5	7
24	Dark Mt.	0	5.58	0.00	0.00	**0.00**	5	11
25	Watson Lake	0	6.15	0.00	0.00	**0.00**	5	8
26	Llangorse Mt.	0	1.30	0.00	0.00	**0.00**	5	10
27	The Thumb	0	1.00	0.00	0.00	**0.00**	5	12
28	Bell-Irving	0	3.70	0.00	0.00	**0.00**	5	10

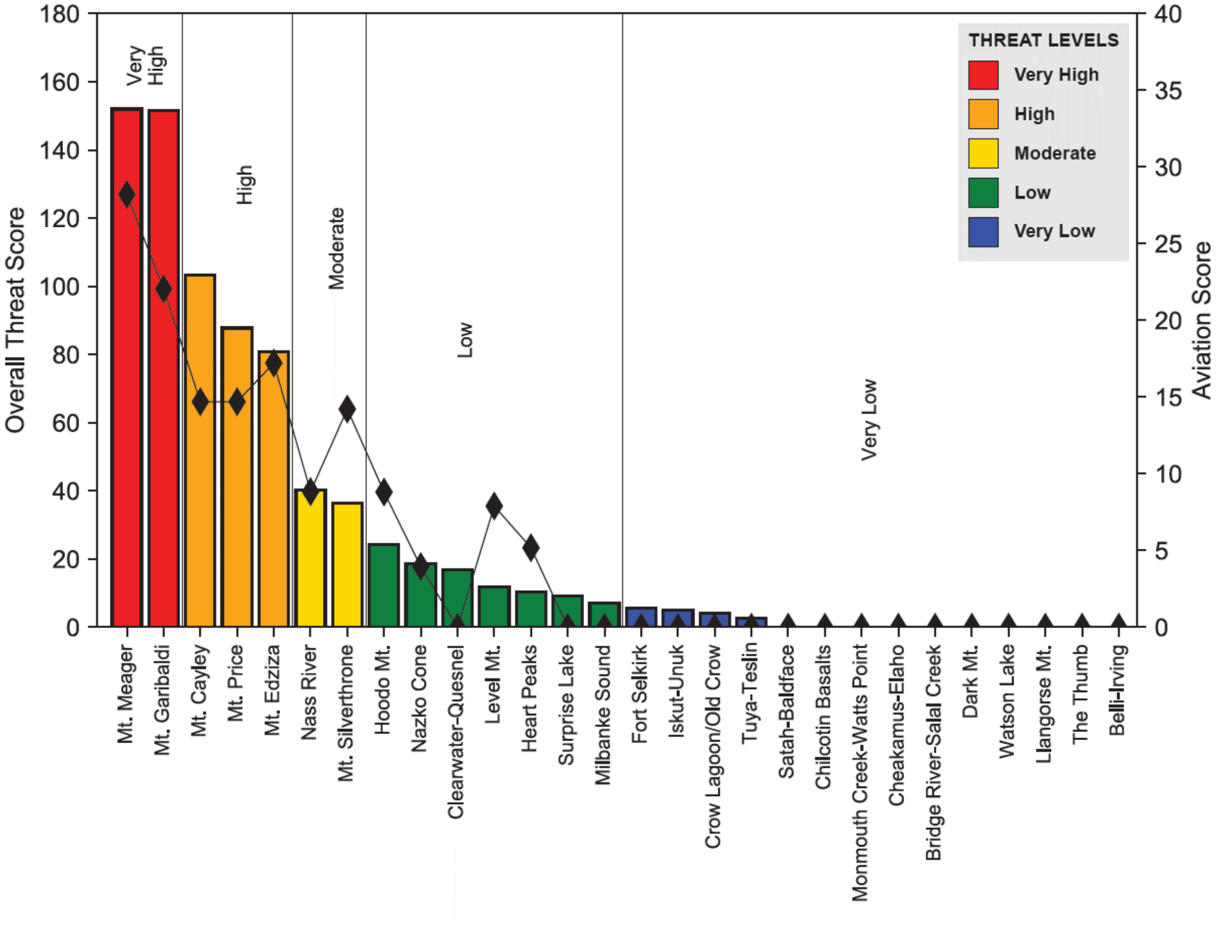

Figure 4. Graph showing distribution of overall threat scores (coloured bars) and aviation threat scores (black diamonds) for Canadian volcanoes. Category divisions are consistent with Ewert et al. (2018).

Figure 5. Map showing geographic distribution of overall threat for classified volcanoes in northwestern British Columbia and the adjacent Yukon Territory.

