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**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7679**

**A Preliminary Volcanic Ash Fall
Susceptibility Map of Canada**

M.C. Kelman

2015

Canada



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Abstract

Volcanic ash has the potential to impact the economy and human health in many ways, including interfering with air travel, damaging machinery, damaging crops, and contaminating water supplies. We present a semi-quantitative 1:12 million scale map of volcanic ash fall susceptibility in Canada (Figure 1), which shows the locations, types, and ages of 320 Canadian volcanoes with the potential for future eruptions, and four zones of estimated annual ash fall probability. Hazards other than volcanic ash are assumed to affect areas smaller than the symbols used to depict the volcanoes; therefore, although areas susceptible to all other volcanic hazards are encompassed by this map, the map only explicitly delineates areas susceptible to volcanic ash hazards. Four elliptical volcanic Ash Fall Hazard Zones (A, B, C, and D) are defined around Canadian and American volcanoes that pose high ash hazards for Canada, and then merged to form regional ash hazard zones.

For the two outermost zones, C and D, the shape, size, orientation, and placement of ash fall hazard ellipses are based on ash distribution data compiled for the six largest ash fall events in Canada during the last 10,000 years. Zone D is defined for hypothetical eruptions of Volcanic Explosivity Index (VEI) ≥ 6 ("huge"), while Zone C is defined for hypothetical eruptions of VEI 5-6 ("large"). Volcanoes are placed at the leftmost foci of the ellipses, which are oriented east-west for Canadian and Alaskan volcanoes, and northeast for volcanoes in Washington and Oregon. The distance from each volcano to the far margin of the hazard ellipse is estimated based on average maximum dispersal distances (D_x) for the compiled Holocene ash data. Annual ash fall probabilities for zones C and D are based on the number of huge and large eruptions that deposited significant ash in Canada during the last 10,000 years. Since there were 2 huge events, the annual probability of ash fall at some unspecified point within zone D is 1 in 5000. Since there were 2 huge events and 4 large events, the annual probability of ash

fall at some unspecified point within zone C is 6 divided by 10,000, which is approximately 1 in 1700.

For Ash Hazard Zone B (“medium” events, VEI 4-5), we assume that the apparent frequency-magnitude trend for Pleistocene and Holocene eruptions of $VEI \geq 5$ within or on the border of Canada (1 huge event, 2 large events) is meaningful. By this reasoning, we would expect 4 medium eruptions. Therefore, we estimate 4 medium ash fall events within Canada during the last 10,000 years. For Ash Hazard Zone B, we would thus predict a total of 10 ash fall events (including the 6 events used to define Ash Hazard Zones C and D), leading to an ash fall recurrence interval of 1000 years, or an annual probability (of ash fall at some unspecified point within zone B) of 1 in 1000. The average maximum ash dispersal distance for Zone B is crudely estimated based on ash fall data from the 1980 Mount St. Helens eruption. Because actual data about Canadian eruptions smaller than VEI 5 are scarce, we have not estimated the number of Holocene events for Ash Hazard Zone A (“small” events, $VEI < 4$); we simply assume that the annual probability of ash fall (at some unspecified point within zone A) is higher than for Zone B (therefore, >1 in 1000). The maximum dispersal distance, D_x , for Zone A, is speculatively extrapolated from Zone B.

Acknowledgements

GIS expertise was provided by Rob Cocking. The volcanic ash compilation was initiated by Hickson and Edwards (2001), and was expanded with the encouragement and guidance of Catherine Hickson. Kelly Russell provided useful comments on early drafts of the map. Garry Rogers provided guidance and feedback as part of Natural Resources Canada’s Public Safety Geoscience program. The map and Accompanying Notes were reviewed by Glyn Williams-Jones, Dov Bensimon, and Malaika Ulmi. René Servranckx and Dov Bensimon also provided helpful input about volcanic ash transport and dispersal models. Access to Ash3d was provided by the United States Geological Survey through Larry Mastin (although the results are not presented herein). Rose Gallo assisted

by running Ash3d numerous times and by tracking down bibliographic references.

1.0 Introduction

1.1 Introduction

This Preliminary Volcanic Ash Fall Susceptibility Map of Canada (Figure 1) was produced by Natural Resources Canada's Public Safety Geoscience Program as one of a series of national-scale natural hazard and susceptibility maps, in order to identify regions likely to be affected by specific hazards, quantify the hazards as much as possible, and prioritize key areas for future research.

FIGURE 1

A PRELIMINARY VOLCANIC ASH FALL SUSCEPTIBILITY MAP OF CANADA

Author: M. Kelman, 2015

Digital cartography by R. Cocking

Initiative of the Geological Survey of Canada, conducted under the auspices of Natural Resources Canada's Public Safety Geoscience program.

Digital base map from data compiled by Geomatics Canada

Projection: Statistics Canada Lambert, North American Datum 1983

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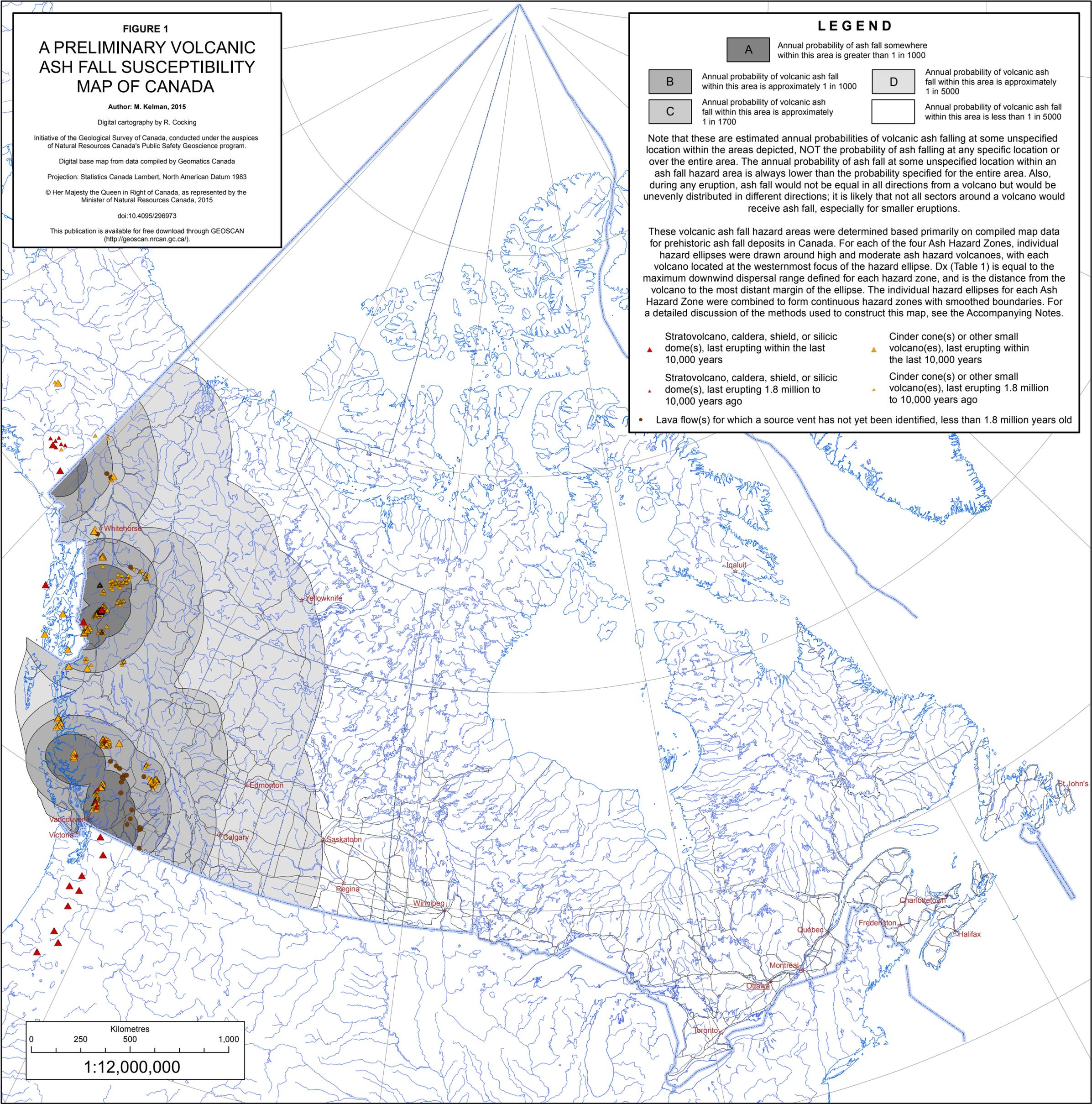
LEGEND

- | | |
|---|--|
| <p>A Annual probability of ash fall somewhere within this area is greater than 1 in 1000</p> <p>B Annual probability of volcanic ash fall within this area is approximately 1 in 1000</p> <p>C Annual probability of volcanic ash fall within this area is approximately 1 in 1700</p> | <p>D Annual probability of volcanic ash fall within this area is approximately 1 in 5000</p> <p>Annual probability of volcanic ash fall within this area is less than 1 in 5000</p> |
|---|--|

Note that these are estimated annual probabilities of volcanic ash falling at some unspecified location within the areas depicted, NOT the probability of ash falling at any specific location or over the entire area. The annual probability of ash fall at some unspecified location within an ash fall hazard area is always lower than the probability specified for the entire area. Also, during any eruption, ash fall would not be equal in all directions from a volcano but would be unevenly distributed in different directions; it is likely that not all sectors around a volcano would receive ash fall, especially for smaller eruptions.

These volcanic ash fall hazard areas were determined based primarily on compiled map data for prehistoric ash fall deposits in Canada. For each of the four Ash Hazard Zones, individual hazard ellipses were drawn around high and moderate ash hazard volcanoes, with each volcano located at the westernmost focus of the hazard ellipse. Dx (Table 1) is equal to the maximum downwind dispersal range defined for each hazard zone, and is the distance from the volcano to the most distant margin of the ellipse. The individual hazard ellipses for each Ash Hazard Zone were combined to form continuous hazard zones with smoothed boundaries. For a detailed discussion of the methods used to construct this map, see the Accompanying Notes.

