Canadian Journal of
Earth Sciences

OPEN ACCESS | Article

Assessing the relative threats from Canadian volcanoes

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Abstract

We assessed 28 Canadian volcanoes in terms of their relative threats to people, aviation, and infrastructure. The methodology we used was developed by the United States Geological Survey for the 2005 National Volcano Early Warning System. Each volcano is scored on multiple hazard and exposure factors, producing an overall threat score. The scored volcanoes are assigned to five threat categories, ranging from Very Low to Very High. We developed a knowledge uncertainty score to provide additional information about assessed threat levels; this does not affect the threat scoring. Two Canadian volcanoes are in the Very High threat category (Mt. Garibaldi and Mt. Meager). Three Canadian volcanoes are in the High threat category (Mt. Cayley, Mt. Price, and Mt. Edziza) and one volcano is in the Moderate threat category (Mt. Silverthrone). We compare the ranked Canadian volcanoes to volcanoes in the USA and assess current levels of monitoring against internationally recognized monitoring strategies. We find that even one of the best-studied volcanoes in Canada (Mt. Meager) falls significantly short of the recommended monitoring level and is currently monitored at a level commensurate with a Very Low threat edifice. All other Canadian volcanoes are unmonitored (apart from falling within a regional seismic network). This threat ranking has been used to prioritize hazard and risk assessment targets and to help select monitoring activities that will most effectively address the undermonitoring of Canadian volcanoes.

Key words: British Columbia, volcanic hazards, threat, risk, hazard assessment

1. Introduction

1.1. Volcanic hazards, risks, and threat in western Canada

Western Canada lies within a zone of active tectonism and volcanism and is part of the Pacific "Ring of Fire". There is a rich and diverse history of Quaternary volcanism, with at least 347 Pleistocene to Holocene vents in British Columbia and the Yukon, 54 of which were active during the Holocene (Hickson 1994; Hickson and Edwards 2001) (Fig. 1). Based on counts of 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 thousands of Canadians live near dormant volcanoes whose eruptions could have devastating effects on human life, infrastructure, and the economy. Although there is some public awareness of volcanic hazards in Canada (Pan et al. 2023), scientific knowledge about many volcanoes is low, and few resources for assessment and monitoring are available. This is likely due to the low frequency of eruptions, lack of societal experience of volcanism, remoteness of many volcanoes, spatial patchiness or temporal incompleteness of the volcanic record, cost and analytical challenges of dating young volcanic rocks, false perceptions that many volcanoes are extinct or pose minimal threats, and beliefs that mitigation may be too costly or impossible.

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; Williams-Jones et al. 2020; Le Moigne et al. 2022*a*, 2022*b*). Pumiceous tephra dispersed throughout western Canada is evidence for a major Plinian (volcanic explosivity index (VEI) 4) eruption at Mt. Meager, BC (Qw'elqw'elústen) in 2360 BP (Read 1990; Clague et al. 1995; Leonard 1995). The lahar and outburst flood associated with this eruption can be traced at least 65 km downstream (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 (PDCs) during eruptions of Mt. Garibaldi (Nch'k̲ay') at 11 700 BP (Friele and Clague 2009; Wilson and Russell 2018). Most recently, in 2010, structural weakening due to hydrothermal alteration and high pore water pressures resulting from ice and snow melting caused a 53 million m^3 volcanic debris flow at Mt. Meager (Roberti et al. 2018), temporarily damming Meager Creek and prompting evacuation orders for some Lillooet River valley residents.

Reducing the risk from volcanic eruptions requires a combination of activities, including first, hazard and risk assessment, and second, monitoring (e.g., Tilling 1989; Sparks et al. 2012; National Academies of Sciences, Engineering, and Medicine 2017). Eruptions span a broad range of magnitude,

Fig. 1. Map of Canadian vents (grey triangles), lumped volcanoes used for this study (red triangles), and volcanic belts/provinces. GVB—Garibaldi volcanic belt; CB—Chilcotin basalts; AVB—Anahim volcanic belt; CQVP—Clearwater–Quesnel volcanic province; NCVP—Northern Cordilleran volcanic province. Locations of individual vents are from various sources and are compiled in Table S1 in the Supplementary material. Locations and references for lumped volcanoes are listed in Table S3 in the Supplementary material. The basemap topography is from the USGS EROS Archive ——Digital Elevation——Global 30 Arc-Second Elevation(GTOPO30). Forests are from the Global Forest Watch Intact Forest Landscapes IFL_forested_landscapes_2016. Water (sea) is from the ETOPO1 arc-minute global relief model. Rivers and lakes are from the Government of Canada CanVec 5 m data series (CanVec Series).

intensity, and duration, and volcanic hazards, which include PDCs, explosions, lava flows, lahars, landslides, ballistic projectiles, ash fall, gas emissions, earthquakes, and tsunamis, have various behaviours and impacts. This means that the hazard footprint can vary considerably between eruptions or throughout a single eruption, and may be limited to the immediate vicinity or could include areas thousands of kilometres downwind. Hazard footprints and potential impacts can be better understood through hazard and risk assessments; however, these are costly and time-consuming and the basic geological understanding needed to assess hazards may be absent. The second broad volcano risk reduction activity, monitoring, utilizes unrest signals that may precede eruptions by hours to years and result from magmatic intrusions into the crust, which deform and fracture rocks and interact with groundwater and hydrothermal systems. Tracking these signals from the Earth's surface through the systematic collection, analysis, and interpretation of observations and instrumental measurements offers a tool for forecasting eruptions (e.g., National Academies of Sciences, Engineering, and Medicine 2017; Furtney et al. 2018; Poland and Anderson 2020). The knowledge can be used to take appropriate mitigating actions such as evacuations or airspace closures (e.g., Ewert et al. 2005; Sparks et al. 2012); however, this requires that volcanoes are monitored at a level commensurate with their hazard and impact potential, which is rarely possible due to the complexity and cost of monitoring and the minimal information available about many volcanoes. Thus, knowledge of which volcanoes have the greatest potential to cause harm (threat) is useful because it may be used to prioritize hazard and risk assessment, monitoring, and other costly and time-consuming volcano risk reduction activities.

Volcanic threat is the qualitative risk that a volcano may pose to people and property, based on its hazard potential (the likelihood of events such as lava flows), and on the degree of exposure of people and property to the hazards. Threat is distinguished from risk, the quantified possibility of a loss, which is calculated by

$$\text{Risk} = \text{Value} \times \text{Vulnerability} \times \text{Hazard}$$

(Fournier d'Albe 1979).

"Value" includes quantified elements at risk (e.g., number of lives or property value). "Vulnerability" is the proportion of the value likely to be lost during the hazard event. "Hazard" is the probability that the event (e.g., lava flow) will affect the elements at risk within a given time period. Calculating risk requires a numerical estimate of a hazard event's probability, as well as information about value and vulnerability, and is required to fully understand the potential consequences of an eruption. However, this detailed information is not available for most Canadian volcanoes, quantitative risk assessment is time-consuming and may not be necessary where the risk is very low, and it may not be obvious where risk assessment will be of greatest benefit. Assessing threat rather than risk means that less detailed hazard and exposure information is required, and assessing multiple volcanoes for threat allows for comparisons between volcanoes and prioritization of activities. For example, the formally assessed threat posed by Mount St. Helen's, WA, is Very High, while the threat posed by Craters of the Moon, ID is Low, and thus, these volcanoes do not require or receive the same level of scientific attention (Ewert et al. 2018).

This study has two goals: to identify high-threat Canadian volcanoes by evaluating associated hazards and exposure, and to quantify knowledge and monitoring gaps, in order to help prioritize the assignment of future resources for hazard and risk assessment and monitoring.

1.2. Geologic setting

Canada's Pleistocene to Holocene volcanoes are typically divided into five belts or regions (Fig. 1): the Garibaldi Volcanic Belt (GVB), the Northern Cordilleran volcanic province (NCVP), the Anahim Volcanic Belt (AVB), the Clearwater–Quesnel volcanic province (CQVP), and the Chilcotin basalts (CB). A more detailed discussion of the tectonic context of these volcanic belts is provided by Russell et al. (2023, *This Volume*).

The GVB is the northern end of the Cascade Volcanic Arc of the northwestern United States and formed as a result of the northeastward subduction of the Juan de Fuca plate beneath the North American plate west of Vancouver Island over the last 2 million years (e.g., Hildreth 2007). It includes volcanoes from Glacier Peak, WA to Mount Silverthrone, BC, and includes three significant long-lived stratovolcanoes: Mount Garibaldi (Nch'ḵay'), Mount Cayley (Sxel'tskwu'7), and Mount Meager (Qw'elqw'elústen), as well as numerous smaller volcanic centres (e.g., Souther 1991; Hildreth 2007). The GVB experiences dominantly calc–alkaline, intermediate composition volcanism, with both large stratovolcanoes and smaller basaltic to felsic monogenetic centres, and a higher proportion of alkaline basalts at the northernmost end (e.g., Green et al. 1988; Souther 1991; Wilson and Russell 2018; Venugopal et al. 2020; Harris et al. 2023, *This Volume*).