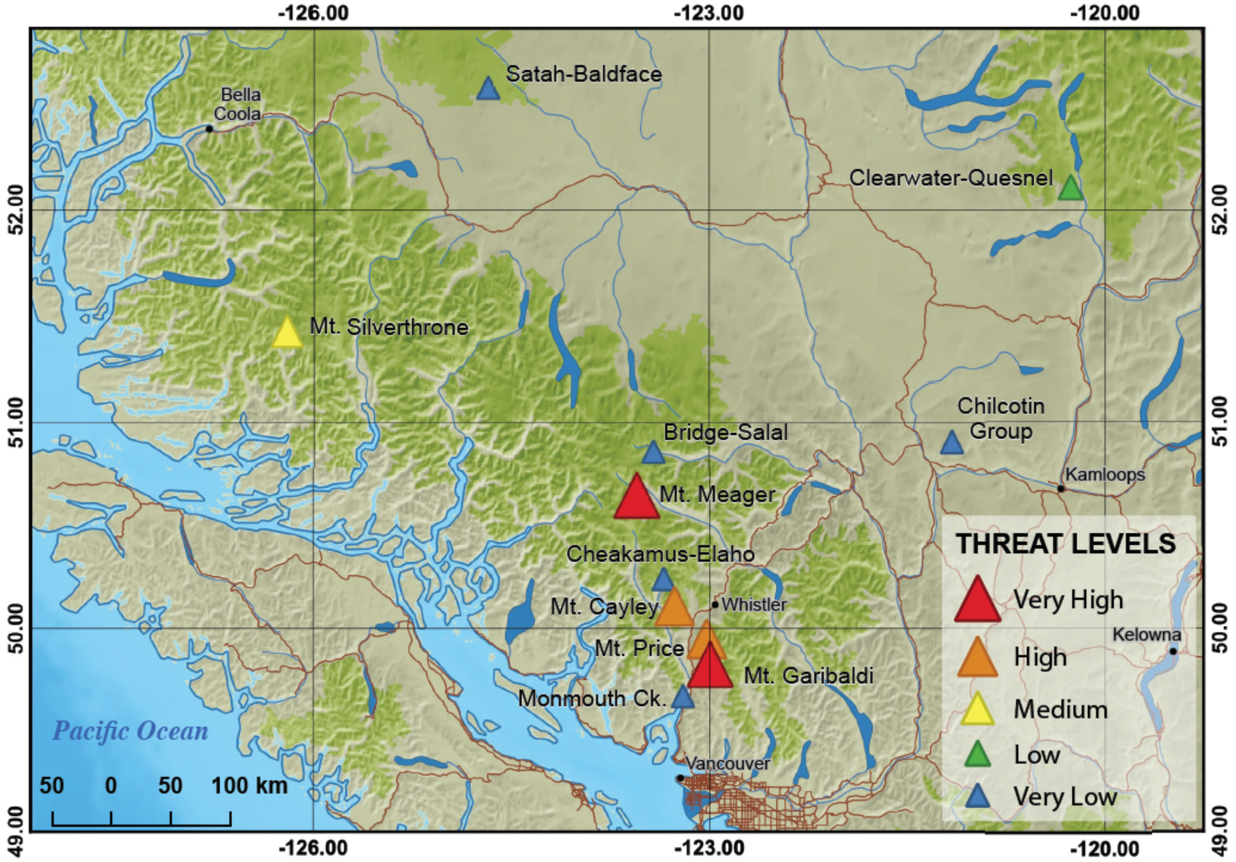

Figure 6. Map showing geographic distribution of overall threat for classified volcanoes in southwestern British Columbia.

4.1. Very High threat (262–122 points)

Two volcanoes (Mt. Meager and Mt. Garibaldi) are classified as *Very High* threat, with similar overall threat scores of approximately 150 each. For Mt. Meager, the *Very High* threat score is largely attributed to recent indicators of volcanic unrest and a large (VEI 4) Holocene eruption. The *Very High* ranking at Mt. Garibaldi reflects a high exposure score (one of the highest of all Canadian volcanoes). The aviation threat scores are 21.2 and 22.0 for Mt. Meager and Mt. Garibaldi, respectively.

4.2. High threat (121–63 points)

Three Canadian volcanoes classify as *High* threat: Mt. Cayley, Mt. Price, and Mt. Edziza. Of these volcanoes, Mt. Cayley is the only volcano that has evidence for volcanic unrest (hot water seeps). Although there are potential Holocene rocks at Mt. Cayley (the Slag Hill and Tricouni Southwest deposits [Kelman et al., 2002; Kelman, 2005]), we have elected to not include these deposits and score the recurrence interval for Mt. Cayley conservatively. Due to the proximity to the Sea to Sky Highway and the towns of Squamish and Whistler, British Columbia, both Mt. Cayley and Mt. Price have exposure scores similar to Mt. Garibaldi. Mt. Edziza has the highest recurrence interval of all Canadian volcanoes, with more than 29 Holocene eruptions. Mt. Edziza is extremely remote, however, resulting in a relatively low exposure score.

4.3. Moderate threat (62–30 points)

Two Canadian volcanoes classify as *Moderate* threat: the Nass River group and Mt. Silverthrone. Overall threat at Nass River is largely attributed to the relatively high eruption recurrence interval (two Holocene eruptions) and a positive fatality score associated with the 220 BP Tseax cone eruption. Mt. Silverthrone scores highly for primary volcanic hazard factors, however, the extreme remoteness of the edifice results in a relatively low exposure score.

4.4. Low threat (29–6 points)

Seven Canadian volcanoes classify as *Low* threat: Hoodoo Mountain, Nazko cone, the Clearwater-Quesnel volcanic province, Level Mountain, Heart Peaks, the Surprise Lake volcanic field and the Milbanke Sound cones. Of these, only Hoodoo Mountain, Nazko cone, and the Milbanke Sound cones have evidence for Holocene activity. No volcanic unrest indicators are observed for any volcanoes in this group and aviation scores are all <10.

4.5. Very low threat (<5 points)

Fourteen volcanoes score in the *Very Low* threat category. Only the Fort Selkirk volcanic field, Iskut-Unuk volcanic field, Crow Lagoon, and Tuya-Teslin volcanic fields show positive overall threat scores. All *Very Low* threat volcanoes show aviation scores of 0 and most are situated in extremely remote areas.

5. DISCUSSION

Our threat assessment does not forecast which Canadian volcano will erupt next. Rather, it provides an indication of relative threat by evaluating potential hazard events and the impact an eruption may have on people and infrastructure. The goal of our analysis is to guide and prioritize future research and monitoring efforts by providing a clear and logical numerical foundation for decision-making, and to increase awareness of relative volcanic threats in order to support land use and emergency planning activities.