- | | |
|---|--|
| <p>▲ Stratovolcano, caldera, shield, or silicic dome(s), last erupting within the last 10,000 years</p> <p>▲ Stratovolcano, caldera, shield, or silicic dome(s), last erupting 1.8 million to 10,000 years ago</p> <p>● Lava flow(s) for which a source vent has not yet been identified, less than 1.8 million years old</p> | <p>▲ Cinder cone(s) or other small volcano(es), last erupting within the last 10,000 years</p> <p>▲ Cinder cone(s) or other small volcano(es), last erupting 1.8 million to 10,000 years ago</p> |
|---|--|



1.2 Background

Most volcanic hazards (e.g., pyroclastic flows, volcanic gases) cannot be shown on a Canada-scale map because they affect areas less than a few tens of kilometres from the source, which means that affected areas are smaller than the symbols used to depict the volcanoes. Although lahars (volcanic mudflows and debris flows) most often affect areas within this size range also, large lahars can cause catastrophic damage outside this distance: for example, the prehistoric Osceola mudflow from Mount Rainier, Washington, traveled more than 120 km (Vallance and Scott, 1997). At a scale of 1:12 million, this would correspond to 1 cm on the map, which is larger than the symbol size and is resolvable. However, we chose not to depict lahar hazards for two reasons: First, the overwhelming majority of lahar hazards will still be limited to regions a few tens of kilometres from the sources. Second, lahar hazards have not been mapped or studied in detail for any Canadian volcano, so we could at best crudely estimate lahar hazard areas by highlighting all river drainages coming off a volcano (because lahars follow topography), and this could be misleading. Therefore, although we recognize that lahars may be a significant hazard at some Canadian volcanoes (or near the border adjacent to American volcanoes like Mount Baker), the Preliminary Volcanic Ash Fall Susceptibility Map does not explicitly depict lahar hazards; they are assumed to be mostly contained within the areas of the map symbols.

The only volcanic hazard with significant effects mappable at a Canada-wide scale is volcanic ash (tiny particles of shattered rock which may be smaller than 0.01 mm)¹. Volcanic ash is produced by fragmentation of magma and rock during an explosive eruption. As ash is ejected, the eruption column entrains surrounding air and heats it, resulting in a thermally buoyant plume that rises until its density is equal to that of the surrounding atmosphere, at which time the

¹ Fragmental material ejected from a volcano is known as *tephra*. Volcanic ash is the tephra smaller than 2 mm.

plume spreads laterally and downwind, dispersing ash up to thousands of kilometres from a volcano. The largest volumes of volcanic ash are produced by eruptions of gas-rich high-silica lavas that form high eruption columns which may rise more than 35 km into the atmosphere. Numerous volcanic ash layers have been mapped across western Canada, and serve as useful chronological markers.

Volcanic ash is dense (about 1.4 g/cm^3 when dry and about 2.0 g/cm^3 when wet), hard, abrasive, insoluble in water, and electrically conductive (when wet). It can seriously damage aircraft (Casadevall, 1994; Guffanti et al., 2009, 2010), and may pose a real or perceived hazard to aviation even when eruptions are relatively small, as was prominently demonstrated during the 2010 eruption of Iceland's Eyjafjallajökull (Davies et al., 2010). On or near the ground, ash can reduce visibility, make surfaces slippery, cause roofs to collapse, damage crops and wild plants, harm or kill livestock and wildlife, damage machinery, power supplies, and electronics, clog ventilation systems, corrode metal (over long time periods), contaminate or interfere with water supplies (Brantley et al., 1992), irritate or damage eyes, and pose a health risk to people, especially those with pre-existing respiratory problems (Baxter, 1990, 2000; Horwell and Baxter, 2006). Because some of these effects can be mitigated (e.g., by wearing protective masks, covering equipment, cleaning up ash, minimizing travel, etc.), it is useful to know what areas are most likely to be affected.

Volcanic ash dispersal depends on height of the eruption column, ash particle size(s), magma composition, eruption continuity (continuous versus punctuated), magma interaction with water (ice, snow, lakes, groundwater), eruption duration, and wind and weather conditions. All of these variables can change with time, even during a single eruption, and assigning realistic eruption parameters in order to predict ash behaviour can be difficult (e.g., Mastin et al., 2009). Volcanic ash transport and dispersal (VATD) modeling is typically an ongoing process during an eruption, with new information about eruptive and weather conditions

and observed ash dispersal used to constantly improve and refine ash dispersal predictions, and numerous different VATD models exist (e.g., Hurst, 1994; D'Amours et al., 1998; Draxler and Hess, 1998; Searcy et al., 1998; Folch and Felpeto, 2005; Costa et al., 2006; Jones et al., 2007; Peterson and Dean, 2008; Mastin et al., 2009; Schwaiger et al., 2012).

In Canada:

- (a) there are at least 13 volcanoes with the potential for producing explosive eruptions (and at least 40 volcanoes in neighbouring Alaska, Washington, and Oregon have a significant potential for depositing ash on Canadian territory) (Table 1, Figure 2);
 - (b) the recurrence interval for eruptions is not known, nor is it known whether the eruption rate is constant over time;
 - (c) the relative probabilities of eruptions of different magnitudes are not known;
- and
- (d) the most probable eruption parameters are not known for any volcano².

² The one Canadian volcano for which explosive eruption parameters might be reasonably estimated is Mount Meager, because its VEI 5 eruption at 2350 BP has been studied in detail (e.g., Clague et al., 1995; Leonard, 1995; Russell and Stasiuk, 1997; Hickson et al., 1999; Stewart et al., 2004). However, it still is difficult to generalize what a “typical” eruption might be based on a single event.

volcano	state or province	latitude (degrees)	longitude (degrees)	age of most recent activity	ash hazard rank
Dark Mountain	British Columbia	58.63556	-129.43917	Pleistocene	moderate
Heart Peaks 1	British Columbia	58.62139	-131.98444	Pleistocene	moderate
Hoodoo Mountain	British Columbia	56.77194	-131.29639	Holocene	high
Level Mountain North	British Columbia	58.46306	-131.45000	Pleistocene	moderate
Monmouth Creek	British Columbia	49.69306	-123.19056	Pleistocene	moderate
Mount Cayley	British Columbia	50.12028	-123.28944	Pleistocene	high
Mount Edziza	British Columbia	57.71556	-130.63472	Holocene	high
Mount Fee	British Columbia	50.08361	-123.24472	Pleistocene	moderate
Mount Garibaldi	British Columbia	49.85056	-123.00472	Pleistocene	high
Mount Meager	British Columbia	50.63222	-123.50444	Pleistocene	high
Silverthorne Caldera	British Columbia	51.45833	-126.08333	Pleistocene	high
Tricouni Southeast Flow	British Columbia	49.99222	-123.21944	Pleistocene	moderate
Watts Point	British Columbia	49.64972	-123.21667	Pleistocene	moderate
Aniakchak	Alaska	56.905800	-158.209000	Holocene	high
Augustine	Alaska	59.362600	-153.435000	Holocene	high
Black Peak	Alaska	56.551200	-158.787000	Holocene	high
Blue Mountain-Gas Rocks	Alaska	57.705100	-156.846700	Holocene	high
Bona-Churchill	Alaska	61.418700	-141.715200	Holocene	high
Chiginagak	Alaska	57.133480	-156.991470	Holocene	high
Dana	Alaska	55.642050	-161.215510	Holocene	high
Dutton	Alaska	55.186700	-162.274400	Holocene	high
Edgecumbe	Alaska	57.050900	-135.761100	Holocene	high
Emmons Lake	Alaska	55.340900	-162.072600	Holocene	high
Fisher	Alaska	54.669200	-164.352400	Holocene	high
Griggs	Alaska	58.357200	-155.103700	Holocene	high
Hayes	Alaska	61.598500	-152.420000	Holocene	high
Jarvis	Alaska	62.023300	-143.620100	Pleistocene	high
Kaguyak	Alaska	58.611300	-154.024500	Holocene	high
Katmai	Alaska	58.279000	-154.953300	Holocene	high
Kialagvik	Alaska	57.201900	-156.746700	Holocene	high
Mageik	Alaska	58.194600	-155.254400	Holocene	high
Martin	Alaska	58.169200	-155.356600	Holocene	high
Novarupta	Alaska	58.265400	-155.159100	Holocene	high
Redoubt	Alaska	60.485200	-152.743800	Holocene	high
Shishaldin	Alaska	54.755400	-163.971100	Holocene	high
Spurr	Alaska	61.298900	-152.253900	Holocene	high
Trident	Alaska	58.234300	-155.102600	Holocene	high
Ugashik-Peulik	Alaska	57.750300	-156.370000	Holocene	high
Veniaminof	Alaska	56.197900	-159.393100	Holocene	high
Drum	Alaska	62.115900	-144.639900	Pleistocene	moderate
Iliamna	Alaska	60.031900	-153.091800	Holocene	moderate
Sanford	Alaska	62.213300	-144.129500	Pleistocene	moderate
Wrangell	Alaska	62.005720	-144.019350	Holocene	moderate
Crater Lake	Oregon	42.930000	-122.120000	Holocene	high
Hood	Oregon	45.374000	-121.695000	Holocene	high
Newberry	Oregon	43.722000	-121.229000	Holocene	high
South Sister	Oregon	44.103000	-121.768000	Holocene	high
Adams	Washington	46.205556	-121.489722	Holocene	high
Baker	Washington	48.776667	-121.814444	Holocene	high
Glacier Peak	Washington	48.111667	-121.112778	Holocene	high
Rainier	Washington	46.852778	-121.760278	Holocene	high
St. Helens	Washington	46.200000	-122.183333	Holocene	high

Table 1. Volcanoes in Canada and the United States with moderate to high potential for depositing ash in Canada.