The NCVP, the most volcanically active region of Canada, incorporates a broad group of alkaline basaltic to felsic, Miocene to Holocene eruptive centers distributed across northern BC, and the central Yukon Territory and eastern Alaska (Edwards and Russell 1999), with volcanism likely caused by upwelling of asthenosphere related to regional extension linked to the relative motions of the Pacific and North American plates (Edwards and Russell 2000; Batir and Blackwell 2020). Magmatism may also have been influenced by stresses linked to crustal loading and unloading by glaciers (Grove 1974; Edwards et al. 2002), a phenomenon discussed in detail in Russell et al. (2023, *This Volume*). NCVP activity includes the most recent known eruption in Canada, the 150 BP Lava Fork eruption (Elliot et al. 1981; Hauksdóttir 1992), as well as the only eruption with documented fatalities, the 220 BP Tseax cone eruption (Sutherland Brown 1969; Williams-Jones et al. 2020; Le Moigne et al. 2022*a*, 2022*b*), and the frequently active Mount Edziza complex (Souther 1992*a*).

The AVB trends easterly across central BC from north of Vancouver Island to near Quesnel, BC. AVB volcanism is dominantly alkaline basaltic to peralkaline and has been interpreted to result from the North American plate sliding westward over a long-lived mantle hotspot (Kuehn 2014). Nazko cone (erupted 7300 BP) is the most easterly and youngest AVB volcano (Souther et al. 1987) and was the site of magmatic unrest in 2007 (Cassidy et al. 2011). Recent dating of Pleistocene to Holocene volcanoes at the west end of the AVB, at Milbanke Sound, demonstrates simultaneous volcanism at both ends of the postulated hotspot track; Milbanke Sound volcanism has been attributed to unloading stresses during deglaciation (Bednarski and Hamilton 2019; Hamilton et al. 2023, *This Volume*). Asthenospheric upwelling has also been postulated as an explanation for AVB volcanism (Thorkelson and Taylor 1989; Thorkelson et al. 2011).

In eastern BC, the CQVP consists of a collection of monogenetic alkaline basaltic volcanoes erupted from ∼3.5 Ma to 400 BP (Hickson and Souther 1984; Hickson 1986; Metcalfe 1987; Hickson et al. 1995; Kuehn et al. 2015). Most classifications refer to the "Wells Gray–Clearwater volcanic field", based on comprehensive work by Dr. Catherine (Cathie) Hickson and other researchers (e.g., Hickson 1986, 1989, 1994; Hickson et al. 1995); however, we use the label "Clearwater-Quesnel volcanic province" (first used by Souther 1992*b*) to include the Quesnel cones group. The cause of CQVP volcanism is a topic of ongoing debate; however, it has been postulated to be the result of asthenospheric upwelling due to extensional crustal displacement along the Nootka Fault (Madsen et al. 2006; Hickson and Vigouroux 2014).

In the BC interior, the Miocene to Pleistocene calc–alkaline Chilcotin group basalts form a regionally extensive but discontinuous veneer of basaltic lava flows whose origin is enigmatic, covering ∼17 500 km^2 of BC's Interior Plateau and representing numerous relatively small-volume, short-lived eruptions from widely dispersed volcanoes (Bevier 1983; Mathews 1989; Dohaney et al. 2010; Andrews et al. 2011).

We do not include the Alaska–Yukon Wrangell volcanic belt (WRB) in this list, as its Canadian volcanoes are of Late Miocene age or older, although several WRB volcanoes are present in the southwestern Yukon Territory and northwestern British Columbia (Souther 1991; Skulski et al. 1992; Thorkelson et al. 2011; Trop et al. 2022).

2. Methods

2.1. Data compilation and lumping criteria

We compiled a database of 347 Pleistocene or younger Canadian volcanic vents, including vent locations, feature types, compositions, and a summary of existing geochronological information (Table S1 in Supplementary material). For 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 many volcanoes have ages estimated as Pleistocene or Holocene only. In addition, one primary means for Holocene age eruption in western Canada is 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.

We systematically lumped the vents into 28 groups referred to as "volcanoes" (comprising volcanic groups, complexes, or fields) (Table 1 (lumping details are in Table S1 in the Supplementary material)), with locations calculated as the average of the contributing vent locations. This was done because many volcanic vents may share plumbing systems or may be geographically close and similar in age, plus, it would be impractical to evaluate threat to every vent individually. The grouping process was based on spatial proximity, age similarities, and where possible, inferred genetic relationships. 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). All the volcanoes of the broad CB field were grouped together so that their threat could be collectively assessed, because there is no way to determine where in the field the most likely future eruption would be (and the probability is, in any case, extremely low).

This lumping approach has four advantages: (i) the lumped volcanoes provide a simple and approachable means to communicate results with a non-scientific community, (ii) lumping minimizes bias towards well-studied volcanoes by maximizing the available data for all volcanic groups, (iii) if seismic unrest were to occur at any volcano, 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 seismic network, and (iv) to produce short-term activity forecasts, it is necessary to consider each volcanic complex or field as one system because volcano-tectonic seismicity up to 30 km from the eventual vent is typically the earliest unrest sign at long-dormant volcanoes (White and McCausland 2016).

2.2. System for ranking volcanic threat

We used a well-established method for scoring volcanic hazards and exposure, developed by the United States Geological Survey (USGS) as part of the National Volcano Early Warning System (NVEWS) (Ewert et al. 2005, 2018; Ewert 2007). The system ranks each volcano on a series of hazard and exposure factors, yielding a threat score. Volcanoes are then assigned to five different threat groups based on the scoring. This makes it possible to evaluate how monitoring levels at ranked volcanoes compare to recommended monitoring levels for that threat category. Variants of the NVEWS system have been used to evaluate volcanic threat in Europe (Kinvig et al. 2010), New Zealand (Miller 2011), and Central and South America (Lara et al. 2006; Palma et al. 2008). For future volcano ranking methodologies, we propose an additional exposure factor, Isolation, similar to the Volcanic Island exposure factor already included in the NVEWS ranking methodology, to account for the logistical difficulties faced by remote communities adjacent to volcanoes. However, we do not use Isola-

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	Longitude		
Milbanke Sound	AVB	Small volcano	52.33509259	− 128.5132407	14.5–12.3	Baer (1973); Wood and Kienle (1990); Bednarski and Hamilton (2019); Hamilton et al. 2023 (This Volume)
Nazko Cone	AVB	Small volcano	52.92777778	− 123.7347222	7.2	Souther et al. (1987); Hickson et al. (2009)
Satah–Baldface	AVB	Shield volcano	52.56814614	− 124.6770652	1770, 1430, 910, 800	Charland et al. (1993); Cassidy et al. (2011); Kuehn (2014); Kuehn et al. (2015)
Chilcotin basalts	CB	Lava flows	50.90853704	− 121.1643556	180, 170	Bevier (1983); Mathews (1989); Sluggett (2003); Dohaney (2009)
Clearwater–Quesnel	CQVP	Small volcano	52.10715812	− 120.2621688	174, 0.4	Hickson (1986); Hickson (1989)
Mt. Silverthrone	GVB	Stratovolcano	51.43083333	− 126.1943056	472, 12.2	Blake (1986); Green et al. (1988)
Mt. Meager	GVB	Stratovolcano	50.6542138	− 103.0504387	75, 24.3, 17, 2.360	Read (1977); Green et al. (1988); Read (1990); Hickson et al. (1999); Russell et al. (2021)
Mt. Cayley	GVB	Stratovolcano	50.11160908	− 123.2676513	219, 49.1, <12	Green et al. (1988); Kelman (2005); Wilson and Russell (2018)
Monmouth Creek–Watts Point	GVB	Small volcano	49.67138889	− 123.2036111	21.9	Bye et al. (2000); Wilson et al. (2016); Wilson and Russell (2018)
Mt. Garibaldi	GVB	Stratovolcano	49.82649753	− 122.9972654	11.7, 9.3	Mathews (1952*b*); Wilson and Russell (2018)
Mt. Price	GVB	Stratovolcano	49.95225873	− 123.0234937	300, 13	Mathews (1948, 1958); Green et al. (1988); Wilson and Russell (2018)
Cheakamus–Elaho	GVB	Lava flows	50.24325	− 123.3495	18–20	Mathews (1958); Green et al. (1988); Wilson and Russell (2018); Borch et al. 2023 (This Volume); Harris et al. 2023 (This Volume)
Bridge River–Salal Creek	GVB	Small volcano	50.86237407	− 123.4224333	589, 408	Lawrence et al. (1984); Roddick and Souther (1987); Wilson and Russell (2018)
Tuya–Teslin	NCVP	Small volcano	59.25348889	− 130.6909018	961, 140, <10	Watson and Mathews (1944); Gabrielse (1968); Edwards et al. (2011, 2020); Russell et al. (2013)
Dark Mt.	NCVP	Small volcano	58.51407407	− 129.6757716	Pleistocene	Gabrielse (1998)
Level Mt.	NCVP	Stratovolcano	58.42465278	− 131.4140972	Pleistocene	Hamilton and Scarfe (1977); Wood and Kienle (1990)
Heart Peaks	NCVP	Stratovolcano	58.58460648	− 131.9894444	Pleistocene	Casey and Scarfe (1978); Casey (1980)
Watson Lake	NCVP	Lava flows	60.14074074	− 129.3590278	230	Klassen (1987); Colpron et al. (2016)
Nass River	NCVP	Small volcano	55.30097222	− 129.1124306	175, 0.22	Sutherland Brown (1969); Evenchick and Mustard (1996); Haggart et al. (1998); Williams-Jones et al. (2020); Le Moigne et al. (2022*a*, *b*)
Surprise Lake	NCVP	Small volcano	59.70013889	− 133.3549306	Holocene	Clague (1991); Edwards et al. (1996); Edwards and Bye (2003)
Llangorse Mt.	NCVP	Small volcano	59.37314683	− 132.8506595	Pleistocene	Edwards et al. (2003); Harder et al. (2003); Harder and Russell (2006)
Mt. Edziza	NCVP	Stratovolcano	57.64556788	− 130.6634688	6, <6, 1.34	Souther (1992*a*)
Iskut–Unuk	NCVP	Small volcano	56.56048611	− 130.6877361	33, 8.73, 2.555, 0.35, 0.15	Elliot et al. 1981; Stasiuk and Russell (1990); Hauksdóttir (1992); Hauksdóttir et al. (1994).
Hoodo Mt.	NCVP	Stratovolcano	56.77194444	− 131.2963889	9	Edwards et al. (2002); Edwards and Russell (2002)
The Thumb	NCVP	Small volcano	56.23376984	− 126.654127	Pleistocene	Wood and Kienle (1990)
Fort Selkirk	NCVP	Lava flows	62.77388889	− 137.62075	Holocene	Jackson and Stevens (1992); Nelson et al. (2009); Jackson et al. (2012)
Crow Lagoon	NCVP	Small volcano	54.7	− 130.23	140	Souther and Weiland (1993).
Bell–Irving	NCVP	Small volcano	56.91654514	− 129.5014931	430	Edwards et al. (2006)