The *Very High* to *Moderate* threat category volcanoes mostly include GVB and NCVP stratovolcanoes. Mt. Meager and Mt. Garibaldi have the highest overall threat scores, which is consistent with these edifices being two of the largest and most recently active volcanoes in Canada and with their proximity to population centres in southwest BC. In northern BC, Mt. Edziza, a highly active basaltic to intermediate alkalic system with more than 29 Holocene eruptions, is ranked as *High* threat. In general, most basaltic systems occupy the *Low* to *Very Low* threat categories, with the notable exception of the Nass River group (including Tseax cone).

When compared with similarly ranked volcanoes in the United States, Mt. Meager and Mt. Garibaldi have scores nearly identical to Lassen Peak in California and St. Augustine in

Alaska, both of which are considered highly active and have had several, large 20th century eruptions (Ewert et al., 2018) (Figure 7). *High* threat volcanoes such as Mt. Cayley, Mt. Edziza and Mt. Price score similarly to Mt. Churchill in Alaska and Mt. Adams in Washington (Figure 7). Mt. Churchill is believed to be the source of the ~1250 BP White River Ash, a tephra deposit covering a large portion of northern Canada that was produced by a VEI 6 eruption (Richter et al., 1995; Lerbekmo, 2008). Mt. Adams last erupted effusively around CE 950 and has a recent history of large lahar and debris flow events (Scott et al., 1995; Hildreth and Fierstein, 1997).

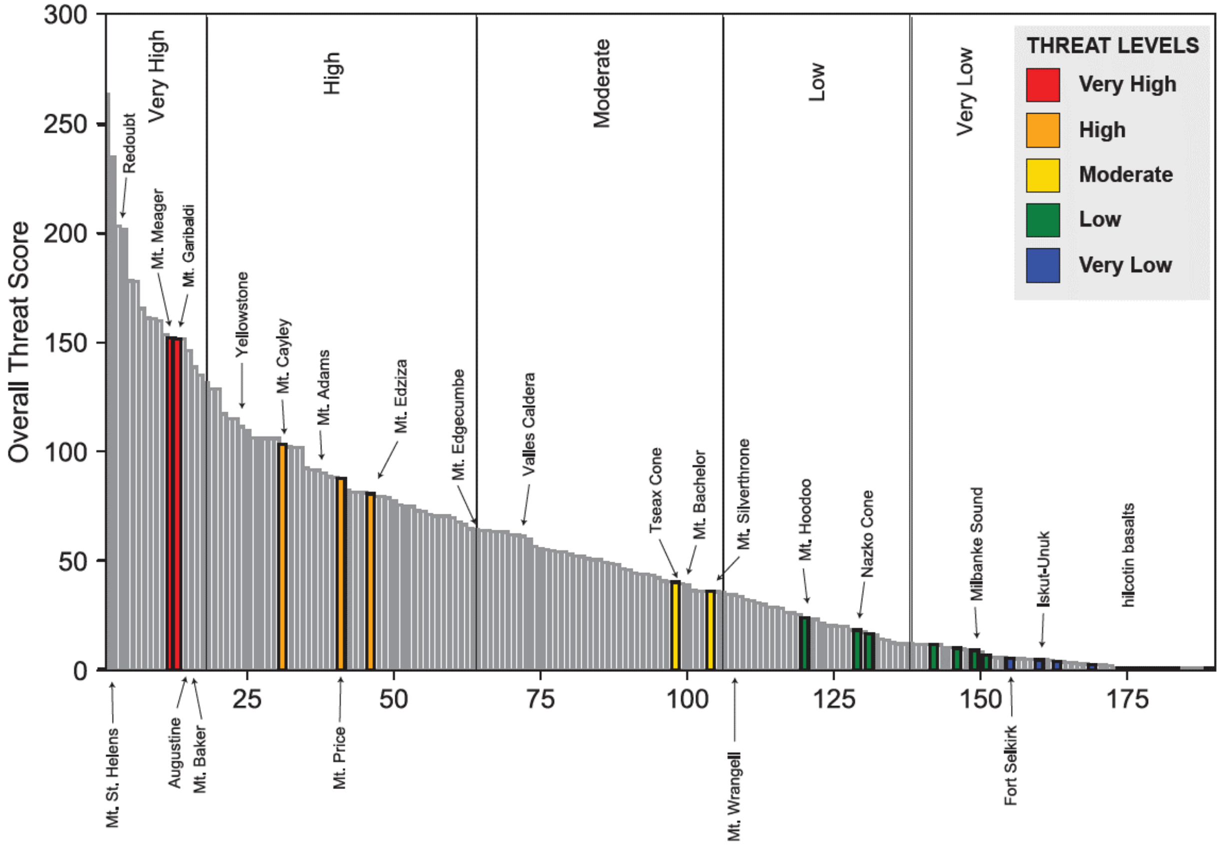

Figure 7. Graph showing distribution of overall threat scores for 169 ranked United States volcanoes (grey bars) and ranked Canadian volcanoes (coloured bars). Volcano threat scores for United States volcanoes are from Ewert et al. (2018). A selection of ranked Canadian and U.S.A. volcanoes are labeled for comparative purposes.