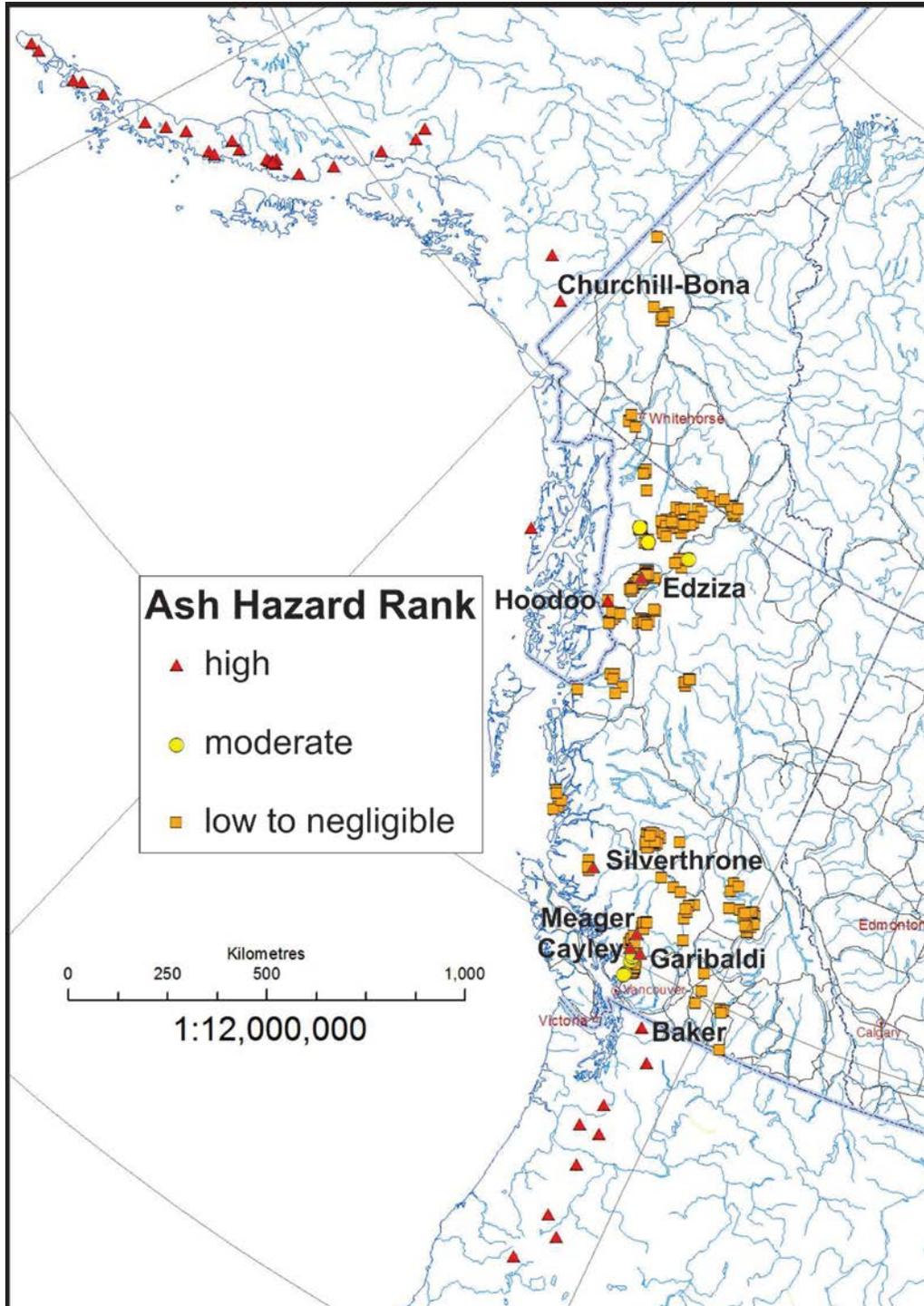


Figure 2. Canadian volcanoes and their ash hazard rankings, and American volcanoes whose ash hazard was ranked as high, according to the procedure above.

1.3 Previous Work

In our attempt to evaluate ash fall hazards for all of Canada, we investigated what had been done elsewhere. Volcanic hazards are most commonly addressed at the single-volcano scale (or even the single-volcano, single-hazard scale). In the few previous cases where volcanic hazards or risks were addressed at a regional or larger scale, several approaches were used:

(a) Quantitative, spatial: For each of 190 volcanoes in the Asia-Pacific region, 1000 ash dispersal scenarios were simulated (with the program ASHFALL), using eruption magnitude-frequency relationships for each volcano (based on its eruptive history and the globally-averaged behaviour of analogous volcanoes) combined with a realistic but random sampling of input parameters for ash dispersal simulation (Jenkins et al., 2012a, b);

(b) Quantitative, spatial: The probabilities of particular thicknesses of volcanic ash at specific sites in New Zealand were estimated using eruption magnitude-frequency distributions based on dated ash layers, eruption parameters from real data or data from analogues, wind distribution statistics, and the program ASHFALL (Hurst and Smith, 2004, 2010; Stirling and Wilson, 2002);

(c) Semi-quantitative, risk-based, spatial: Population density maps were combined with volcano location data to give an indication of the number of people at risk from eruptions (Small and Naumann, 2001);

(d) Semi-quantitative, spatial: Hazard zones around volcanoes were crudely estimated based on semi-quantitative observations, such as wind direction data for different altitudes (Crandell, 1976; Mullineaux, 1976);

- (e) Semi-quantitative, spatial: Hazard zones were extrapolated by generalizing data from a single volcano to multiple volcanoes (Crandell, 1976; Mullineaux, 1976);
- (f) Semi-quantitative, risk-based, spatial: Data for dates and magnitudes of eruptions for a list of volcanoes were combined with population data, several eruption data sets, and wind directions averaged over specified sectors around each volcano, for the purpose of estimating insurance risks in Europe (Spence et al., 2009);
- (g) Semi-quantitative, risk-based, non-spatial: Volcanoes were assigned threat ranks based on scores assigned for various hazard and exposure factors, but hazards were not depicted on a map (Ewert, 2007); and
- (h) Qualitative, spatial: Hazard zones were estimated by applying general volcanological principles (e.g., lahars follow river valleys) to existing maps (Crandell, 1976; Mullineaux, 1976; Hickson et al., 2009).

The first two approaches, (a) and (b), which quantitatively assess regional ash fall hazards, are not appropriate for the Volcanic Ash Fall Susceptibility Map of Canada for several reasons: First, Jenkins et al. (2012a, b) modeled ash dispersal using the program ASHFALL, a greatly simplified two-dimensional model that can run in 1-2 minutes, making it possible to conduct a large number of simulations. However, ASHFALL is designed to estimate ash fall near an eruption (within a few hundred kilometres). Therefore, it may not be appropriate to draw conclusions about long-distance ash dispersal using ASHFALL. Other VATD models, like HYSPLIT (Draxler and Hess, 1998) and CANERM (D'Amours et al., 1998), use three-dimensional time-varying wind fields, and therefore can produce more realistic results when modeling ash dispersal over large areas, but they require much more time to run, so are inappropriate for running large

numbers of scenarios for multiple volcanoes³. For Canada, the area of potential ash fall covers millions of square kilometres, and there are at least 53 potential sources of widespread ash fall, but abundant historical data about eruption parameters are available only for some of the U.S. volcanoes and even where abundant historical data are available, the time spanned is geologically short, and there is still great uncertainty in generalizing future eruptive parameters and wind conditions from a few past events⁴. We conclude that, given the information available for the volcanoes in question, it is neither logistically feasible nor meaningful to use VATD models to generate zones of ash fall hazard for Canada from hypothetical future eruptions.

Approach (c) is not an analysis of actual hazards, merely an evaluation of the settlement density of volcanic versus nonvolcanic regions, so using this method would not fulfill the objectives of the Volcanic Ash Fall Susceptibility Map⁵.

Approach (d) (using semi-quantitative data such as wind directions at a volcano) is a crude way to estimate zones of ash hazard, since it does not consider any of the many eruption parameters that may affect ash dispersal, and grossly

³ As an additional evaluation of whether modeling would be of use for generating ash hazard zones, we used the model, Ash3d (Schwaiger et al., 2012; Ash3d is available from the United States Geological Survey), to run ash fall simulations with realistic but somewhat arbitrary eruption parameters for 4 different eruption magnitudes on 12 dates spaced evenly throughout the year for each of 4 volcanoes in or on the border of Canada (for a total of 192 simulations). There was no discernible pattern in the results. These simulations reinforced what we had learned from conversations with meteorology personnel at the Volcanic Ash Advisory Centre (VAAC) in Montréal, Québec, Canada: there is no meaningful way to use VATD modeling to define zones of volcanic ash fall hazard for Canada.

⁴ In comparison, the quantitative regional assessments by Jenkins et al. (2012a, b), Hurst and Smith (2004, 2010), and Stirling and Wilson (2002) made use of abundant data on eruption frequencies and magnitudes, covering long time periods, with many volcanoes having relatively short recurrence intervals for events of significant magnitudes, and Jenkins et al. (2012a, b) only used volcanoes with proven Holocene eruptions. However, there is only one proven major explosive eruption in Canada during the last 10,000 years (and 2 proven events within 100 km of our border, in the adjacent United States), and the explosive eruption recurrence interval may be longer than 10,000 years for many Canadian volcanoes.

⁵ However, doing population and infrastructure studies for Canadian volcanoes would be useful because this would help to prioritize volcanoes for further targeted research. Even when little is known about eruption frequency, we can reasonably assume that detailed hazard assessment will be of greater net benefit at volcanoes located near population centres (e.g., southwest British Columbia).

simplifies the effects of the wind, with the maps by Crandell (1976) and Mullineaux (1976) assuming that most ash falls in the sector east of the volcano, with a concentric semicircular downwind distribution. However, this approach does yield a result that is more realistic than simply assuming ash dispersal is equal in all directions (which would produce a circular hazard zone, implying that areas west of the volcano have the same ash fall probability as areas to the east).

Approach (e) (applying ash fall data from one volcano to another volcano) is, like (d), similarly crude but it too produces results better than simply assuming equal dispersal in all directions, although the results may still be misleading, particularly if inappropriate analogues are chosen.

Approach (f) uses population data, eruption frequency-magnitude relationships, and wind directions averaged over sectors around volcanoes. This approach combines elements of both hazard assessment (estimating which sectors around a volcano will receive the greatest ash fall) and risk assessment (estimating the socio-economic impacts of hazards). However, such an approach is not appropriate for Canada because we lack detailed frequency-magnitude relationship information and, although the assumptions related to wind are, as discussed above, better than assuming equal dispersal in all directions, they are still oversimplifications. Equally, approach (f) goes beyond the scope of the Volcanic Ash Fall Susceptibility Map in that it evaluates not only hazard but risk.