Table 2. Canadian volcanoes ranked and categorized according to NVEWS threat analysis, including constituent hazard, exposure, unrest and aviation scores, and geologic uncertainty score.

Rank	Volcano	Hazards score	Exposure score if Isolation assessed	**Exposure score (without Isolation)**	Aviation score	Unrest score	Threat score if Isolation assessed	**Overall threat score (without Isolation)**	Threat category	Geologic uncertainty
1	Mt. Garibaldi	9.5	15.9546	**14.95**	22.0454	0.50	151.57	**142.07**	Very High	8
2	Mt. Meager	10.5	14.48	**13.48**	21.16	2.50	152.04	**141.54**	Very High	4
3	Mt. Cayley	6.5	15.91	**14.91**	7.3483	1.50	103.39	**96.89**	High	7
4	Mt. Price	5.5	15.9548	**14.95**	14.6969	0.50	87.75	**82.25**	High	8
5	Mt. Edziza	7.5	10.77	**9.77**	17.22	0.50	80.78	**73.28**	High	6
6	Mt. Silverthrone	6.5	5.59	**5.59**	14.22	0.50	36.31	**36.31**	Moderate	10
7	Hoodoo Mt.	5.5	4.40	**4.40**	8.81	0.50	24.22	**24.22**	Low	7
8	Nass River	2	13.44	**11.44**	4.40	0.00	26.90	**22.87**	Low	4
9	Clearwater–Quesnel	2.5	6.72	**6.72**	0.00	0.50	16.81	**16.81**	Low	6
10	Nazko Cone	2	9.28	**8.28**	3.95	1.00	18.56	**16.56**	Low	2
11	Level Mt.	3	3.95	**3.95**	7.90	0.00	11.85	**11.85**	Low	11
12	Heart Peaks	2	5.18	**5.18**	5.18	0.00	10.36	**10.36**	Low	10
13	Surprise Lake	2	4.58	**4.58**	0.00	0.00	9.17	**9.17**	Low	10
14	Fort Selkirk	2	2.85	**2.85**	0.00	0.00	5.69	**5.69**	Very Low	8
15	Milbanke Sound	1	7.19	**5.19**	0.00	0.00	7.19	**5.19**	Very Low	8
16	Iskut-Unuk	2.5	2.00	**2.00**	0.00	0.50	5.00	**5.00**	Very Low	8
17	Crow Lagoon	0.5	8.24	**8.24**	0.00	0.50	4.12	**4.12**	Very Low	8
18	Tuya–Teslin	1	2.69	**2.69**	0.00	0.00	2.69	**2.69**	Very Low	8
19	Satah–Baldface	0	5.40	**4.40**	0.00	0.00	0.00	**0.00**	Very Low	8
20	Chilcotin basalts	0	9.42	**9.42**	0.00	0.00	0.00	**0.00**	Very Low	7
21	Monmouth Creek–Watts Point	0	9.47	**8.47**	0.00	0.00	0.00	**0.00**	Very Low	7
22	Cheakamus–Elaho	0	8.35	**7.35**	0.00	0.00	0.00	**0.00**	Very Low	7
23	Bridge River–Salal Creek	0	2.45	**2.45**	0.00	0.00	0.00	**0.00**	Very Low	7
24	Dark Mt.	0	5.58	**4.58**	0.00	0.00	0.00	**0.00**	Very Low	11
25	Watson Lake	0	6.15	**6.15**	0.00	0.00	0.00	**0.00**	Very Low	8
26	Llangorse Mt.	0	1.30	**1.30**	0.00	0.00	0.00	**0.00**	Very Low	10
27	The Thumb	0	1.00	**1.00**	0.00	0.00	0.00	**0.00**	Very Low	12
28	Bell–Irving	0	3.70	**2.70**	0.00	0.00	0.00	**0.00**	Very Low	10

tion to calculate overall threat scores because this would invalidate comparisons with ranked volcanoes outside Canada.

We use the NVEWS threat assessment system to evaluate the 28 volcanoes in terms of 15 hazard factors (e.g., volcano type, eruption recurrence interval, etc.) and 9 exposure factors (ground-based population, previous fatalities, etc.). The scores from each factor are summed within the two categories and then, the categories are multiplied to produce an overall threat score. Selected factors are also subtotaled to give an unrest score and an aviation threat score (aviation threat score and unrest score calculations are in Table S3 in the Supplementary material). The hazard and exposure factors are designed to be general enough to be applied easily to most volcanoes yet sufficiently detailed that the absence of data for one or two factors will not inordinately bias overall results. Data and methods are briefly summarized below. We adhered closely to the NVEWS methodology in order that assigned threat levels for Canadian volcanoes might be meaningfully compared to those for volcanoes outside Canada. The proposed inclusion of an Isolation factor score was not used in overall scoring (although we discuss its utility for understanding threat at various Canadian volcanoes). Threat scores are summarized in Table 2 (Data sources and details for scoring methodology for Hazard and Exposure factors for each volcano are in Table S2, and scoring details are in Table S3, of the Supplementary material). For a detailed discussion of the development of the threat ranking system and scoring rationale, we refer the reader to Ewert (2007) and Ewert et al. (2005, 2018), and to Wilson and Kelman (2021).

2.3. Hazard factors and scoring

Volcano type is scored 0 or 1. Ewert et al. (2005, 2018) used the Smithsonian Institution's Global Volcanism Program classification of volcano types to help qualify this scoring criterion; we have modified the wording slightly. Type 0 volcanoes are typically less explosive and include cinder cones, tuyas, basaltic volcanic fields, and shield volcanoes. Type 1 volcanoes include more explosive stratovolcanoes, lava domes, complex volcanoes, and calderas. The score is assigned based on the main volcanic feature in each of the 28 lumped volcanoes (e.g., Mt. Edziza is scored 1 for the stratovolcano, although it is surrounded by a basaltic lava and cinder cone field).

Maximum VEI is scored from 0 to 3. VEI is a relative measure of eruption explosivity and ranges from 0 to 8, with every interval above VEI 2 representing a tenfold increase in ejecta volume and is widely used to report and compare the magnitude of explosive eruptions (Newhall and Self 1982). According to the NVEWS ranking system, volcanoes with Holocene VEI 3–4 eruptions are scored as 1, VEI 5–6 eruptions are scored as 2, and VEI 7–8 eruptions are scored as 3. Type 1 volcanoes without reported eruption magnitudes are scored as 1 and type 0 volcanoes are scored as 0. Mt. Meager's 2360 BP eruption (Clague et al. 1995; Leonard 1995) is the only Canadian eruption with an assigned VEI (VEI 4) (Andrews et al. 2014), so it is scored 1.

Explosive eruption activity (VEI $\geq$ 3) in the past 500 years is scored 0 or 1. There are no documented explosive eruptions (VEI $\geq$ 3) during the last 500 years, so all Canadian volcanoes scores 0 (This and the following factor are meant to emphasize particularly active and explosive systems and de-emphasize systems without recent explosivity (Ewert et al. 2005)).

Explosive eruptive activity (VEI 4/5) in the past 5000 years is scored 0 or 1. The 2360 BP eruption of Mt. Meager is the only VEI 4 or 5 eruption known in Canada in the past 5000 years (Andrews et al. 2014) and is scored 1 for this category, while all other volcanoes are scored 0.