5.1. Volcano knowledge uncertainty

There is an acute lack of scientific information surrounding Canadian volcanism and this lack of knowledge contributes to uncertainty in the overall threat scores (Hickson and Edwards, 2001; Stasiuk et al., 2003). Although the method of assessment outlined by Ewert et al. (2005) is intentionally broad to minimize informational bias, it was designed for application to volcanoes that are mostly well-studied and monitored (e.g. Mt. St. Helens). In contrast, very few edifices in Canada have received detailed lithofacies studies (exceptions include Mt. Edziza [Souther, 1992)] and Mt. Meager [e.g. Read, 1990; Hickson et al., 1999]). Furthermore, most Canadian volcanoes have not had their full eruptive histories documented using modern geochronology, and the vast majority of lithofacies on even the most well-studied volcanoes are not dated. Some of the *High* and *Very High* threat volcanic systems have received essentially no recent scientific attention (e.g. Mt. Garibaldi [Mathews, 1952b; Green et al., 1988; Souther, 1991]).

We evaluate the Canadian volcanoes using a simple metric that semi-quantitatively assesses the uncertainty in geologic, geochronometric, geophysical and geohazard knowledge. This "volcano knowledge uncertainty" score does not contribute to the overall threat score. Instead, it is evaluated alongside the threat ranking to gain a broad idea of the scientific knowledge base that exists for each volcano and to assist in directing future research efforts._We compile published literature for each volcano and divide it into 4 categories: i) deposit lithofacies mapping (including petrologic and geochemical studies), ii) geochronology studies, iii) geophysical studies (e.g. seismic imaging or seismic monitoring), and, iv) studies investigating geohazards (e.g. lahar, lava, and/or debris flow modelling and hazard assessments). The deposit lithofacies mapping category (scored from 0 to 4), is based on the number of published studies that contribute lithofacies mapping, petrologic or geochemical studies. Volcanoes with at least one study contributing deposit lithofacies structure and characteristics are given a score of 0. Conversely, volcanoes with no lithofacies mapping are given a score of 4. The geochronology studies category (scored from 0 to 4) evaluates units based on the quantity and quality of dated geologic units. If an edifice has most of the eruption units dated using high-quality geochronological methods, it is given a score of 0. Similarly, volcanoes with no available geochronological determinations are given a score of 4. The geophysical studies category is scored from 0 to 1. Volcanoes that have received geophysical analysis (e.g. seismic monitoring or imaging) receive a score of 0, while those that have not receive a score of 1. Finally, the geohazard studies category (scored from 0 to 3) is designed to evaluate the quality of existing volcano hazard maps. Volcanoes that have received dedicated studies involving computational hazard inundation zone modelling or hazard mapping are given a score of 0. Conversely, volcanoes with no analyses of volcanic hazards are given a score of 3. The detailed criteria for evaluating volcano knowledge uncertainty are outlined in Tables 4 and A2. The results of our uncertainty assessment are compared with the overall threat ranking in Figure 8 and are listed in Table A2 in the Appendix.

Table 4. Factors contributing to "volcano knowledge uncertainty", and their evaluation criteria

Knowledge factor	**Score**
Deposit lithofacies mapping	
At least one published study with detailed lithofacies analysis and interpretation.	0
At least one published study; most units delineated and broadly interpreted.	1
At least one volcano-specific study; low resolution or partial lithofacies map.	2
Low resolution regional geological map or crude written description.	3
No known maps or lithofacies interpretations	4
Geochronology studies	
Most eruptive units dated using high-quality geochronology.	0
Most eruptive units dated; some low-quality age estimates.	1
At least one high quality age estimate; most units not dated.	2
At least one low quality age estimate; most units not dated.	3
No geochronological age determinations.	4
Geophysical studies	
Some geophysical studies, and/or temporary high-resolution seismic arrays installed.	0
No geophysical studies.	1
Geohazard studies	
Comprehensive hazard maps exist.	0
Some hazard modelling (e.g. lahar runout modelling) or deposit hazard studies; partial or preliminary hazard maps exist.	1
Some crude hazard modelling or qualitative assessment of hazards; crude hazard maps exist.	2
No modelling or hazard maps exist.	3