Approach (g), ranking volcanoes in terms of hazard, is very useful for identifying volcanoes likely to produce ash and for identifying targets for intensive monitoring or research, but it does not provide quantitative information about areas likely to be affected by ash or give a general picture of the geographical areas most at risk, unless the results are displayed on a map.

Approach (h) (applying general volcanological principles to existing maps), is very useful when dealing with localized hazards, particularly for lahars and pyroclastic flows, which follow topography, and can be useful as a method for rapid preliminary hazard assessment when the time and resources required for more detailed assessments are not available.

With this previous work taken into consideration, we developed a procedure for evaluating ash fall hazards for Canada that takes into account the frequency of events and the data available.

1.4 Brief summary of procedure

We defined 4 zones of decreasing ash fall probability (Ash Hazard Zones A, B, C, D) by using a combination of several of the approaches described in section 1.2:

- (a) We ranked individual volcanoes in Canada and the adjoining United States according to their likelihood of producing significant ash (section 3.1) and plotted the volcano locations on a map (Figure 2);
- (b) We made generalizations about the sizes, shapes, orientations, and geographical locations of areas most likely to be affected by ash fall from eruptions of 4 different magnitudes, based on data from the 6 most widespread Holocene ash layers in Canada and on data from the 1980 Mount St. Helens eruption (sections 3.2-3.7)⁶;

⁶ This Volcanic Ash Fall Susceptibility Map does not reflect research by Jensen et al. (2014), which was published after formal review of this Open File Report, which correlated the eastern lobe of the White River Ash with the AD860B tephra found in Greenland and northern Europe. This new research substantially expands the known distribution of the eastern White River Ash, however, the results may not easily be mappable due to the scant distribution of sample sites at the extreme downwind range. This is typical for eruptions in this size range, where it has been demonstrated that ash can be identified at vast distances from the source (Zielinski et al., 2007) but are in most cases not preserved widely over the intervening landscape. Future versions of this map will need to determine how to produce a map that reflects these extreme downwind ash distributions.

(c) We made generalizations about recurrence intervals for ash fall events associated with eruptions of 4 different magnitudes within and near Canada, based on data for prehistoric Holocene eruptions of Volcanic Explosivity Index (VEI) ≥ 5 , and on apparent frequency-magnitude relationships for explosive eruptions in and near Canada (sections 3.8, 3.9).

(e) We applied these generalizations to the ranked volcanoes and defined 4 zones of ash fall probability (A, B, C, D) around each volcano whose ash hazard was ranked as high, then merged the individual hazard zones into 4 regional-scale hazard zones (section 3.10).

There is a caveat for consideration when viewing the Preliminary Volcanic Ash Fall Susceptibility Map: in comparison to some other natural hazards for which there are abundant data, the quality, quantity, and type of data available for volcanic hazards in Canada (particularly ash) make production of even a semi-quantitative hazard susceptibility map very challenging. It is clear that the volcanoes that are potentially hazardous to Canada are located in British Columbia, the Yukon, and the adjacent United States, that the hazards are greatest closest to the volcanoes, that ash fall probability decreases as distance from a volcano increases, and that prevailing winds tend to skew ash fall towards the east in northwestern North America, however, it is difficult to move from these vague statements to a more quantitative assessment, and different strategies for defining Ash Fall Hazard Zones would result in similar but not identical final products. Therefore, whether a specific geographical location falls on one side or another of an Ash Fall Hazard Zone boundary is less important than the overall national-scale depiction of hazard. Any of the obvious approaches to this problem has shortcomings and is debatable. The approach used here was chosen with the end objective in mind: *to produce a map of Canada that gives a realistic if imprecise picture of which areas are most likely to be impacted by ash fall.*

2.0 Glossary of terms

Annual probability

This is the estimated probability, during any given year, that an event will occur. It can be seen as the reciprocal of recurrence interval: if an event occurs 10 times during a 1000 year period, it would (assuming the event occurrence rate is constant) have an annual probability of 1 in 100 and a recurrence interval of 100 years.

Hazard

A dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or economic disruption, or environmental damage (United Nations International Strategy for Disaster Risk Reduction, <http://www.unisdr.org/we/inform/terminology>).

Holocene epoch

The Holocene is the time period from approximately 11,700 years ago to the present, according to the most recent chronostratigraphic chart from the International Commission on Stratigraphy (Cohen et al., 2013). However, Holocene ash fall event frequencies herein are estimated using 10,000 years BP (before present) as a time cutoff for two reasons: First, the data on tephra distribution were compiled over multiple years, and the compilation commenced before publication of the current chronostratigraphic chart, and therefore used 10,000 BP as the start of the Holocene. Second, 10,000 BP roughly corresponds to the time of deglaciation in British Columbia (although actual times of deglaciation vary considerably depending on location, elevation, and other factors), and the quality of the tephra record is likely to be much better for postglacial eruptions.

Maximum dispersal distance, D_x

On Figure 3, a compilation of location data for the 6 most widespread prehistoric Holocene ash layers in Canada, D_x is the greatest distance from a source volcano at which a visible ash layer is found. We refer to this as the *maximum dispersal distance, D_x* . Due to erosion, patchy ash fall, paucity of data, and non-preservation of very thin ash layers, this is not actually the maximum range at which ash would have fallen during each eruption. However, we postulate that it may correspond to original ash fall thicknesses of at least several millimetres, and the original areas of ash fall would have been much larger. On the Volcanic Ash Fall Susceptibility Map, we used average D_x values to estimate the ranges within which “significant” (i.e., at least several millimetres) ash would fall during an eruption (sections 3.6-3.7).

Pleistocene epoch

This is the time period from 2.588 million years ago to 11,700 years ago, according to the most recent chronostratigraphic chart from the International Commission on Stratigraphy (Cohen et al., 2013). However, we have used 1.8 million years BP as a cutoff for the start of the Pleistocene, according to older versions of the geological time scale (Gradstein et al., 2004). In many cases of volcano ages in Canada, this distinction is not significant because the few radiometric dates available have large errors, and many ages are approximated based on field evidence (evidence or lack of evidence for glaciation, degree of dissection, and stratigraphic relationships). Additionally, volcanoes whose last eruption was more than 2 million years ago are unlikely to erupt again: the Siebert et al. (2010) compilation of volcanic eruptions worldwide focuses on Holocene and Pleistocene activity⁷.

Recurrence interval

⁷ It should be noted that there are in many cases no definitive criteria for telling a volcano is extinct: Smith and Luedke (1994) showed that terrestrial volcanoes may be intermittently active over periods of up to 10 million years.

Recurrence interval is a statistical measurement based on chronological data for event occurrence over a given time period; it is the average time between events. If an event occurs 10 times during a 1000 year period, it would (assuming the event occurrence rate is constant) have a recurrence interval of 100 years and an annual probability of 1 in 100. Recurrence interval is also known as *return period*, and can be seen as the reciprocal of annual probability. Note that this does not mean that an event will occur every 100 years or will occur only once in 100 years; it merely means that events have occurred, on average, every 100 years. In any given 100 year period, events may occur once, multiple times, or not at all.

Tephra

The term *tephra* refers to all fragmental material ejected from a volcano. Larger fragments are called bombs and blocks, while ash comprises fragments smaller than 2 mm, commonly smaller than a micrometre (1 μm).

VATD

Volcanic Ash Transport and Dispersal models (VATD) are computer models used to forecast the displacement of volcanic ash clouds so that they can be avoided by aircraft and to determine which ground areas are most likely to experience ash fall. VATD models use input parameters like plume height, mass eruption rate, particle size distribution, and eruption duration. The accuracy of a model depends on how accurate the eruption and weather parameters are, and how well the model corresponds to the actual physical processes. Satellite observations are often used to validate VATD models during or after an eruption.

Volcanic Explosivity Index (VEI)

The overall level of hazard posed by a volcano generally correlates with the magnitude of eruption. Volcanic Explosivity Index (VEI) is a semi-quantitative scale of an eruption's explosivity, ranging from 0-8, and is based on eruption column height, volume of ejecta (pyroclastic debris and tephra), and on

qualitative observations of eruption style (Newhall and Self, 1982). VEI provides a basis to compare both historic and prehistoric eruptions. Above VEI 2, each increase in VEI represents a tenfold increase in the volume of tephra erupted and, with each increase of VEI, eruption frequency decreases by about an order of magnitude (Simkin and Siebert, 1994). This means that globally, on average, eruptions of VEI 5 are 10 times less frequent than eruptions of eruptions of VEI 4. Note that because not all large-volume eruptions are explosive, Pyle (2000) and Mason et al. (2004) separated measures of volume and explosivity into two discrete scales for magnitude (M) and intensity (I). In many cases, an eruption's rating on the Magnitude (M) scale will be similar to the Volcanic Explosivity Index (VEI). In this publication, we use the VEI exclusively.

3.0 Detailed Procedure

3.1 Tabulation of volcanoes within and near Canada; ranking of volcanoes according to their probability of generating ash (high, moderate, or low to negligible)

We compiled a spreadsheet of the locations of Pleistocene and Holocene volcanoes in Canada, based on the volcanological literature⁸. Volcanic features were assigned to one of three categories:

⁸ Submarine volcanoes are not represented on the map because we do not have a comprehensive list of Canadian submarine volcanoes and have little or no information about their ages, compositions, or eruptive histories. Active submarine volcanoes exist in Canadian waters but it is difficult to evaluate what hazards they may pose, although the hazards are probably low relative to the hazards from terrestrial volcanoes. The most probable hazard from submarine volcanoes is likely to be tsunamis from volcanogenic mass movements or pyroclastic flows, both of which have been documented for Alaskan subaerial coastal volcanoes (Waythomas and Neal, 1998; Waythomas et al., 2009) and coastal volcanoes elsewhere. There is little research about tsunamis generated by entirely submarine volcanoes, and few instances where a tsunami can be confidently attributed to an entirely submarine eruption (e.g., Begét, 2000; Lindsay et al., 2005; Harbitz et al., 2012). Tsunami hazards for Canada are tabulated in Leonard et al. (2012).