Eruption recurrence is scored from 0 to 3. We calculated the eruption recurrence interval by dividing 11 000 by the number of Holocene eruption events. Many young Canadian eruption events are not dated quantitatively but are inferred to be of Holocene age based on the absence of post-eruptive glacial overriding indicators (e.g., Souther 1992*b*). Mt. Edziza scores the highest in this category with an eruption recurrence interval of 379 years and a score of 3. We note that in the first iteration of this threat ranking (Wilson and Kelman 2021), the Nass River group received a higher recurrence score (2) than was given here due to two reported Holocene eruptions at Tseax cone; however, because recent field studies show evidence for only one Tseax cone event (~1700 CE), Nass River scores only 1 for eruption recurrence, which results in a lower final threat score (Williams-Jones et al. 2020; Le Moigne et al. 2022*b*).

Holocene pyroclastic flows, lahars, and lava flows are scored 0 or 1. If a volcano has produced Holocene pyroclastic flows, it is scored 1. For lahars and lava flows, a positive score is only assigned if the lava flows or lahars travelled beyond the immediate eruption vicinity and inundated currently populated areas. We include all lahar and debris flow events from volcanoes, including those 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 PDC deposits situated in and around the town of Squamish (11 700 ± 475 BP (Friele and Clague 2009; Wilson and Russell 2018)), a positive lava flow factor is assigned for the Ring Creek lava (an 18 km dacite 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., the western flank of Mt. Garibaldi (Friele et al. 1999; Friele and Clague 2009; Morison and Hickson 2023)). Mt. Meager is scored positively for pyroclastic flows category due to its 2360 BP eruption (Read 1990; Hickson et al. 1999). Both Mt. Cayley (Sxel'tskwu7) and Mt. Meager receive positive lahar scores due to 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 due to the basaltic lava flow at Tseax cone in 220 BP (Sutherland Brown 1969; Williams-Jones et al. 2020; Le Moigne et al. 2022*a*, 2022*b*). 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)) as there are no permanent populations within their inundation zones.

Holocene tsunami is scored 0 or 1. There is no evidence of tsunamis from Canadian volcanoes and no large unstable volcanic edifices are located adjacent to significant water bodies, so there is no tsunami potential. All Canadian volcanoes score 0.

Hydrothermal explosion potential is scored 0 or 1. This factor is meant to capture those systems that have significant Holocene phreatic explosive activity, and (or) those systems whose thermal features are extensive enough to pose a threat for explosive activity (Ewert et al. 2005, 2018). No Canadian volcano has documented Holocene phreatic explosive activity, and most have few or no documented thermal features. In keeping with the conservative scoring for this factor by Ewert et al. (2005), all Canadian volcanoes score 0.

Sector collapse potential is scored 0 or 1. 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 snow and ice accumulations. Sector collapse is a major hazard at many Canadian volcanoes (Friele et al. 2008; Jakob et al. 2013), with positively scored volcanoes, including Mt. Silverthrone, Mt. Garibaldi, Mt. Cayley, Mt. Price, Mt. Meager, Mt. Edziza, and Hoodoo Mountain.

Primary lahar source is scored 0 or 1. Volcanoes were scored positively if they host a permanent snow/ice accumulation of $>10^6$ m^3, which could provide a water source for lahars or debris flows. These included Mt. Silverthrone, Mt. Garibaldi, Mt. Cayley, Mt. Price, Mt. Meager, Mt. Edziza, and Hoodoo Mountain. The "Sector collapse potential" and "Primary lahar source" factors do not apply to the Holocene Rubble Creek lava flow, which originated at Mt. Price and forms the cliff known as "The Barrier", which has a history of landslides; however, this feature merits consideration in future volcanic hazard assessments, particularly due to the presence of 1 billion m^3 Garibaldi Lake immediately east and above it (Mathews 1952*a*; Moore 1976; Moore and Mathews 1978; Hickson 1994; Quane et al. 2016).

Historical unrest factors (seismic, deformation, or degassing) are scored 0 or 1. Historic or current volcanic unrest provides a reliable indicator of latent or active magmatism. Unrest indicators include fumaroles or hot springs, local seismicity, or active ground deformation (e.g., Sparks et al. 2012; Ewert et al. 2005). Due to the lack of dedicated volcano monitoring in Canada (Cassidy and Mulder 2023, *This Volume*), the number of volcanoes scoring positively for these factors is low.

Observed seismic unrest is scored 0 or 1. The current seismic network in Canada was installed to monitor tectonic earthquakes and most stations are not near volcanoes. Since 1980, however, this seismic network has recorded small magnitude, shallow crustal seismicity near 10 volcanoes, including the CQVP, the Iskut–Unuk River Cones, Hoodoo Mountain, Crow Lagoon, Mt. Silverthrone, Mt. Meager, Mt. Cayley, Mt. Garibaldi, Mt. Price, and Mt. Edziza (Stasiuk et al. 2003; Cassidy and Mulder 2023, *This Volume*). Because these earthquakes are not demonstrably magmatic, these volcanoes are scored 0.5 (using 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 magma injection into the lower crust (Cassidy et al. 2011). Nazko cone is scored 1. A swarm of more than 40 felt earthquakes occurred at the western end of the AVB from 1940 to 1943, but these were not demonstrably volcanic in origin (Cassidy and Mulder 2023, *This Volume*), so was not considered in scoring this factor.

Observed ground deformation is scored 0 or 1. Canada does not routinely monitor volcano deformation with ground-based global positioning systems (GPS), tiltmeters, or remote sensing, although an Interferometric Synthetic Aperture Radar (InSAR) monitoring system is under development as part of Natural Resources Canada's Volcano Risk Reduction in Canada project (Kelman et al. 2023; Rotheram-Clarke et al. 2023). Previous InSAR, light detection and ranging (LIDAR), Structure from Motion photogrammetry, analysis of glacier loss, and field mapping at Mt. Meager showed 27 large (>500 000 m^2) unstable slopes (Roberti et al. 2018; Roberti 2018). The movements 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). Current InSAR monitoring at Mt. Meager has detected other ongoing slope movements (e.g., at Mosaic Creek). Mt. Meager is scored 1 for ground deformation.

Observed fumarolic or magmatic degassing is scored 0 or 1. Thermal features like hot springs or fumaroles indicate an active magmatic system (Sparks et al. 2012). Mt. Meager is scored 1 due to its multiple fumaroles and hot springs (Lewis and Souther 1978; Venugopal et al. 2017). Mt. Cayley, with four hot water seeps that are up to 40 °C (Souther 1980), is scored 1.

2.4. Exposure factors and scoring

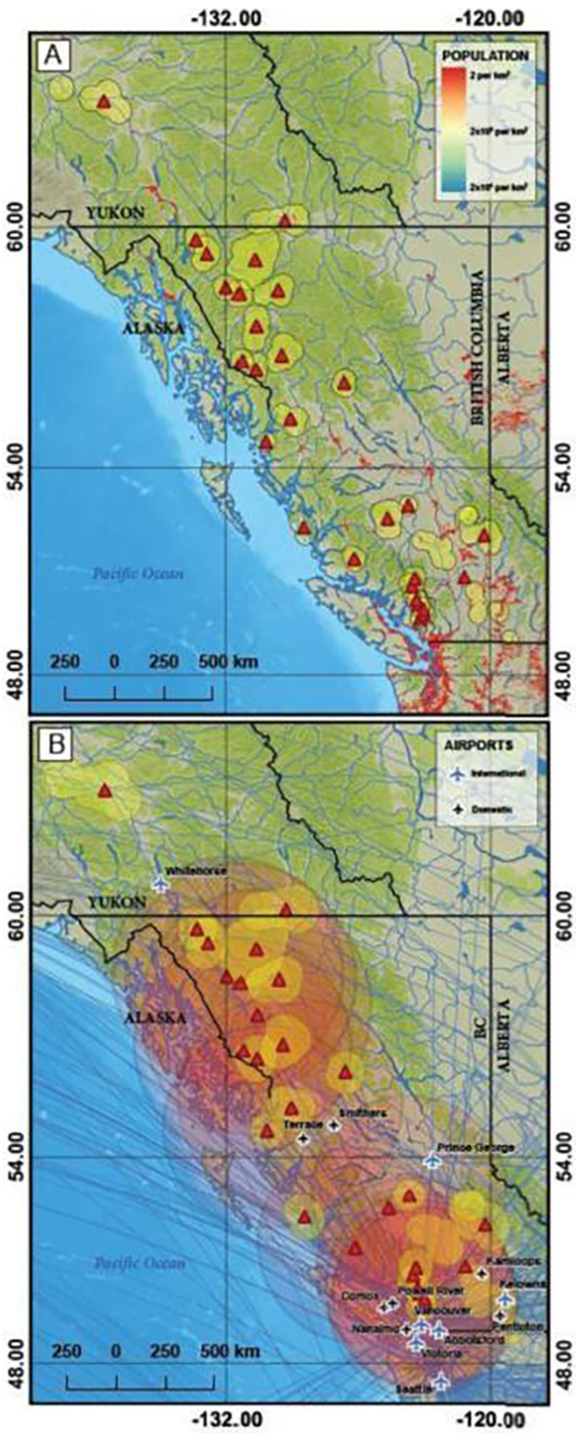
Assessing volcanic threat includes evaluating the populations, infrastructure, and aviation traffic that may be exposed. We implement the methodology of Ewert et al. (2005, 2018) and Ewert (2007), identifying population and infrastructure within a 30 km radius of the volcano, and aviation infrastructure within 50 and 300 km radii (for type 0 and type 1 volcanoes, respectively). We also evaluate daily air traffic within 300 km radii of all type 1 volcanoes. Because the 28 lumped volcanoes represent multiple vents, we construct 30, 50, and 300 km exposure zones around each of the 347 known vents and merge the contributing zones (Fig. 2). While this raises the exposure footprint of several sparsely populated volcanic fields (e.g., the CB), we suggest that it provides a more reasonable assessment of exposure, given the unpredictability of future vent locations, particularly broad volcanic fields with many monogenetic vents.