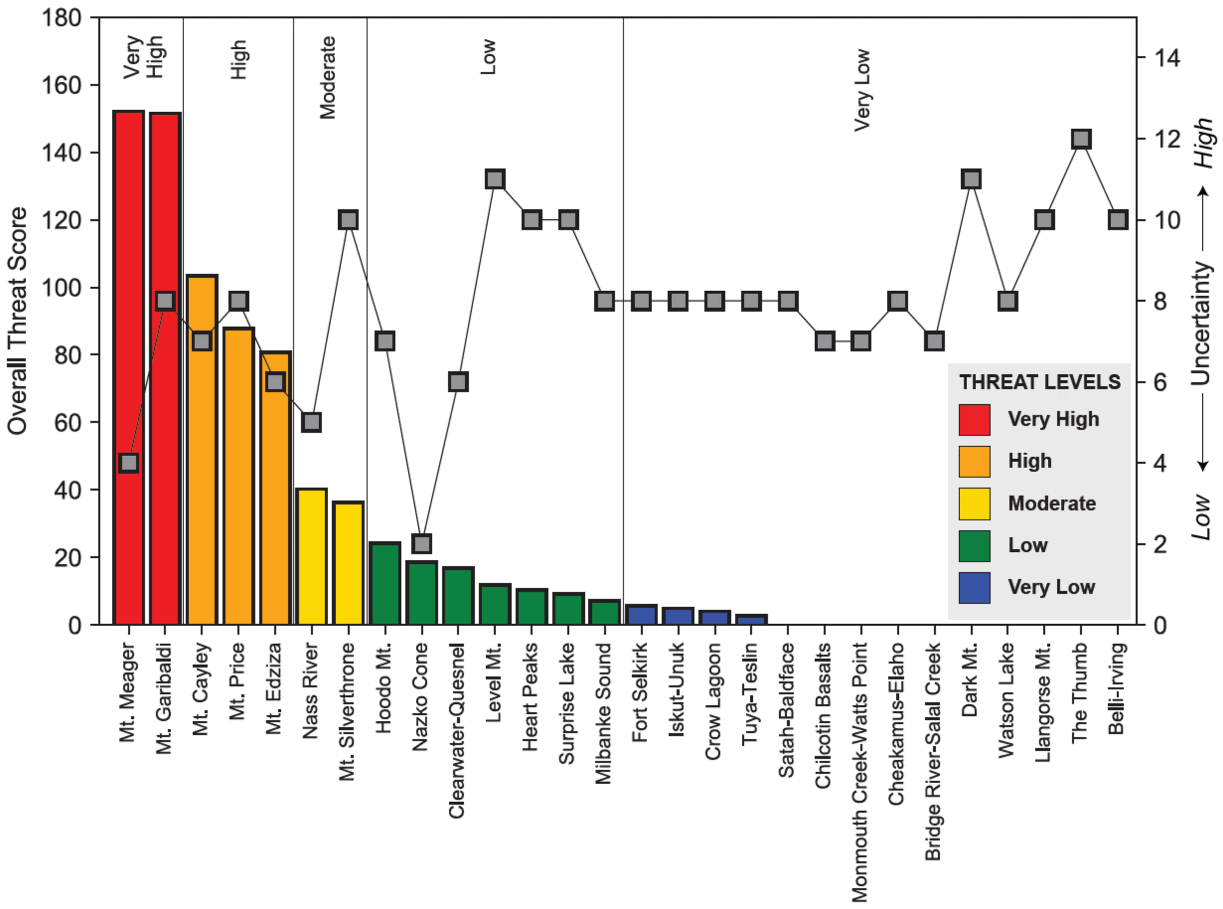

Figure 8. Graph showing distribution of overall threat scores (coloured bars) and semi-quantitative assessment of geologic uncertainty (grey squares), reflecting a lack of knowledge surrounding physical volcanology (i.e. lithofacies studies), geochronology, geophysics, and geohazards at each volcano.

Volcano knowledge uncertainty is highest for many of the *Low* threat volcanoes (Figure 8). This is due to a combination of their predominantly remote locations, generally older ages, and poorer deposit preservation, making them less attractive targets for scientific studies. Nazko cone, the Nass River group, and Mt. Meager share the lowest volcano knowledge uncertainty scores, reflecting a relatively large number of studies examining their lithofacies, geochronology, geophysical character, and geohazard potential (e.g. Lewis and Souther, 1978; Souther et al., 1987; Read, 1990; Hickson et al., 1999; Stewart et al., 2002; Friele et al., 2008; Hickson et al., 2009; Andrews et al., 2014). The remoteness of western Canada has severely limited scientific analysis at a number of volcanoes, including Mt. Edziza and Hoodoo Mountain. These volcanoes have only one or two targeted studies each (Souther, 1992; Edwards et al., 2002, 2009). Many GVB stratovolcanoes, including Mt. Silverthrone, Mt. Price, Mt. Cayley and Mt. Garibaldi also have relatively high volcano knowledge uncertainty, reflecting a major deficiency in scientific understanding (e.g. Mathews, 1952b; Souther, 1980; Green et al., 1988; Kelman, 2005). These volcanoes score within the *High* and *Very High* threat categories, making them critical targets for future research.

Our method for assessing the knowledge gap at Canadian volcanoes offers a semi-quantitative indication of the potential for threat score changes in response to future scientific research and investigation. In general, more knowledge will, if anything, increase rather than decrease the threat scores due to the fact that geologic studies typically reveal more eruptive complexity, rather than less. Monitoring studies could also potentially impact threat scores; for example, if ground deformation and degassing were detected at Mount Garibaldi, its overall threat score would increase to 183.5. If its eruption recurrence were to increase from 2 to 3 and ground deformation and unrest were also detected, its overall threat score would increase from 151.6 to 200 (similar to Mt. Rainier or Redoubt Volcano [Ewert et al., 2018]). However, additional mapping at Mt. Garibaldi would need to uncover 8 previously unknown Holocene eruptions in order to raise the eruption recurrence factor score from 2 to 3. At Mt. Cayley, confirmation of at least 2 Holocene eruptions (entirely likely, given the interpreted ages of the Tricouni Southwest and Slag Hill deposits [Kelman, 2005]) would raise the overall threat score from 103.4 to 135.2, moving Mt. Cayley from the *High* to the *Very High* threat group.

The volcano knowledge uncertainty scores provide clear priorities for future research directions. Mt. Garibaldi is a *Very High* threat volcano for which there is a very low level of scientific understanding. Detailed lithofacies and hazard mapping would significantly improve the level of scientific understanding of this volcano and would aid in developing a conceptual model of its magmatic system, an important component in generating both short-term (hours to months) and long-term activity forecasts (National Academies of Sciences, Engineering and Medicine, 2017). Seismic and ground monitoring at Mt. Garibaldi would increase the likelihood that any unrest would be detected in time for an effective scientific and emergency management response and would improve the quality of short-term forecasts made in response to unrest, because a baseline of pre-unrest data would be available. Mt Cayley, Mt. Price, and Mt. Edziza have *High* threat scores that also indicate a need for further research in terms of their geologic histories and hazard potential. Lithofacies and geochronological studies at these edifices would improve understanding of these factors. Though this is a lower priority due to their isolation and low exposure scores, reconnaissance studies involving lithofacies and satellite remote sensing mapping at Mt. Silverthrone, Level Mountain, and Heart Peaks (all stratovolcanoes with high uncertainty scores) would provide baseline geological and geodetic information, improving confidence in the assigned threat levels.