- (a) *stratovolcano, caldera, shield, or silicic dome(s)*;
- (b) *cinder cone or other small volcano(es)*; or
- (c) *lava flow(s) for which a source vent has not been identified.*

Pleistocene to Holocene volcanoes in Alaska and the conterminous United States were also tabulated and were similarly categorized, based on the volcanological literature, including the websites for Alaska Volcano Observatory (<http://www.avo.alaska.edu/>) and Cascades Volcano Observatory (<http://volcanoes.usgs.gov/observatories/cvo/>).

To determine which volcanoes pose a potential ash hazard to Canada, we assigned all volcanoes within and near Canada a numerical hazard score from 0-4, using the guidelines below, and then ranked each volcano's ash hazard as *low to negligible, moderate, or high ash hazard* based principally on the numerical hazard score (Table 1). The ranking procedure is as follows⁹:

- (a) Composition: Volcanoes erupting dacite, rhyolite, or trachyte scored 1, and all other compositions scored 0 (because composition, especially silica content, determines viscosity, which affects explosivity)¹⁰.
- (b) History: Volcanoes with known or suspected eruptions of $VEI \geq 3$ during the Holocene scored 2, volcanoes with known or suspected eruptions of $VEI \geq 3$ during the Pleistocene (but not the Holocene) scored 1, and volcanoes with no

⁹ The procedure used is somewhat similar to that used for American volcanoes in Ewert (2007).

¹⁰ Silica content was considered to be a major factor in determining which volcanoes are most likely to erupt explosively because of the large number of documented examples of explosive silicic volcanism and the link between viscosity and silica content. However, it should be noted that although most explosive eruptions of basaltic (low-silica) magma are of a low intensity (e.g., Simkin and Siebert, 1994), high-intensity basaltic explosive eruptions are more common than was previously recognized (e.g., Williams, 1983; Walker et al., 1984; McPhie et al., 1990). Because there are few known examples of explosive basaltic volcanism in western North America (one exception is the 1999 eruption of Shishaldin in Alaska [Nye et al., 2002]), we have herein assumed that explosive eruptions are most probable at volcanoes with a silica content similar to or greater than dacite.

known or suspected eruptions of $VEI \geq 3$ during the Pleistocene or Holocene scored 0.

(c) Current activity: Volcanoes with historic seismicity, historic geothermal activity, or historic eruptions scored 1; all other volcanoes scored 0.

The numerical scores were then used to rank each volcano as *high ash hazard* (scores of 3-4), *moderate ash hazard* (scores of 2), or *low to negligible ash hazard* (scores of 0-1). Note that this process was fairly subjective because of uncertainties in volcano ages, because of lack, scarcity, or uncertainty in information about volcano histories and compositions, because of the difficulty in assigning a VEI to prehistoric eruptions, and because some volcanoes whose products include minor rhyolite or dacite nonetheless usually erupt less silicic lavas (which are less likely to produce large explosive eruptions). In rare cases, a subjective judgment overrode the numerical score, and the verbal rank given did not match the numerical score. *The dominant erupted composition was considered to be the most important factor in determining the hazard*, so some volcanoes with a total score of 1 were still ranked as high ash hazard because of their high-silica compositions.

Most cinder cones or lava flows (many of whose source vents are unknown) scored 0-2 and were ranked as low to negligible ash hazard¹¹ while most volcanoes identified as stratovolcanoes, shields, calderas, or silicic domes scored from 2-4 and were ranked as moderate ash hazard or high ash hazard. For American volcanoes, the NVEWS (National Volcano Early Warning System) threat rank and monitoring priority rank (Ewert, 2007) were also considered, as was distance from the Canadian border: American volcanoes that were assigned an ash hazard rank of high were discarded from the list if they were more than 1600 km from the Canadian border, those with an ash hazard rank of moderate

¹¹ Basaltic cinder cones pose a minimal ash fall hazard because they typically experience a lower degree of fragmentation and deposit tephra within a much smaller range than do more silica-rich volcanoes, and coarse tephra fragments typically fall out on ballistic trajectories near the vent.

were discarded if they were more than 700 km from the Canadian border, and those with a low to negligible ash hazard were discarded if they were more than 200 km from the Canadian border. Thus, the rankings for U.S. volcanoes are only meaningful for Canada, and the volcano list would be incomplete from an American hazard perspective. The list of ranked volcanoes is given in Appendix I¹²

For example:

Redoubt, an Alaskan volcano about 640 km from the Canadian border, has erupted compositions that include andesite, dacite, and rhyolite (Begét and Nye, 1994; Begét et al., 1994), so it scored 1 for composition. It experienced several significant explosive eruptions during the Holocene, so it scored 2 for history. It has experienced repeated historic eruptions, so it scored 1 for current activity. This yielded a total score of 4, which produced a straightforward ranking of high ash hazard.

However:

Hoodoo Mountain, a volcano in northwestern British Columbia, has erupted phonolite and trachyte compositions (Edwards and Russell, 1994, 1995, 2000; Edwards, 1997), so it scored 1 for composition. It is not known to have experienced any significant explosive events during the Pleistocene or Holocene, so scored 0 for history. It has experienced historic seismicity (Stasiuk et al., 2003)¹³, so it scored 1 for current activity. This yielded a total score of 2. Hoodoo does not have a history of producing widespread ash deposits. However, at least three Holocene phonolitic tephra are present in northern British Columbia, and they are postulated to have originated within the Northern Cordilleran volcanic

¹² The final volcano list in Appendix I includes all Canadian volcanoes with evidence for Holocene or Pleistocene eruptions, and those American volcanoes with evidence for Pleistocene or Holocene eruptions that have significant potential for impacting Canada with ash fall or other hazards during a future eruption.

¹³ It is unclear whether this seismicity was volcanogenic or simply occurred in the vicinity of the volcano.

province (Lakeman, 2006). Hoodoo is one possible source (Edwards, 1997): it is long-lived (erupting for the last 100,000 years) and experienced pre-Pleistocene pyroclastic eruptions, and its history of subglacial eruptions, coupled with an existing ice cap, suggest that it has the potential to generate ash that is locally to regionally significant, because interaction between erupting lava and water or ice tends to promote high degrees of fragmentation, resulting in extremely fine ash that can travel great distances. Thus, Hoodoo was assigned a ranking of high ash hazard based on both the numerical score and subjective observations.

The 367 ranked volcanoes were plotted on a base map of western North America at a scale of 1:12 million, with different volcano types and ages distinguished with different symbols and colours. The initial working map included Alaska, Washington, and Oregon because some volcanoes in these areas were used to help define ash hazard zone boundaries, however, most portions of the United States do not appear on the final map because it was cut to display Canada. Around all Canadian volcanoes where ash hazard was evaluated as high, 4 Ash Hazard Zones were drawn following the procedure below (sections 3.4-3.9). For the United States, Ash Hazard Zones were similarly drawn around high hazard volcanoes. Table 1 lists all volcanoes in Canada and the United States that were used to draw the Ash Fall Hazard Zones. A complete list of all Canadian volcanoes, and all American volcanoes with the potential to directly affect Canada, is given in Appendix I. For volcanoes ranked as low to negligible ash hazard, no Ash Hazard Zones were depicted. It is assumed that all non-ash hazards will affect areas smaller than the volcano symbols on the map. The final map shows all Canadian volcanoes with activity in the Pleistocene or Holocene and all moderate to high ash hazard American volcanoes that are visible within the limits of the map box.

This subjective approach to ranking the ash hazards posed by specific volcanoes leaves considerable grounds for uncertainty or disagreement. However, the process as a whole should be considered in light of the existing knowledge about

Canadian volcanoes and the main objectives of the Volcanic Ash Fall Susceptibility Map of Canada. Local variations in the depiction of Ash Fall Hazard Zones would not change the large-scale picture of Canada's volcanic ash fall hazards.

3.2 Grouping of hypothetical eruptions into 4 categories (huge, large, medium, small), based on magnitude

For the purposes of defining 4 zones of ash fall hazard around those volcanoes whose ash hazard was ranked as high (section 3.1), hypothetical eruptions were categorized as *huge, large, medium, or small*¹⁴:

Huge eruptions (Ash Hazard Zone D)

- VEI ≥ 6
- $>10 \text{ km}^3$ of ash
- ash layer is preserved $>1000 \text{ km}$ from the source
- e.g., Pinatubo, 1991: VEI = 6; Krakatau, 1883: VEI = 6

Large eruptions (Ash Hazard Zone C)

- VEI $\sim 5-6$
- $\sim 1-10 \text{ km}^3$ of ash
- ash layer is preserved $100-1000 \text{ km}$ from the source
- e.g., Vesuvius, 79 AD: VEI = 5; Mount St. Helens, 1980: VEI = 5

Medium eruptions (Ash Hazard Zone B)

- VEI $\sim 4-5$

¹⁴ Note that these magnitude categories for hypothetical eruptions are not equivalent to the ranking of ash hazards described above. A volcano with a high ash hazard ranking could experience eruptions of different magnitudes throughout its history: huge, large, medium, or small.

- ~0.1-1 km³ of ash
- ash layer is preserved <100 km from the source
- e.g., Mont Pelée, 1902: VEI = 4; Eyjafjallajökull, 2010: VEI = 4

Small eruptions (Ash Hazard Zone A)

- VEI ≤4
- ≤0.1 km³ of ash
- ash layer is preserved <100 km from the source
- e.g., Nevado del Ruiz, 1985: VEI = 3; Soufrière Hills, 1995: VEI = 3

3.3 Compilation of data for widespread Holocene ash layers in Canada (representing huge and large eruptions, VEI≥5) in map form

In order to define zones of potential ash hazard from huge and large eruptions (Ash Hazard Zones D and C), we expanded a previously published data compilation (Hickson and Edwards, 2001) for the distributions of the six most widespread Holocene volcanic ash layers mapped across parts of western Canada:

Ash layers from huge eruptions

- Mazama (VEI 6, erupted from the site of Crater Lake, Oregon, at ~7700 BP; Hallett et al., 1997; Zdanowicz et al., 1999; Bacon and Lanphere, 2006)
- White River east¹⁵ (VEI 6, erupted from the Bona-Churchill massif in eastern Alaska, at ~1150 BP; Bostock, 1952; Lerbekmo et al., 1975; Clague et al., 1995; Mashiotta et al., 2004; Lerbekmo, 2008; Jensen et al., 2014)¹⁶

¹⁵ Lerbekmo (2008) refers to this ash deposit as WRAe.