Debris flows and lahars commonly inundate areas more than 30 km from the source. Thus, Ewert et al. (2005) suggested that hazard zones for volcanoes with the potential for significant lahars and debris flows should include previously inundated areas or areas indicated by plausible modelling. Geologic data and debris flow and lahar modelling (e.g., Friele et al. 2008) 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 Mt. Meager, at least six debris flows during the last 8000 years inundated, now-inhabited portions of the Lillooet River valley (Friele and Clague 2004; Friele et al. 2005, 2008; Simpson et al. 2006). Multiple landslides at Mount Cayley were large enough to temporarily dam the Squamish River (Brooks and Hickin 1991; Evans and Brooks 1991). According to the procedure of Ewert et al. (2005), we extended the 30 km radii hazard zones to include runout zones for Mt. Meager (reaching Pemberton and Lillooet Lake), Mt. Cayley (reaching Squamish and Howe Sound), and Mt. Garibaldi (reaching Squamish and Pitt Lake).

Ground-based population (Log_{10} of exposed population) is scored from 0 to 5.42. To estimate the exposed human population, we use the Joint Research Centre Global Human Settlement layer (Schiavina et al. 2019), a 1 km resolution dataset constructed using satellite-based imagery and 2015 Canadian census data. Population evaluations use the 30 km exposure footprints (discussed above), which encompass likely inundation zones for most volcanic hazards (Ewert et al. 2005). For Mt. Meager, Mt. Cayley, and Mt. Garibaldi, we include populations within the extended lahar runout zones, as described above.

Seasonal visitors and workers comprise a key vulnerable population 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 annual tourists, an additional 8200 people may be at risk in the Sea to Sky corridor daily. These 8200 additional people are added to the population for volcanoes within 30 km of Highway 99, and an additional 2000 people are added to volcanoes within 30 km of Whistler

Fig. 2. 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) within 50 (yellow circles) and 300 km (red circles) exposure zones. The basemap topography is from the USGS EROS Archive—Digital Elevation—Global 30 Arc-Second Elevation (GTOPO30). Forests are from the Global Forest Watch Intact Forest Landscapes IFL_forested_landscapes_2016. Water (sea) is from the ETOPO1 arc-minute global relief model. Rivers and lakes are from the Government of Canada CanVec 5 m data series (CanVec Series).



to account for seasonal workers. Following Ewert et al. (2005), we take the Log_{10} of the total population in each exposure zone and score the population factor accordingly (details of population factor scoring are given in Table S4 in the Supplementary material).

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 10 people. The CB score the highest (5.42), primarily due to the large area covered and their proximity to cities (Kelowna and Kamloops). The scores for Mt. Garibaldi and Mt. Price are the second highest (4.61), reflecting the >40 000 people in Squamish and Whistler.

Historical evacuations and fatalities are scored 0 or 1. The evacuations and fatalities factor applies to only two events. The 220 BP eruption at Tseax cone (in the Nass River group) emitted a 32 km basaltic lava flow, which dammed the Nass River and killed approximately 2000 people of the Nisga'a First Nation (Sutherland Brown 1969; Williams-Jones et al. 2020; Le Moigne et al. 2020, 2022*a*, 2022*b*). Accordingly, the Nass River group is scored 1 for fatalities. The 2010 Mt. Meager landslide, one of the largest worldwide since 1945, dammed Meager Creek for 19 h, leading to evacuation orders for 1500 Lillooet valley residents (Guthrie et al. 2012). Mt. Meager is scored 1 for evacuations.

Local aviation exposure is scored as 0 or 1. This 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 scheduled passenger service, the volcano is scored 1. We include international airports in British Columbia, Yukon Territory, and Washington state, plus multiple smaller domestic Canadian airports.

Regional aviation exposure (Log_{10} of daily passengers) is scored from 0 to 5.35. This score is designed to quantify the daily number of passengers transiting the airspace above Canadian volcanoes. It is applied to type 1 volcanoes and type 0 volcanoes with Holocene pyroclastic activity. Type 0 volcanoes included are Nazko cone, the Nass River Group, and the Crow Lagoon tephra source. Ewert et al. (2018) used the Air Carrier Statistics (T100) databank (United States Department of Transportation 2019) to estimate aviation routes and passengers within United States airspace. Similar data for passengers transiting Canadian airspace are not readily available. However, annual enplaned and deplaned passenger data exist for major airports. For Vancouver International Airport (YVR), these data are divided into domestic, international, transborder (United States), and Asia–Pacific passenger segments (https://www.yvr.ca/en/about-yvr/facts-and-stats). To estimate daily passenger air traffic, we evaluate flights originating in Canada and terminating at Canadian airports, flights connecting the Asia–Pacific region with western Canada, and flights transiting Canadian airspace without landing in Canada.

We calculate regional aviation scores as follows. First, using the T100 aviation databank, we construct great circles connecting departure and destination airports. Routes intersecting 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 airports within 300 km exposure zones of each volcano and add the average daily passenger count to each volcano's total (Details of air traffic passenger exposure scoring are given in Table S5 of the Supplementary material). Transborder passengers are removed, where possible, as they are already counted in the T100 databank. Transborder passengers are not reported for all Canadian international airports (e.g., Victoria), so these passengers represent a small overestimation of daily air traffic. Finally, YVR serves a major air transit corridor over western Canada, connecting the Asia–Pacific with North America. To account for passengers originating or landing at YVR, we add the Asia–Pacific portion of YVR traffic to all volcanoes with 300 km exposure zones overlapping the western continental margin. 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), due to their proximity to YVR and the Seattle–Tacoma airports.

Power, infrastructure, and major developments is scored 0 or 1. To assess this exposure, we use a proprietary Natural Resources Canada database indicating locations of major roads, railways, ferry and shipping routes, pipelines, active mines, other industry, and power generation or dissemination structures. We also include proximity to ski resorts 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 hazard footprint overlaps with any infrastructure or sensitive area locations.

Volcanic Island is scored 0 or 1. All Canadian volcanoes score zero. In the original methodology (Ewert et al. 2005), this factor was meant to address the fact that mitigating eruptions on small populated islands is difficult due to logistical challenges such as difficulty in evacuating.

Although Canada has no populated volcanic islands, it has many remote landbound communities located adjacent to dormant volcanoes. Like islands, these communities would be effectively isolated during eruptions and have difficulties in receiving aid or evacuating residents due to singular transportation routes, rugged terrain, or distance to the nearest population centre. Limited road access has been shown to play a critical role impacting communities during and after various types of natural disaster events, including wildfires (e.g., McGee 2019; Maranghides et al. 2023) and landslides (e.g., Sepúlveda et al. 2023). Hence, we propose a new exposure factor, *Isolation*, although we have not included it in our final scoring because we want our threat rankings to remain comparable to other rankings using the methodology of Ewert et al. (2005, 2018).

Isolation is scored from 0 to 2. We 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 (there is only one road in/out), the volcano is scored 2. If there are two access routes, the volcano is scored 1. If there are three or more access routes to the community, the volcano is scored 0. This factor is important for several remote western Canadian communities and may be particularly significant for some remote communities for which large portions of their populations and cultural sites are located near a volcano. For example, an eruption at Tseax cone (Nass River) may significantly restrict access to communities along British Columbia Highway 113 (Nisga'a Highway). We document the impact of scoring for *Isolation* on threat scores in Table 2 (We describe the scoring methodology for Isolation in Table S2 and document its scoring results in Table S3, both in the Supplementary material). However, these tabulations are not included in any figures, which reflect only the standardized threat ranking methodology (Ewert et al. 2005, 2018).

Isolation affects threat rankings in a manner similar to the Volcanic Island exposure factor (Ewert et al. 2005, 2018); thus, we propose that it may be of benefit in future volcanic threat ranking systems, as it would likely be scored positively for many remote volcanoes worldwide. Both the Volcanic Island factor and our Isolation factor are essentially scores reflecting isolation and poor access, so should be considered jointly; if Isolation were to be included in future threat ranking systems, we recommend that volcanoes be scored on either the Volcanic Island factor or the Isolation factor, but not both, to avoid artificially inflating exposure scores at volcanic islands. We note that in Wilson and Kelman (2021), the Isolation factor was included in the total threat scoring; removing it from the scoring reduces the exposure, and thus, the threat scores of a number of volcanoes (Mt. Garibaldi, Mt. Meager, Mt. Cayley, Mt. Price, Mt. Edziza, Nass River, Nazko cone, and Milbanke Sound) changed slightly. A single volcano (Milbanke Sound) changed its threat category (from Low to Very Low), and several volcanoes changed rank order. The two volcanoes with the highest threat rankings, Mt. Meager and Mt. Garibaldi, changed places because, although Mt. Meager was slightly higher in the original threat ranking (Wilson and Kelman 2021), Mt. Garibaldi was less affected by the removal of a single point from its exposure score because its overall exposure was higher to begin with.