5.2. Existing monitoring and hazard infrastructure

Despite evidence for active volcanism in Canada, no routine or continuous monitoring is conducted at any Canadian volcano. A network of seismographs to monitor tectonic earthquakes has existed in Canada since 1975, however, it is sparse in terms of seismometer proximity to volcanoes (Hickson and Edwards, 2001; https://earthquakescanada.nrcan.gc.ca/index-en.php). A temporary POLARIS (Portable Observatories for Lithospheric Analysis and Research

Investigating Seismicity) array deployed in the Nazko cone region of BC facilitated analysis of the earliest events in the 2007 seismic swarm, but its presence was fortuitous with respect to the magmatic unrest, and the Geological Survey of Canada deployed additional instruments to the epicentral area in order to determine earthquake depths and better understand the sequence (Cassidy et al., 2011). Permanent volcano-focused seismic monitoring is not available for any Canadian volcano.

Mt. Meager has been the focus of a significant proportion of volcanological research in Canada, primarily due to its major explosive eruption at 2360 BP (Clague et al., 1995; Leonard, 1995), potential as a geothermal resource (Grasby et al., 2012), and recent history of large debris flows (Simpson et al., 2006b; Friele et al., 2008; Guthrie et al., 2012; Roberti et al., 2017a, b; Roberti, 2018). Even so, lithofacies mapping, geochronological studies and hazard investigations have been sporadic, and are limited to a regional geological map (Read, 1977), several higher resolution lithofacies studies targeting the 2360 BP VEI 4 event (Hickson et al., 1999; Stewart et al., 2002; Campbell et al., 2013; Andrews et al., 2014), intermittent remote sensing ground deformation studies (Roberti et al., 2017b; Roberti, 2018), and infrequent hot spring water and fumarole gas chemistry sampling (Ghomshei et al., 1986; Venugopal et al., 2017). A volcanic hazard map is currently being prepared as a Master’s thesis at Simon Fraser University (Warwick et al., 2019; Warwick, 2020). In contrast, the scientific research for essentially all other volcanoes in Canada (e.g. Mt. Garibaldi and Mt. Cayley) does not utilize the most up-to-date methods of dating, geochemical analysis, data processing, and modeling that are currently available, and most geologic studies at volcanoes are of low resolution, and/or lack application to volcanic hazard assessments (e.g. Mathews, 1952b, 1958; Souther, 1980; Green et al., 1988; Kelman, 2005). While several studies have reported the hazard implications of various volcanic phenomena in some places (e.g. Moore and Mathews, 1978; Friele et al., 2008; Hickson et al., 2009), and the broad impact of volcanic hazards in Canada (Hickson and Edwards, 2001; Stasiuk et al., 2003), comprehensive hazard mapping, hazard modelling, and response planning for all *High* and *Very High* threat volcanoes are absent.

5.3. Monitoring gaps at Canadian volcanoes

Our volcano threat ranking can be used to prioritize the need for volcano hazard assessments, volcano monitoring, land use planning, and emergency preparedness activities. Ewert et al. (2005) provide guidelines for appropriate volcano monitoring levels for each of the 5 threat groups. Moran et al. (2008) provide fuller details on recommended instrumentation. These guidelines are similar to those developed by the Geological and Nuclear Sciences (GNS) institute for volcanoes in New Zealand (Miller, 2011). Table 5 provides a summary of the USGS recommended monitoring strategies as they would be applied to Canadian volcanoes based on their threat rankings. The monitoring strategies are divided into 5 disciplines: seismic, geodetic (deformation), gas, hydrologic, and remote sensing.

Table 5. Canadian volcanoes listed in five threat groups, with required level of monitoring indicated. Recommended monitoring levels, and format of table, are from Ewert et al. (2005).

Volcano	Recommended Level of Monitoring
Level 4: Well monitored in real time	
Mt. Meager Mt. Garibaldi	***Monitoring should provide the ability to track detailed changes in real-time and to develop, test and apply models of ongoing and expected activity.*** **Seismic:** 12-20 stations within 20 km of vent, including several near-field sites. Network includes numerous three-component stations and mix of other instrument types, including digital broadband stations, acoustic sensors, and accelerometers. Borehole instruments where practicable. **Deformation:** Routine surveys along with sufficient continuous stations (GPS, tiltmeters, and/or borehole dilatometers) to track closely geodetic changes in space and time and do detailed source modeling. **Gas:** Frequent airborne or campaign gas measurements. Arrays of continuous sensors and other types of gas measurements as appropriate for the volcano. **Hydrologic:** Level-3 coverage along with real-time monitoring of hill-slope soil moisture, stream discharge, etc., as appropriate. Systems for lahar early detection where warranted.
Mt. Cayley Mt. Price Mt. Edziza	
Level 3: Basic real-time monitoring	
Nass River Mt. Silverthrone	***Monitoring should provide the ability detect and track pre-eruptive and eruptive changes in real-time, with a basic understanding of what is occurring.*** **Seismic:** Network with 3-4 near-field stations and a total of at least six within 20 km of vent. **Deformation:** Routinely repeated surveys. At least six continuous stations (GPS and/or tiltmeters) in vicinity of volcano. LIDAR-derived images available for active features. **Gas:** Frequent airborne or campaign measurements of gas emissions (annually to monthly, as appropriate) along with support of 1-2 telemetered continuous sensors. **Hydrologic:** Level-2 coverage along with continuous-sensing probes in features of primary interest, including water wells. LIDAR-derived DEMs for lahar-runout modeling. **Remote sensing:** Level 2 coverage along with routine use of multi-channel thermal-infrared data from ASTER-class satellite. Thermal and/or SAR overflights, as indicated by other monitoring data. Where practicable, remote video camera in operation…*continued on next page.*