¹⁶ As discussed above, this map does not reflect eastern White River Ash distributions as recently published by Jensen et al. (2014) due to the timing of the publication of that research.

Ash layers from large eruptions

- Mount St. Helens Yn (VEI 5, erupted ~4300 BP; Mullineaux et al., 1975; Mullineaux, 1996; Clynne et al., 2005)
- Bridge River (VEI 5, erupted from Mount Meager, British Columbia, at ~2350 BP; Clague et al., 1995; Leonard, 1995)
- White River north (VEI 5, erupted from the Bona-Churchill massif in eastern Alaska at ~1800 BP; Bostock, 1952; Lerbekmo et al., 1975; Clague et al., 1995; Mashiotta et al., 2004; Lerbekmo, 2008)
- Mount St. Helens Wn (VEI 5, ~520 BP; Mullineaux et al., 1975; Mullineaux, 1996; Clynne et al., 2005)

Figure 3 shows the mapped dispersals for these tephra deposits, based on our data compilation.

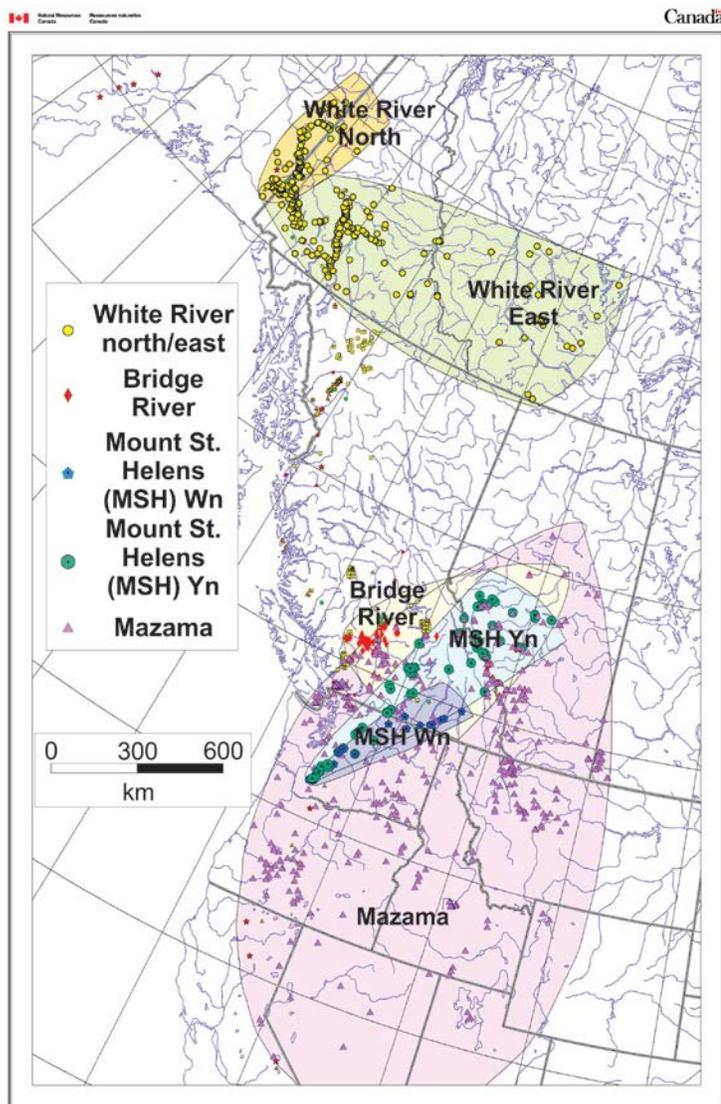


Figure 3. Widespread Holocene ash layers in Canada. The map contains data previously compiled into a map (Hickson and Edwards, 2001), plus new data (data sources are listed in Appendix II).

We used the ash fall areas shown on the map above to make generalizations about the sizes, shapes, and directionalities of future hypothetical ash deposits

around volcanoes of western North America ranked as having high ash hazards, including many volcanoes for which we have little or no ash fall data¹⁷.

This visual approach to predicting future potential areas of ash fall was chosen over a more quantitative approach (e.g., using ash layer thicknesses to infer deposit volumes and eruption magnitudes [e.g., Walker, 1981; Pyle, 1989, 1995; Bonadonna et al., 1998], or using spatial variations in ash particle size distribution to infer mass eruption rates and eruption cloud heights [e.g., Carey and Sparks, 1986; Sparks et al., 1992; Wilson and Walker, 1987, 2009]¹⁸) because at many Holocene tephra localities in Canada, tephra layers are used only to establish chronology and thus, many published accounts do not provide information on layer thicknesses or tephra characteristics. At some sites, the ash layer is present not as a discrete layer but as a zone of soil enriched with ash, suggesting local resedimentation (e.g., Zoltai, 1989). For some ash layers (particularly the Mount St. Helens Wn and Yn tephtras), the data point distribution in Canada is quite sparse, especially as distance from the source increases. The only information consistently available for all 6 ash layers is the presence of the ash at a particular location (Figure 3)¹⁹.

3.4 Generalizations about the expected shapes of areas affected by future ash fall events

The map areas of Holocene ashes in Canada vary significantly in shape, so it was challenging to decide how to most realistically depict ash fall hazards from

¹⁷ We note that the categories “huge” and “large” are very broad: “large” eruptions are defined as having VEI 5-6, but not all eruptions in this VEI range leave widespread ash layers. For example, the 1980 Mount St. Helens eruption was assigned a VEI of 5, but it did not produce a widespread mappable ash layer so is not included in our tabulation of ash layers from “large” Holocene eruptions.

¹⁸ For example, ash data have been used to infer eruption rate and magnitude and eruptive wind conditions for the eastern White River Ash (Lerbekmo, 2008).

¹⁹ Note that Figure 3 depicts only locations where ash layers are visible to the naked eye. Cryptotephtras (ash layers that are only identifiable microscopically) cover much larger areas but are, for obvious reasons, not mapped continuously over their probable ranges.

high ash hazard volcanoes based on this limited, probably nonrepresentative, data set, which represents 6 eruptions under specific eruptive, weather, and preservation conditions. We chose to depict ash hazard zones around volcanoes as ellipses with an eccentricity²⁰ of 0.6 with the source volcano at the leftmost focus (Figure 4), a visual compromise between assuming equal dispersal in all directions (a circle, which would clearly be inappropriate) and assuming dispersal along a narrow axis (possible, but we do not know the relative probabilities of different dispersal axes). The use of an ellipse for depicting ash hazard zones does not mean that we believe a typical ash fall will cover an area of this size and shape, but rather that at the specified annual probability, ash fall is likely to occur somewhere within the elliptical area.

Examples of the hazard zone ellipses are depicted on the mapped area of the eastern White River ash in Figure 4. The orientations of the ellipses are discussed below (section 3.5). The distance D_x from the volcano focus to the far margin of the ellipse was chosen as discussed below for Ash Hazard Zones D and C (section 3.6) and Ash Hazard Zones B and A (section 3.7).

²⁰ The eccentricity of an ellipse is the ratio of the distance between the ellipse's two foci to the length of the ellipse's major axis.

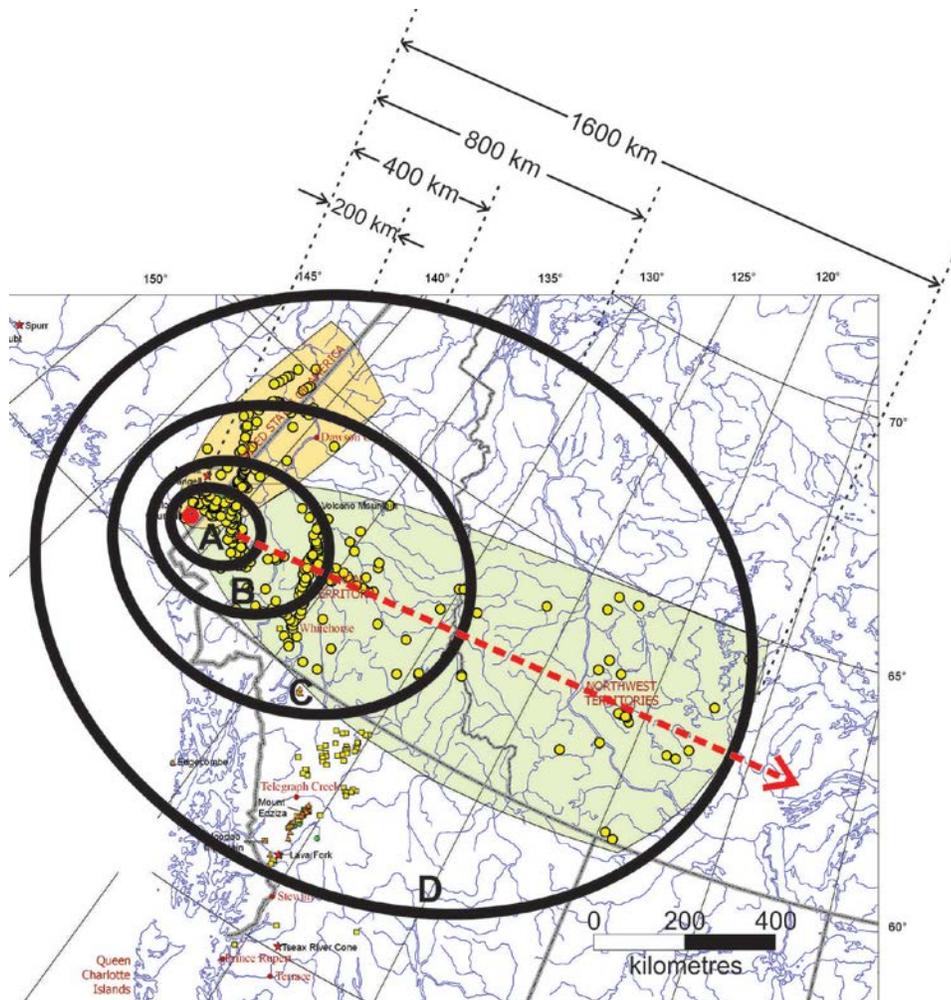


Figure 4. The ellipses used to depict ash fall hazard around individual volcanoes for zones A, B, C, and D, superimposed upon the eastern White River ash (pale green). The northern White River ash is also shown (pale orange). Eccentricity of the ellipse is 0.6. The volcanic ash source, the Bona-Churchill massif in eastern Alaska, is placed at the leftmost focus (red dot). The distance from the ash source to the far edge of the ellipse is D_x , which is the maximum dispersal distance. D_x values for A (small eruptions), B (medium eruptions), C (large eruptions), and D (huge eruptions) are 200 km, 400 km, 800 km, and 1600 km, respectively. On the Volcanic Ash Fall Susceptibility Map, individual hazard ellipses are merged to form regional hazard zones.