2.5. Volcano knowledge uncertainty

There is an acute lack of scientific information surrounding Canadian volcanism, which contributes to uncertainty in the overall threat scores. Although the NVEWS threat ranking methodology 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, only a few Canadian volcanoes have received lithofacies studies to elucidate the nature of past eruptions (examples include Mt. Edziza (Souther 1992*a*), Hoodoo Mountain (Edwards et al. 2002), Mt. Meager (e.g., Read 1990; Hickson et al. 1999), Mt. Cayley (Kelman 2005), the Cheakamus basalts (Borch et al. 2023, *This Volume*), and Tseax cone (Le Moigne et al. 2020)), and some of the lithofacies studies available describe volcanoes that likely pose a minimal threat due to their age and (or) remoteness (e.g., Mathews tuya (Edwards et al. 2011), Llangorse Mountain (Harder and Russell 2006), and Monmouth Creek complex (Wilson et al. 2016)). Furthermore, most Canadian volcanoes have not been studied using modern geochronology, and most lithofacies on even the best-studied volcanoes are undated. Some High and Very High

Table 3. Factors contributing to "volcano knowledge uncertainty" scores 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

threat volcanic systems have received minimal modern scientific attention (i.e., Mt. Garibaldi, Mt. Price, and Mt. Silverthrone).

To assess this lack, we evaluated Canadian volcanoes using a simple metric that semiquantitatively assesses the uncertainty in geologic, geochronometric, geophysical, and geohazard knowledge. This *volcano knowledge uncertainty* score is unrelated to the threat score, but it provides a broad idea of the scientific knowledge base existing for each volcano. The detailed criteria for evaluating volcano knowledge uncertainty are outlined in Table 3. To calculate volcano knowledge uncertainty, we compiled published literature for each volcano and divided it into four categories: (i) deposit lithofacies mapping (including petrologic and geochemical studies), (ii) geochronology studies, (iii) geophysical studies (e.g., seismic imaging or monitoring), and (iv) geohazard studies (e.g., flow modelling and hazard assessments).

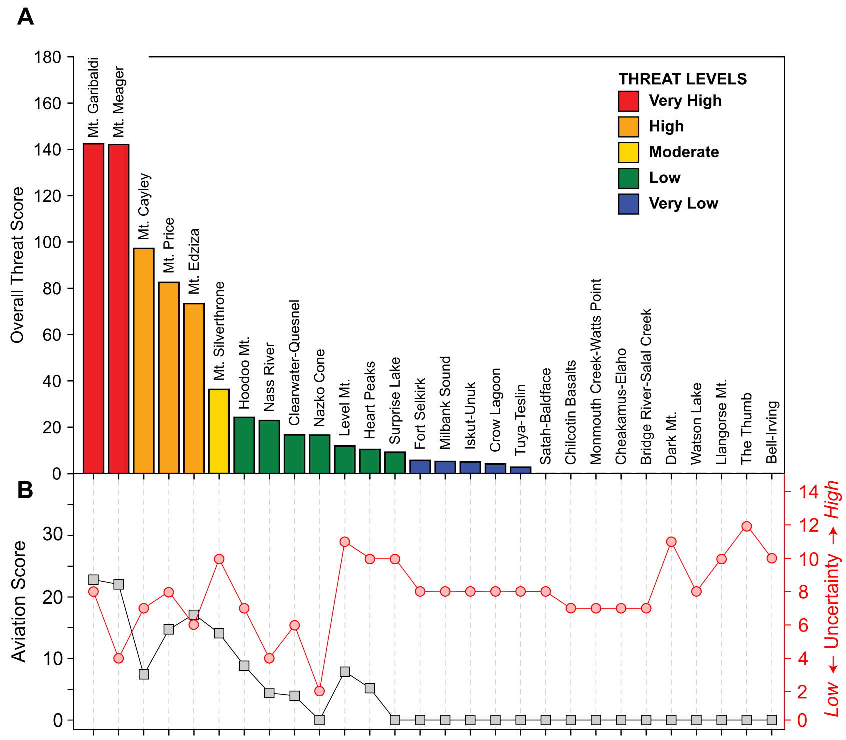
The *deposit lithofacies mapping* category (scored from 0 to 4) is based on the number of published studies that contribute lithofacies mapping, petrologic, or geochemical studies. Volcanoes with at least one study are scored 0, while those with none are scored 4. Scoring this item was somewhat subjective because of the variation in level of detail (e.g., ranging from regional or reconnaissance mapping to detailed lithofacies mapping); we considered whether mapping or studies were aimed at elucidating eruptive history details or were broader regional studies with few details about volcanic deposits. The *geochronology studies* category (scored from 0 to 4) evaluates volcanoes based on the quantity and quality of dated geologic units. If a volcano has most eruption units dated using high-quality geochronological methods, it is scored 0, while volcanoes with no available geochronology are scored 4. The *geophysical studies* category is scored from 0 to 1. Volcanoes that have received any geophysical analyses (e.g., seismic monitoring or imaging) are scored 0, while those that have not are scored 1. Finally, the *geohazard studies* category (scored from 0 to 3) is designed to evaluate the quality of existing volcano hazard maps. Volcanoes with studies involving computational hazard inundation zone modelling or hazard mapping are scored 0, while those with no hazard studies are scored 3.

3. Results

Threat assessment scores, broken down by components, and volcano knowledge uncertainty scores for the 28 volcanoes, are summarized in Table 2. The overall threat score for each volcano was calculated without including the proposed Isolation exposure factor, although we depict the threat scores that would have resulted had Isolation been included. The geographic distribution of volcanoes in different threat categories is shown in Fig. 3 (threat scoring details and source references are given in Table S3 of the Supplementary material). The distributions of threat scores and corresponding aviation threat scores, and volcano knowledge uncertainty scores, are shown in Fig. 4. In most cases, our threat ranking likely represents a minimum, as knowledge of past explosive activity, eruptive behaviour, and eruption recurrence for many Canadian volcanoes is low. Typically, new lithofacies studies and data provide evidence for more eruptions, not fewer (e.g., Stasiuk et al. 2003; Van Daele et al. 2014). Overall threat scores range from 0 to 142.07 and show a broadly decreasing exponential distribution. Aviation scores range from 22.0 to 0 and follow a similar, decreasing exponential

Fig. 3. (A) Map showing geographic distribution of overall threat for classified volcanoes in northwestern British Columbia and the adjacent Yukon Territory and (B) in southern British Columbia. The basemap topography is from the USGS EROS Archive—Digital Elevation—Global 30 Arc-Second Elevation (GTOPO30). Forests are from the Global Forest Watch Intact Forest Landscapes IFL_forested_landscapes_2016. Water (sea) is from the ETOPO1 arc-minute global relief model. Rivers and lakes are from the Government of Canada CanVec 5 m data series (CanVec Series).

Fig. 4. (A) Distribution of overall threat scores (coloured bars) for Canadian volcanoes. Category divisions match Ewert et al. (2018). (B) Graph showing semiquantitative assessment of aviation threat scores (grey squares) and geologic uncertainty (red circles), which reflects the availability of knowledge physical volcanology, geochronology, geophysics, and geohazards at each volcano.



trend. Canadian threat group classifications are kept consistent with Ewert (2007) and Ewert et al. (2018).

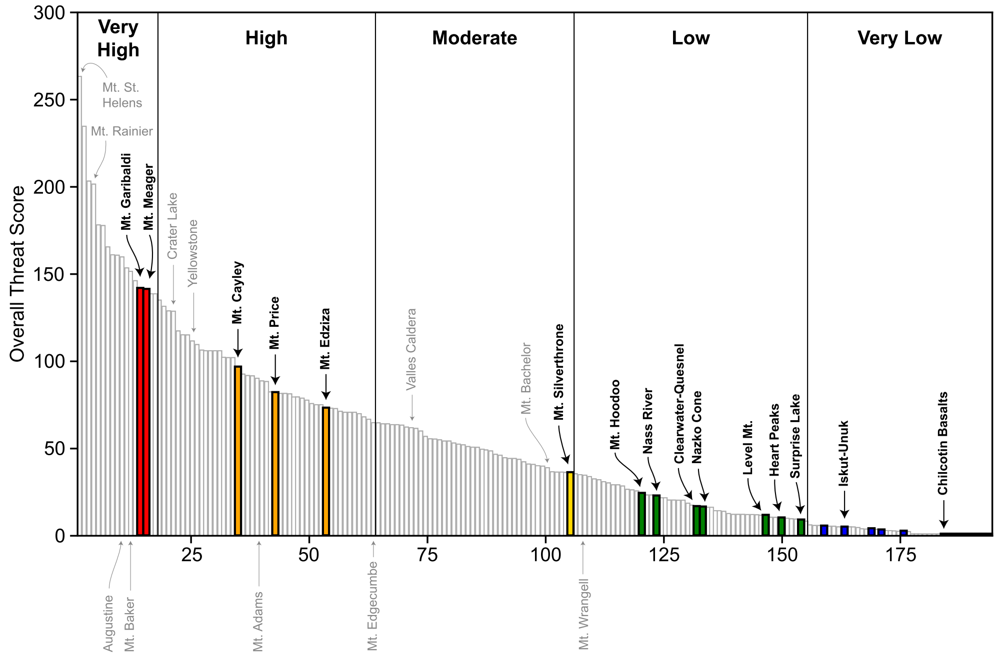
Two volcanoes (Mt. Garibaldi and Mt. Meager) are classified as Very High threat (262–122 points), with similar overall threat scores of approximately 140. The Very High ranking at Mt. Garibaldi reflects a high exposure score (one of the highest of all Canadian volcanoes). For Mt. Meager, the Very High threat score is largely attributed to recent indicators of volcanic unrest and a large (VEI 4) Holocene eruption. Although the Isolation exposure factor was not used to tabulate the overall threat rankings, it would have increased both volcanoes' threat scores by about 10 points; this information provides an indication of how poor access might create logistical challenges in eruption response. Mt. Garibaldi's knowledge uncertainty score is 8, indicating it is not well studied compared to many other Canadian volcanoes (as 0 is the best possible score and 12 is the worst possible score). Mt. Meager's knowledge uncertainty score is 4, which is comparatively good.