Level 2: Limited monitoring for change detection	
Hoodo Mt. Nazko Cone Clearwater-Quesnel Level Mt. Heart Peaks Surprise Lake Milbanke Sound	***Monitoring should provide the ability to detect and track activity frequently enough in near real time to recognize that anomalous activity is occurring.*** **Seismic:** Regional network with 1-2 near-field stations in place (within ~10 km of volcano). **Geodetic:** Two or more surveys for establishing baseline. InSAR observations possible on summerto-summer basis. At least three continuous stations (GPS or tiltmeters) in vicinity of volcano. **Gas:** Baseline of carbon-dioxide emission rate (or other gas as appropriate to the volcano). **Hydrologic:** Comprehensive database on temperatures and chemistry of springs and fumaroles. **Remote-Sensing:** Regular processing and review of near-real-time meteorological satellite images (AVHRR, GOES), and/or review of non-real-time research satellite images (e.g., MODIS) by an observatory. Baseline inventory of air photos and/or satellite images with high spatial resolution (1 m).
Level 1: Minimal monitoring	
Fort Selkirk Iskut-Unuk Crow Lagoon Tuya-Teslin Satah-Baldface Chilcotin Basalts Monmouth Creek-Watts Point Cheakamus-Elaho Bridge River-Salal Ck Dark Mt. Watson Lake Llangorse Mt. The Thumb Bell-Irving	***Monitoring should provide the ability to detect that an eruption is occurring or that gross changes are occurring/have occurred near a volcano.*** **Seismic:** Volcano lies within a regional network; no near-field stations are in place but at least one station is within 50 km of the volcano. Or, a single near-field station is present, but no regional network exists. **Remote sensing:** Baseline inventory exists of Landsat-class satellite images. Routine scans for eruption clouds are conducted by meteorological agencies.

The USGS recommends that monitoring at *Very High* and *High* threat volcanoes should "*provide the ability to track detailed changes in real-time and to develop, test, and apply models of ongoing activity*". This involves installation of >12 real-time-broadcasting, 3-component and broadband seismometers, regular GPS and tiltmeter surveys to track geodetic change, frequent or continuous gas chemistry analyses, hydrologic monitoring, including lahar early-warning systems where appropriate, and regular (i.e. daily) remote satellite imaging, including thermal-infrared and ground-based thermal imagery (Ewert et al., 2005).

For *Moderate* and *Low* threat volcanoes, the USGS recommends that monitoring should *"provide the ability to detect and track pre-eruptive and eruptive changes in real, or near-real-time, with a basic understanding that anomalous activity is occurring"*. The guidelines suggest a reduced number of nearby seismic field stations (1–4), sparser geodetic coverage (e.g. a reduced number of GPS and tiltmeter stations), and less frequent gas emission and thermal spring geochemical testing. *Low* and *Moderate* threat volcanoes require regular near-real-time remote sensing imagery and a baseline inventory of satellite images at high resolution (Ewert et al., 2005).

For *Very Low* threat volcanoes, the USGS guidelines suggest that monitoring should *"provide the ability to detect that an eruption is occurring or that gross changes are occurring/have occurred near a volcano"*. The guidelines suggest that a volcano must be within ~50 km of a regional seismic network station, a baseline inventory of satellite imagery should exist, and routine satellite scans should be conducted for eruption clouds by meteorological agencies (Ewert et al., 2005).

Currently, no volcanoes in Canada are monitored at a level that approaches the recommended guidelines from US and New Zealand geoscience institutions. Mt. Meager (*Very High* threat) meets a standard slightly higher than recommended for a *Very Low* threat edifice with some infrequent seismic, hydrologic, gas, geodetic, and remote sensing studies. The sporadic nature of these studies, however, means that the ability to detect anomalous activity is extremely limited, since it does not provide a continuous picture of background activity that would aid in distinguishing what phenomena are anomalous. Furthermore, the sporadic nature of these observations means that unrest that occurred when no targeted monitoring was ongoing (e.g. during the winter when ground-based access may be inhibited by snowfall accumulation), even if it were unequivocally anomalous, would not be detected unless it comprised seismic activity of sufficient magnitude to be detected by the nearest seismic station, 107 km away in Lillooet. The other *Very High* and *High* threat volcanoes Mt. Garibaldi, Mt. Cayley, Mt. Price, and Mt. Edziza do not meet the monitoring standard recommended for *Very Low* threat edifices. Should unrest occur at any of these volcanoes, the likelihood of early unrest detection would be extremely low. Even if unrest were detected at one of these *High* or *Very High* threat volcanoes, the lack of permanent, on-site, ground-based monitoring would limit the amount of data for generating short-term activity forecasts and hinder any response, and the installation of equipment in response to the unrest might well be hampered by logistical considerations (e.g. winter weather, or the lack of available instruments and expertise). The lack of hazard mapping or detailed lithofacies mapping would also hinder the development of conceptual models of the magmatic systems, reducing the quality of short-term forecasting.