3.5 Generalizations about the expected directionality of future hypothetical ash fall events

The six ash deposits in Figure 3 vary significantly in area, shape, directionality, and maximum dispersal distance, D_x . The most obvious trend is that ash is preferentially deposited in the 180° sector lying east of the volcanoes and, for the two Mount St. Helens ash layers, in a much narrower sector with a well-defined dispersal axis to the northeast. In only one case (the northern White River Ash) is the ash fall not skewed dominantly east or northeast; in that case, it is directed to the north, and this directionality is postulated to be the result of a winter eruption (West and Donaldson, 2000). However, in spite of this general trend of most deposition to the east for prehistoric tephras, significant variability in ash deposit area, shape, directionality, and maximum dispersal distance is possible, depending on eruptive parameters and weather conditions.

For Canadian and Alaskan volcanoes, we have assumed ash fall probability is highest due east of the volcano. This is obviously not universally true, however, there were no quantifiable grounds for choosing one dispersal axis over another for most volcanoes, so we chose a main dispersal axis of due east (090°) because it correlates well with the eastern White River ash (dispersed almost due east) and fairly well with the Bridge River ash (dispersed at $\sim 063^\circ$; Nasmith et al., 1967). For volcanoes in Washington and Oregon, we assumed ash fall is highest northeast of the volcano, so we used a dispersal axis of 026° , which is intermediate between the two similar dispersal axes for the two major Holocene ash layers from Mount St. Helens, Yn and Wn. Although this may not be representative of the most probable dispersal axes for ash from every volcano in the conterminous United States, it agrees fairly well with the typical dispersal directions for Holocene ash deposits from Mount St. Helens (Carey et al., 1995), which is the most prolific ash source in the American Cascades. Furthermore, dispersal to the northeast (as opposed to dispersal towards the east) from volcanoes in Oregon and Washington is a more problematic scenario for

Canada, and therefore from a hazards perspective is a more conservative approach.

Although the choice of ellipse eccentricity, the placement of the volcanoes at the leftmost focus, and the orientation of the ellipses all lead to a significantly larger ash hazard to the east of the volcano, this still results in a higher apparent ash hazard to the west, north and south of the volcanoes than seems to be evident from the six mapped Holocene tephra. Based on the ash compilation map (Figure 3), the percentages of tephra deposit areas lying west of the source volcanoes are: Mount Mazama O: 5.9%, Mount St. Helens Yn: 1.0%, Bridge River: 0.3%, White River east: 0.1%, White River north: 32%, and Mount St. Helens Wn: 0.2%. Therefore, with the exception of the northern White River ash, it would seem that ash fall anywhere in the 180° sector west of a volcano is very minimal. However, over long enough time periods, the ash fall hazard west, north, and south of the volcanoes is probably not insignificant (although the hazard is arguably highest for the eastern sector), and the ash hazard zones as drawn allow for some ash to fall west of the volcanoes.

3.6 Generalizations about the distances to which ash would be dispersed during future hypothetical ash fall events from huge or large eruptions (Ash Hazard Zones D and C)

For huge and large Holocene eruptions affecting western Canada, we have defined a value, D_x , the maximum dispersal distance, which is the maximum distance from a source volcano at which a visible ash layer is preserved. This quantity is clearly related to eruption magnitude; all other things being equal, a higher magnitude eruption will have a greater maximum dispersal distance than a smaller eruption, because tephra will be more finely fragmented, will be injected higher in the atmosphere, and will take longer to settle out, allowing for dispersal to greater distances. However, D_x is also strongly dependent on wind conditions,

so using it as a guide to what constitutes a typical eruption of a particular magnitude could be very misleading. Furthermore, when averaging the value of D_x for several mapped tephra layers, we are effectively averaging all the characteristics that influenced the fall pattern and preservation of that ash layer, including the wind conditions. With reservations about the validity of this measure, we have chosen to use D_x simply because no other attribute is consistently available. Maximum dispersal distances (D_x) and other information related to the defined ash hazard zones are listed in Table 2.

Ash Hazard Zone	magnitude of events used to define the zone	magnitude of events included in the zone	how was the number of zone-defining events determined?	number of zone-defining events	recurrence interval for zone-defining events	location of ash fall sources for events	estimated annual probability of ash fall*	D_x	volcanoes for which hazard zone is drawn	D_x based on
D	VEI \geq 6 "huge"	VEI \geq 6 huge only	counting Holocene ash falls in Canada, VEI \geq 6	2	5000 years	in Canada or the USA	1/5000	1600 km	high ash hazard volcanoes only	mapped limits of: Mazama ash, eastern White River ash
C	VEI 5-6 "large"	VEI \geq 5 huge, large	counting Holocene ash falls in Canada, VEI 5-6	4	2500 years	in Canada or the USA	1/1700	800 km	high ash hazard volcanoes only	mapped limits of: northern White River ash, Mount St. Helens Yn, Mount St. Helens Wn, Bridge River ash
B	VEI 4-5 "medium"	VEI \geq 4 huge, large, medium	extrapolation from Holocene eruptions in/near Canada: 1 huge, 2 large -->4 medium	4	2500 years	in or near Canada	1/1000	400 km	all high and moderate ash hazard volcanoes	extrapolation from Mount St. Helens 1980 reported ash fall thicknesses
A	VEI \leq 4 "small"	any	not applicable	unknown	unknown, <2500 years	in Canada only	>1/1000	200 km	all high and moderate ash hazard volcanoes	speculation

*This is the probability of ash fall at some unspecified point within the zone, NOT the probability of ash falling at any specific location or over the entire area.

Table 2. Information used to define Ash Hazard Zones A, B, C, and D.

For Ash Hazard Zone D, associated with huge eruptions (VEI \geq 6), we have 2 Holocene examples, the eastern White River ash and the Mazama ash. The maximum dispersal distance, D_x , of the eastern White River ash lies in the vicinity of Great Slave Lake, about 1400 km east of the source area, where it is <5 mm thick, discontinuous, and identified only in peatlands (Robinson, 2001; Lerbekmo, 2008)²¹. The Mazama ash, sourced from the Mount Mazama eruption that formed Crater Lake, has a less well-defined dispersal axis than that of the

²¹ As discussed above, Jensen et al. (2014) correlated the eastern White River Ash with the AD860B ash found in Greenland and northern Europe, however, this new data is not incorporated in this Volcanic Ash Fall Susceptibility Map.

White River ash, but its maximum dispersal distance, D_x , is about 1600 km to the northeast of its source, in Alberta, where it occurs as both single and multiple visible ash layers, as well as ash-enriched layers, and may have been resedimented by wind (Zoltai, 1989); sites in this area are clearly near the limits of the preserved visible Mazama ash layer. Abundant evidence indicates that both these tephras originally fell over much larger areas than are apparent from visible tephra layers: Mazama ash has been identified in Greenland ice cores (about 5000 km downwind; Zdanowicz et al., 1999), and the eastern White River Ash has been identified as a cryptotephra (a tephra layer not visible to the naked eye) in Newfoundland (Pyne-O'Donnell et al., 2012), Nova Scotia (Jensen et al., 2014), and northern Europe (at least 7000 km downwind; Jensen et al., 2014). Because few cryptotephra studies have been done in eastern Canada, it is possible that many more occurrences of these and other tephras are present across all of Canada, thus reflecting much larger original areas of ash fall than are evident from mapped visible tephra distributions. We also note that a known historical eruption of VEI 6 in Alaska (the 1912 Novarupta eruption) was accompanied by reports of ash fall 2500 km downwind (Payne and Symeonakis, 2012), although the ash layer that records this eruption covers a much smaller area. Therefore, we have chosen the higher D_x (from Mount Mazama), 1600 km, as the D_x for the Ash Hazard Zone D on the Volcanic Ash Fall Susceptibility Map (Table 2). For a huge eruption ($VEI \geq 6$), we would expect, at this distance, at least several millimetres of ash fall somewhere within Ash Hazard Zone D, with the heaviest ash fall closest to the source volcano.

For Ash Hazard Zone C, associated with large eruptions (VEI 5-6), we have 4 Holocene examples, the northern White River ash, the Bridge River ash, the Mount St. Helens Yn ash, and the Mount St. Helens Wn ash. Mapped ash layers from these eruptions vary significantly in shape and size: the Mount St. Helens Yn and Wn tephras are dispersed along well-defined narrow swathes to the northeast of their source, while the Bridge River Ash and northern White River Ash are more broadly dispersed. The averaged measurement of maximum

dispersal distance, D_x , for all 4 eruptions, is about 800 km. This is the maximum dispersal distance used to depict Ash Hazard Zone C (Table 2). It is probable that some part of this area would receive at least several millimetres of ash fall during a large eruption in Canada, Alaska, or the conterminous United States, with the heaviest ash fall closest to the source.