Three Canadian volcanoes are classified as High threat (121–63 points): Mt. Cayley, Mt. Price, and Mt. Edziza. Although there are potential Holocene rocks at Mt. Cayley (Kelman 2005), these have not been dated, so we did not count them and scored Mt. Cayley conservatively. Due to the proximity to Highway 99 and the towns of Squamish and Whistler, 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, but its remoteness results in a relatively low exposure score. Mt. Cayley's knowledge uncertainty score is 7, which is relatively poor, especially given that it is the third highest threat volcano in Canada. The knowledge uncertainty score of the fourth highest threat volcano, Mt. Price, is 8, which is similarly poor. Mt. Edziza's knowledge uncertainty score is 6. All three volcanoes' threat scores would be higher if Isolation were included in the assessment, but this would not have impacted their threat categories.

One Canadian volcano, Mt. Silverthrone, is classified as Moderate threat (62–30 points). Mt. Silverthrone scores highly for primary volcanic hazard factors but its remoteness leads to a relatively low exposure score, with its proximity to air traffic the primary contributing factor. It has a very high knowledge uncertainty score of 10. It has no nearby communities, so is not scored for Isolation.

Seven Canadian volcanoes are classified as Low threat (29–6 points): Hoodoo Mountain, the Nass River group, the CQVP, Nazko cone, Level Mountain, Heart Peaks, and the Surprise Lake volcanic field. Of these, only Nass River, Hoodoo Mountain, and Nazko cone have evidence for Holocene activity. Threat at Nass River is due to its 220 BP Tseax cone eruption with a positive fatality score. No volcanic unrest indicators are observed for any volcanoes in this group and aviation scores are all <10. These Low threat volcanoes have a range of knowledge uncertainty scores: Hoodoo Mountain (7), Nass River (4), Clearwater–Quesnel (6), Nazko cone (2), Level Mountain (11), Heart Peaks (10), and Surprise Lake (10). Inclusion

Fig. 5. 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 United States volcanoes are labelled for comparative purposes.



of Isolation in the threat scoring would not have significantly affected any of the overall threat scores.

Fifteen volcanoes score in the Very Low threat category (<5 points). Only the Fort Selkirk volcanic field, Milbanke Sound, Iskut–Unuk volcanic field, Crow Lagoon, and Tuya–Teslin volcanic fields show positive overall threat scores. All Very Low threat volcanoes have aviation scores of 0 and most are situated in extremely remote areas. The knowledge uncertainty for all is relatively high: Fort Selkirk (8), Milbanke Sound (8), Iskut–Unuk (8), Crow Lagoon (8), Tuya–Teslin (8), Satah–Baldface (8), Chilcotin Basalts (7), Monmouth Creek–Watts Point (7), Cheakamus–Elaho (8), Bridge River–Salal Creek (7), Dark Mountain (11), Watson Lake (8), Llangorse Mountain (10), The Thumb (12), and Bell–Irving (10). Inclusion of Isolation in the threat scoring would not have significantly affected any of the overall threat scores.

4. Discussion

4.1. Threat ranking discussion and comparison

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

The Very High to Moderate threat category volcanoes are mostly GVB and NCVP stratovolcanoes. Mt. Garibaldi and Mt. Meager have the highest overall threat scores, which is consistent with them 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.

When compared with ranked volcanoes in the United States (Fig. 5), Mt. Garibaldi and Mt. Meager have scores slightly higher than Mount Baker, WA, which has experienced historic unrest (e.g., Crider et al. 2011; Nichols et al. 2011) and has a hazard map (Gardner et al. 1995). Their scores are slightly lower than those for Lassen Peak, CA and Augustine, AK, both of which are considered highly active and have had several large 20th century eruptions (e.g., Begét and Kienle 1992; Clynne 1999; Ewert et al. 2018). High threat volcanoes such as Mt. Cayley, Mt. Edziza, and Mt. Price score similarly to Mt. Churchill, AK and Mt. Adams, WA. Mt. Churchill is the probable source of the ~1250 BP White River Ash, a tephra deposit that was produced by a VEI 6 eruption and covers a large portion of northern Canada (Richter et al. 1995; Lerbekmo 2008), while Mt. Adams last erupted effusively around CE 950 and has a recent history of large lahars and debris flows (Scott et al. 1995; Hildreth and Fierstein 1997).

4.2. Volcano knowledge uncertainty and knowledge gaps

Volcano knowledge uncertainty is lowest for Nazko cone, the Nass River group, and Mt. Meager (Fig. 4), reflecting a relatively large number of studies examining their lithofacies, geochronology, geophysical character, and geohazard potential, in comparison to other Canadian volcanoes. Mt. Meager in particular has been the focus of a significant proportion of volcanological research in Canada, primarily due to its 2360 BP explosive eruption (Clague et al. 1995; Leonard 1995), geothermal potential (Grasby et al. 2012, 2020, 2021; Witter 2019), and recent history of large debris flows (Simpson et al. 2006; Friele et al. 2008; Guthrie et al. 2012; Roberti et al. 2017, 2018, 2021). The work includes 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), a study of a pre-2360 BP eruption (Russell et al. 2021), intermittent remote sensing ground deformation studies (Roberti et al. 2017, 2018), a retrospective earthquake study (Lu and Bostock 2022), magnetotelluric imaging (Hanneson and Unsworth 2023, *This Volume*), gravity surveys (Calahorrano-Di Patre and Williams-Jones 2021), and infrequent hot spring water and fumarole gas chemistry sampling (Ghomshei et al. 1986; Venugopal et al. 2017). A volcanic hazard assessment was prepared as a Master's thesis at Simon Fraser University (Warwick et al. 2019, 2022; Warwick 2020).

Volcano knowledge uncertainty is relatively high for the GVB stratovolcanoes Mt. Silverthrone, Mt. Price, Mt. Cayley, and Mt. Garibaldi. In contrast to Mount Meager, these stratovolcanoes have not been studied in detail, and most studies have been done at a general or reconnaissance level and do not include detailed lithofacies mapping or recent high-precision dates (e.g., Mathews 1952*b*; Souther 1980; Green et al. 1988; Kelman 2005; Morison and Hickson 2023), or are focused on the broader impact of volcanic hazards in Canada (Hickson and Edwards 2001; Stasiuk et al. 2003). This high knowledge uncertainty is problematic because these volcanoes pose Moderate, High, or Very High threat levels.

Volcano knowledge uncertainty is highest for many of the Low and Very Low threat volcanoes. This is in most cases due to a combination of predominantly remote locations, older ages, and poorer deposit preservation, making them less attractive targets for scientific studies. The remoteness of western Canada has severely limited scientific analysis at many volcanoes, many of which have had few or no studies, although there are several examples where the few studies available are very comprehensive and detailed (e.g., Souther 1992*a*; Edwards et al. 2002, 2009), a fact which we attempted to capture in this knowledge uncertainty assessment by scoring such volcanoes 0 or 1 for *detailed lithofacies mapping*.

This knowledge gap assessment for Canadian volcanoes offers a semiquantitative 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 threat scores because geologic studies typically reveal more eruptive complexity, rather than less. For example, at Mt. Cayley, confirmation of at least two Holocene eruptions would raise the overall threat score from 96.9 to 126.7, moving it from the High to the Very High threat group. More comprehensive monitoring could also reveal unrest signals that might increase threat scores. However, the opposite effect is also possible, as demonstrated by changes in the NVEWS United States volcano threat rankings between 2005 and 2018 (Ewert et al. 2018). A Canadian example of a reduction in threat scoring is the Nass River group; during the initial threat assessment (Wilson and Kelman 2021), Nass River scored 40.3 (Moderate). However, its threat score decreased in this study because more detailed mapping and dating that demonstrated that only a single Holocene eruption had occurred (Le Moigne et al. 2020, 2022*b*; Williams-Jones et al. 2020), a fact which lowered its threat score to 26.9 (Low) (the Nass River threat score also decreased due to removing the Isolation score used in Wilson and Kelman (2021) from the threat score tabulation, resulting in a final threat score of 22.9 (the threat scoring breakdown, both with and without the Isolation score, is given in Table S3 of the Supplementary material)).

4.3. Monitoring needs and gaps

This volcano threat ranking can be used to prioritize volcano monitoring targets. Ewert et al. (2005) provide guidelines for appropriate volcano monitoring levels for each of the five 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 institute for volcanoes in New Zealand (Miller 2011). Table 4 provides a summary of the USGS recommended monitoring strategies as they would be applied to Canadian volcanoes based on their threat rankings.