5.4. Aligning Canadian volcano monitoring and research directives with global best practices

Five monitoring and research activities would move Canada closer to alignment with global best practices for reducing volcanic risk:

(a) Installation of a single telemetered broadband or 3 component seismic station within 5 km of each *Very High* or *High* threat volcano (Mt. Meager, Mt. Garibaldi, Mt. Cayley, Mt. Price, and Mt. Edziza) will increase the likelihood of detecting magmatic unrest at early stages of an earthquake swarm. The Garibaldi Volcanic Belt volcanoes are the highest priority due to their proximity to population centres. Although a single seismic station would be of limited use for locating all magmatic earthquakes and in forecasting eruptions, it would be useful, in combination with the existing regional seismic network, to alert authorities that unrest was occurring so that additional monitoring resources could be deployed. Several authors have suggested this approach as a trade-off between the expense of installing costly monitoring networks of multiple stations at long-dormant volcanoes and the disastrous consequences of an unforecast major eruption (e.g. Brown et al., 2015; National Academies of Sciences, Engineering, and Medicine, 2017).

(b) A comprehensive lithofacies mapping campaign at Mt. Garibaldi would reduce geologic uncertainty surrounding eruptive behaviour and recurrence interval. This is a prerequisite to a comprehensive hazard assessment for Mt. Garibaldi.

(c) Comprehensive hazard assessments for Mt. Garibaldi and Mt. Cayley, including probabilistic lahar/debris flow and volcanic pyroclastic density current inundation zone modelling, would improve the effectiveness of the response to any future volcanic unrest, and would provide risk reduction information to guide emergency preparedness activities and land use planning. In addition, incorporating existing hazard mapping at Mt. Meager (Warwick et al., 2019; Warwick, 2020) into a publicly-accessible format would make it available to a broad audience, including local stakeholders in the Lillooet River valley.

(d) Regular satellite imagery monitoring and Interferometric Synthetic Aperture Radar (InSAR) ground deformation monitoring, implemented at all *Very High* to *Moderate* threat volcanoes, would allow for early detection of subtle ground deformation caused by magmatic unrest, as well as providing information on slope stability that might indicate a heightened probability of landslides. This would not replace adequate ground-based monitoring but would provide an additional tool to screen for unrest and interpret its outcome.

(e) At Mount Meager, a landslide detection and alerting system, functionally similar to those in place around Mount Rainier, Washington (Kramer et al., 2017), would be of benefit in order to provide real-time warnings of dangerous volcanic debris flows and enable at-risk inhabitants of the Lillooet River valley to move to high ground. This action would reduce risk to inhabitants of the Lillooet River valley because most landslides occur in the absence of volcanic unrest. The risk is continuous and ongoing, and exceeds internationally-accepted risk tolerance thresholds for loss of life (Friele et al., 2008; Roberti, 2018). This system would require a significant emergency planning and preparedness component beyond the basic technical and scientific aspects of installing the system.

6. CONCLUSION

Despite the fact that Canada has dozens of potentially active volcanoes, many Canadians are unaware of their presence, and the nature, likelihood, and footprint of hazards from Canada's volcanoes has been given minimal scientific attention. Canada does not conduct any routine volcano monitoring and falls significantly short of internationally-recommended volcano monitoring guidelines. We present an analysis of the volcanic threat posed by 28 active volcanoes in Canada, using a methodology developed by the United States Geological Survey that scores individual volcanoes on a variety of volcanic hazard and exposure factors, producing an overall threat score. This threat assessment procedure has been employed by numerous countries, including the United States and New Zealand, and is used to identify weaknesses in volcano monitoring strategies and guide emergency response planning.

The results from our threat assessment show that Canada has five *Very High* and *High* threat volcanoes with similar eruption potential to many well-studied and well-monitored international examples, such as Lassen Peak in California, St. Augustine in Alaska, and Mt. Adams in Washington. Four of the five highest threat volcanoes in Canada (Mt. Meager, Mt. Garibaldi, Mt. Cayley, and Mt. Price) are situated within close proximity to major populations (e.g. Squamish) with critical civil and economic infrastructure (e.g. Whistler-Blackcomb Ski Resort). All of these volcanoes are minimally studied and unmonitored. Volcanic unrest at a Canadian volcano has the potential to cause a major socio-economic crisis, however the existing level of monitoring makes the chance of early volcanic unrest detection and adequate scientific and civil defence preparation for an eruption unlikely.

We outline five critical volcano monitoring activities and research objectives that will bring Canada closer to alignment with global best practices for volcanic risk reduction: (a) installation of real-time, telemetered, broadband seismic stations at Mt. Meager, Mt. Garibaldi, Mt. Cayley, Mt. Price, and Mt. Edziza, (b) comprehensive lithofacies mapping at Mt. Garibaldi, (c) hazard mapping at Mt. Garibaldi and Mt. Cayley, (d) initiation of regular satellite-based ground deformation monitoring for all *Very High* to *Moderate* threat edifices, and (e) installation of a real-time landslide and debris flow detection and alerting system for Mount Meager and the Lillooet River valley. Although these activities will not bring Canadian volcano research and monitoring to the levels recommended by the United States Geological Survey (Ewert et al., 2005, 2018) or in place at numerous volcanoes worldwide, they will bring Canada significantly closer to recommended best practices for volcano monitoring, will aid in future prioritization of monitoring and research resources, and will increase the likelihood of early detection of magmatic unrest.

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9. APPENDIX

Table A1: Database of 348 Pleistocene volcanic vents in Canada, including: volcano group assignments, volcano type, age of eruption, primary composition, and literature sources.

Table A2: Volcano threat ranking categories and scoring for 28 Canadian volcanoes (modified from Ewert et al., 2018).

Table A3: Ground-based population estimated from Joint Research Centre, Global Human Settlement layer (GHS) (Schiavina et al., 2019).

Table A4: Regional aviation exposure scores (Log_{10} of daily passengers) calculated using T100 databank and local airport reports.