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 ability requires at least 12 real-time broadcasting, three-component and broadband seismometers, regular GPS, and tiltmeter surveys to track geodetic change, frequent or continuous gas chemistry analyses, hydrologic monitoring, lahar early-warning systems where appropriate, and regular remote satellite imaging, including thermal infrared and ground-based thermal imagery. 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 1–4 seismic stations, sparser geodetic coverage, 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. 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", 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. Notably, no dedicated continuous permanent seismic monitoring is conducted at any Canadian volcano, and existing monitoring is not oper-

Table 4. Canadian volcanoes listed in five threat groups, with required level of monitoring indicated.

Volcano	Recommended level of monitoring
Level 4: well monitored in real time	
Mt. Garibaldi Mt. Meager Mt. Cayley Mt. Price Mt. Edziza	***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 modelling. **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 plus real-time monitoring of hill-slope soil moisture, stream discharge, etc., as appropriate. Systems for lahar early detection where warranted
Level 3: basic real-time monitoring	
Mt. Silverthrone	***Monitoring should provide the ability to 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 plus continuous-sensing probes in features of primary interest, including water wells. LIDAR-derived DEMs for lahar-runout modelling. **Remote sensing:** Level 2 coverage along with routine use of multichannel 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	
Hoodoo Mt. Nass River Clearwater–Quesnel Nazko Cone Level Mt. Heart Peaks Surprise Lake	***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 summer-to-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 Milbanke Sound 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

Note: Recommended monitoring levels, and format of table, are from Ewert et al. (2005).

ational (in the sense of being systematic, continuous, consistent, and linked to a planned scientific or emergency response). 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; Cassidy and Mulder 2023, *This Volume*). A temporary Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity array deployed in the Nazko cone region of BC facilitated analysis of early 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 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 (Cassidy and Mulder 2023, *This Volume*).

Mount Meager (Very High threat) meets a standard that is only slightly higher than that recommended for a Very Low threat volcano, with some infrequent seismic, hydrologic, gas, geodetic, and remote sensing studies. The sporadic nature of these studies, and the fact that they are conducted by several different organizations without a systematic monitoring or information-sharing plan, however, means that the ability to detect and respond to anomalous activity is extremely limited, since there is no continuous picture of background activity that would aid in detecting and identifying anomalous behaviour. Local monitoring currently under development comprises two optical cameras that acquire images daily, one broadband seismometer (operated by the Meager Creek Development Corporation), and optical satellite imagery acquisition (Russell et al. 2023, *This Volume*), as well as the nascent InSAR deformation monitoring system being developed by Natural Resources Canada. If unrest occurred during a gap in data acquisition (e.g., during the winter when ground-based access may be inhibited and high-quality InSAR results might not be available), even unequivocally anomalous activity 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. Mount Meager also has no landslide detection and alerting system (functionally similar to those in place around Mount Rainier, Washington (Kramer et al. 2017; Thelen et al. 2021)), which is warranted 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 is key for reducing risk to inhabitants of the Lillooet River valley because most landslides occur in the absence of volcanic unrest. The landslide risk is continuous and ongoing, and exceeds internationally accepted risk tolerance thresholds for loss of life (Friele et al. 2008; Roberti et al. 2018). A landslide detection and alerting system would require a significant emergency planning and preparedness component beyond the basic technical and scientific aspects of installing the system.

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 these sites, the likelihood of early detection would be extremely low. Even if unrest were detected, the lack of permanent, on-site, and ground-based monitoring would limit the available data for generating short-term activity forecasts, and the installation of equipment in response to the unrest might well be hampered by logistical considerations (e.g., winter weather, wildfire season, or the lack of available instruments and expertise). Mt. Garibaldi, in particular, is a Very High threat volcano for which there is a very low level of scientific understanding. Seismic and deformation 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 pre-unrest data baseline would be available. At Mt. Cayley and Mt. Price, minimal seismic monitoring and remote sensing would also greatly improve our understanding of their background behaviour and increase likelihood of unrest detection. Though isolated volcanoes with low exposure scores are a lower priority, satellite remote sensing at Mt. Silverthrone, Level Mountain, and Heart Peaks (all remote stratovolcanoes with high uncertainty scores) would provide baseline geological and geodetic information useful for understanding their dormancy or unrest status.

4.4. Addressing volcano knowledge and monitoring gaps

This threat ranking has significant implications for volcano research and risk reduction activities in Canada. It clearly ties Canadian volcanoes to recommended monitoring levels, indicates that the current monitoring levels are not commensurate with the threat, and provides a rational basis for comparisons between Canadian volcanoes and better-known US volcanoes (e.g., Mt. St. Helens), for which activities like monitoring and hazard and risk assessment have been undertaken. This has facilitated the development of ongoing Canadian volcano risk reduction activities, including hazard and risk assessment and monitoring (Kelman et al. 2023; Rotheram-Clarke et al. 2023). The threat ranking was instrumental in selecting Nch'ḵay' (Mt. Garibaldi) as a target for hazard and risk assessment: the volcano was chosen both due to its Very High threat and the comparatively low level of scientific understanding available (Kelman et al. 2023). The linking of Canadian volcanoes to recommended monitoring levels also played a role in prioritizing the ongoing development of an InSAR deformation monitoring system for Canadian volcanoes (Rotheram-Clarke et al. 2023), because it made clear the extent to which Canadian volcanoes are undermonitored and provided information relevant for estimating the overall costs of different monitoring strategies. Dedicated, long-term, and operational InSAR monitoring will improve situational awareness for multiple volcanoes (including all High and Very High threat volcanoes), will help develop some of the IT infrastructure and expertise needed for long-term monitoring of other unrest phenomena, and may be the most cost-effective way to address the lack of volcano monitoring (Kelman et al. 2023; Rotheram-Clarke et al. 2023). Although remote monitoring cannot take the place of adequate ground-based monitoring, it can provide a tool to help screen for unrest and interpret its outcome; if unrest were detected, additional monitoring resources could be deployed as needed. This monitoring approach attempts to balance the significant cost of monitoring long-dormant volcanoes with the disastrous consequences of an unforecast major eruption, a needed balance identified in volcanic hazard literature (e.g., Brown et al. 2015; National Academies of Sciences, Engineering, and Medicine 2017).

5. 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 their hazards have been given minimal scientific attention. We present an analysis of the volcanic threat posed by 28 active volcanoes in Canada, using a USGS methodology to score individual volcanoes on multiple hazard and exposure factors, producing an overall threat score. This 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. We propose that any future volcano threat ranking methodology changes include a consideration of the effects of isolation of communities adjacent to volcanoes, in a similar manner to the treatment of populated volcanic islands in existing ranking systems (Ewert et al. 2005, 2018).

Canada has five Very High and High threat volcanoes with similar eruption potential to many well-studied and monitored United States volcanoes (Fig. 5). Four of the five highest threat volcanoes in Canada (Mt. Garibaldi, Mt. Meager, Mt. Cayley, and Mt. Price) are situated near major populations and critical civil and economic infrastructure. Most of these volcanoes are understudied. Canada has no routine operational volcano monitoring and falls significantly short of internationally recommended volcano monitoring guidelines for volcanoes of all threat levels. Volcanic unrest at a Canadian volcano has the potential to cause a major socioeconomic 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.

This threat assessment project has aided in prioritizing volcano risk reduction, including ongoing hazard and risk assessment and development of InSAR deformation monitoring (Kelman et al. 2023; Rotheram-Clarke et al. 2023). It is hoped that this threat assessment and ensuing activities spur interest in conducting future volcanic hazard and risk assessments, beginning with the three High threat volcanoes (Mt. Cayley, Mt. Price, and Mt. Edziza), and in making existing volcanic hazard assessments easily accessible to the public and end user organizations. We also hope this depiction of monitoring gaps will spur interest in more comprehensive monitoring, including seismic stations at key Very High and High threat volcanoes, and in other volcanic risk reduction activities such as landslide detection and alerting systems, to bring Canada closer to recommended best practices for volcano risk reduction.

Acknowledgements

The authors gratefully acknowledge conversations with John Ewert, Angie Diefenbach, Ben Pauk, Michael Poland, and other USGS's Cascades Volcano Observatory staff, and the support of the Natural Resources Canada National Scale Geohazards Risk Project Group. The authors also acknowledge partners and contributors to the Volcano Risk Reduction in Canada project, particularly Yannick Le Moigne. We are also very grateful to Kelly Russell and an anonymous referee, who provided thorough and insightful comments and edits that greatly improved the manuscript.

Article information

History dates

Received: 31 May 2023
Accepted: 23 October 2023
Version of record online: 26 February 2024

Notes

This paper is part of a Collection on Canadian Cordilleran Volcanism published by the Canadian Journal of Earth Science.

Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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Competing interests

The authors declare that there are no competing interests.

Funding information

Financial support for this threat assessment was provided by the Geological Survey of Canada (Natural Resources Canada)'s Geoscience to Keep Canada Safe program. The ongoing (2022–2026) Volcano Risk Reduction in Canada (VRRC) project is funded by the Canada Safety and Security Program (CSSP-2022-CP-2537).

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjes-2023-0074.

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