3.7 Extrapolation of distances to which ash would be dispersed during future hypothetical ash fall events from medium and small eruptions (Ash Hazard Zones B and A)

Evaluating potential ash hazards for eruptions of $VEI \leq 5$ is challenging because their tephra deposits may be thin, patchy, and limited to narrow sectors around a volcano and, relative to thicker deposits, are more likely to be erased or at least modified by tephra migration, erosion, bioturbation, or other postdepositional processes²². However, eruptions of $VEI \leq 3$ comprise more than 90% of all Holocene eruptions worldwide, and only 2.4% of Holocene eruptions are $VEI \geq 5$ (Siebert et al., 2010). *This means that the overwhelming majority of probable eruption events are not even represented in the ash fall hazard zones we have defined for huge and large events (D and C).* For this reason, it seems prudent to at least make an attempt to estimate the areas likely to be affected by smaller events, and the recurrence intervals for these events.

Because the data are so sporadic for tephra dispersals from eruptions of $VEI \leq 5$ in Canada, we cannot base the size of Ash Hazard Zone B (associated with medium eruptions, VEI 4-5) on preserved tephra layers, as we did for huge and

²² Detailed tephra studies in the Katmai region of Alaska have shown that preserved tephra layers disproportionately represent the most explosive events, and major cone-building and effusive events may leave little ash beyond the vicinity of the volcano (Fierstein, 2007; Hildreth and Fierstein, 2012).

large eruptions. In order to estimate areas that may be affected by eruptions of VEI 4-5, we have used an historical analogue: reported ash fall data for the May 18, 1980 eruption of Mount St. Helens (VEI 5). We note that although ash fall from this eruption was reported as far away as Oklahoma (~2500 km), the heaviest ash fall was restricted to a narrow sector northeast of the volcano (Sarna-Wojcicki et al., 1981). Ash fall deposit thickness variations are more complex than simple exponential thinning (e.g., Bonadonna et al., 1998; Wilson and Walker, 2009): at Ritzville, Washington, northeast of Mount St. Helens, there was an ash fall thickness high, but this has been attributed to particle aggregation and is not thought to be representative of the overall downwind thinning trend (Carey and Sigurdsson, 1982; Sorem, 1982). The ash deposit thins to <5 mm in the vicinity of the Idaho border, at about 400 km range. We have thus chosen 400 km as a proxy for the maximum dispersal distance for ash from medium eruptions, and this is the maximum dispersal distance, D_x , for Ash Hazard Zone B (Table 2). This is an extremely crude estimate, as it is based on a single eruption that may not be representative, and it does not take into account wind variations.

For Ash Hazard Zone A (associated with small eruptions, $VEI \leq 4$), we know that the average maximum dispersal distance would be smaller than for medium eruptions, but we have no way to justify choosing a particular D_x , therefore we simply halved the maximum dispersal distance used for medium eruptions and used 200 km as the maximum dispersal distance, D_x , for Ash Hazard Zone A (Table 2). *This is a very crude and speculative estimate.* We considered not including this smallest ash hazard zone on the Preliminary Volcanic Ash Fall Susceptibility Map, however, we wanted the map to address the lower magnitude eruptions that have the highest probability of occurrence (Simkin and Siebert, 1994; Siebert et al., 2010).

3.8 Estimation of recurrence intervals for huge and large ash fall events in Canada

To estimate recurrence intervals (and thus, annual probabilities), for huge and large ash fall events in Canada (corresponding to Ash Hazard Zones D and C), we counted Holocene postglacial eruptions in Canada and the United States that deposited significant ash in Canada during the last 10,000 years. It is important to note that our recurrence intervals are not recurrence intervals for huge and large eruptions originating in Canada, but are recurrence intervals for ash fall events in Canada resulting from either huge or large eruptions within Canada or the adjacent United States. Event recurrence intervals and other information related to the defined ash hazard zones are listed in Table 2.

For huge eruptions (corresponding to Ash Hazard Zone D), there have been two events (Mazama at ~7700 BP, and the eastern White River ash at ~1150 BP), so their recurrence interval is 10,000 years divided by 2, or 5000 years. This is the recurrence interval for ash fall events in Ash Hazard Zone D (Table 2):

Recurrence interval (RI)_{ash fall, zone D} = 10,000 years ÷ 2 = 5000 years

Annual probability (AP)_{ash fall, zone D} = 1/5000

The recurrence interval for large ash fall events in zone C is 10,000 years divided by 4, or 2500 years, because there have been 4 Holocene events in this size range (Mount St. Helens Yn at ~4300 BP, Bridge River at ~2350 BP, the northern White River ash at ~1800 BP, and Mount St. Helens Wn at ~520 BP). However, since the areas affected by large events are also affected by huge events, the actual ash fall recurrence interval calculation for Ash Hazard Zone C must include both huge and large events. Therefore, the recurrence interval at sites receiving ash fall from large events would be 10,000 years divided by 6, or 1667. We have rounded this number to the nearest 100, to obtain a recurrence interval of 1700 years (which could also be presented as an annual probability of 1 in 1700) (Table 2).

$RI_{\text{ash fall, Zone C}} = 10,000 \text{ years} \div 6 = 1667 \text{ years (round to 1700 years)}$

$AP_{\text{ash fall, Zone C}} = 1/1700$

We emphasize that these recurrence interval estimates are minima, because they are based on mapped ash deposits. Variations in wind direction and strength may mean that a particular ash is not deposited at a particular location, or is deposited only as a thin layer that is not preserved in the visible stratigraphic record. Any estimate of event frequency based on the tephrochronologic record is overwhelmingly likely to be a minimum.

3.9 Estimation of recurrence intervals for medium or small ash fall events in Canada

Estimating recurrence intervals and typical dispersal areas for eruptions of medium or small size (which correlate with Ash Hazard Zones B and A) is even more uncertain than estimating the effects of higher magnitude events because the tephra fall record is less complete for smaller eruptions, and tephra fall may be constrained to a narrow arc, even if it is carried hundreds of kilometres or more from the source²³. We do not have comprehensive data demonstrating the recurrence interval in Canada for eruptions smaller than VEI 5. However, global frequency-magnitude relationships for volcanic eruptions (Simkin and Siebert, 1994) indicate a factor of 10 increase in the number of eruptions for each magnitude decrease of VEI 1 within the range of VEI 3-7, so we postulated that a frequency-magnitude trend may exist regionally, and examined the scant data available from huge and large eruptions within western North America.

²³ For example, the eruption that produced the Mount St. Helens Yn layer, which erupted about 4 km³ of material (more than 10 times the volume erupted during the 1980 Mount St. Helens eruption), left an ash layer that is preserved in Canada across an arc that is at its broadest only about 21°.

In Canada, we have 1 huge eruption (the eastern White River ash, VEI 6) and 2 large eruptions (the northern White River ash and the Bridge River ash, VEI 5)²⁴. It is highly speculative to assume a trend from such a small data set, but we observe that event frequency apparently doubles with each decrease in VEI. If this trend is real, we would expect about 4 eruptions of medium size (VEI 4-5) in Canada during the Holocene²⁵ although, because smaller eruptions leave thinner and more discontinuous ash layers, it may be more difficult to map these layers and identify their source vents.

Since areas affected by medium events will also be affected by large and huge events, the annual ash fall probability (AP) for Ash Hazard Zone B would be:

$$\begin{aligned}
 AP_{\text{ash fall in Zone B}} &= \\
 AP_{\text{huge eruption in Canada/U.S.}} &+ AP_{\text{large eruption in Canada/U.S.}} + AP_{\text{medium eruption in Canada}} \\
 &= 1/5000 + 1/2500 + 1/2500 \\
 &= 1/1000
 \end{aligned}$$

This annual probability of ash fall in zone B of 1 in 1000 is more than double the probability of a “significant explosive eruption” that Stasiuk et al. (2003) estimated to be 1 in 3333. However, that 1 in 3333 probability was a probability of large or huge eruptions (VEI≥5) within or on the border of Canada (based on a count of the Bridge River eruption and the two White River eruptions) and did not include more distant large magnitude events that might deposit ash in Canada (such as Mount St. Helens Wn and Yn, and Mazama) or smaller magnitude events,

²⁴ We have included the 2 White River ash eruptions in assessing a Canadian frequency-magnitude trend because they originated within 50 km of the Canadian border and deposited much of their ash in Canada. We did not include the 2 Mount St. Helens events (Wn and Yn) or Mazama in this count because the volcanoes are sufficiently far from the Canadian border that a medium or small event at that range might not deposit much (or any) ash in Canada.

²⁵ Note that the number of medium events is the same as the number of large events. We are assuming that all large and huge eruptions in Alaska or the conterminous United States will drop ash on some part of Canada, regardless of the volcano’s location, but that medium eruptions will only deposit ash in Canada if the volcano is located within or on the border of Canada. Therefore, numerous medium and smaller events in Alaska or the conterminous United States are not counted.

whereas the 1 in 1000 probability we have estimated for the Volcanic Ash Fall Susceptibility Map's Zone B is for all ash fall events in Canada (which may be sourced from huge or large eruptions [$VEI \geq 5$] within or outside Canada, or from medium explosive events [$VEI \leq 5$] at volcanoes within Canada).

For small eruptions, a frequency-magnitude relationship whereby event frequency doubles with each decrease of 1 in VEI (as postulated above), we would expect 8 small events (twice as many as medium events). However, given that we have no detailed information about the frequency of medium and small events in Canada, we estimate only that the probability of a small eruption in Canada is greater than that for a medium event, therefore, the annual probability of ash fall in Zone A is greater than 1 in 1000 (Table 2)²⁶.

Our hypotheses that there have been at least 4 ash fall events in Canada associated with medium eruptions, and more than 4 ash fall events associated with small eruptions, are given credence by the presence, in Canada, of a number of ash layers that are far less extensive than those shown in Figure 3, although we do not in all cases know the associated eruption magnitude or even the source of the ash: At least two Holocene tephras from Washington's Glacier Peak have been detected in southern British Columbia, as well as at least one Mount St. Helens tephra other than Yn and Wn (Hallett et al., 2001; Foit et al., 2004)²⁷. In northern British Columbia, at least three unidentified phonolitic tephras and one basaltic tephra are present; all were probably sourced from volcanoes of the Northern Cordilleran volcanic province, and the basaltic tephra probably came from one of the volcanoes in the Iskut region (Lakeman, 2006). Numerous Pleistocene and Holocene tephras probably sourced from Alaska are

²⁶ If the trend of eruption frequency doubling with each decrease of VEI 1 actually exists, we would expect Ash Hazard Zone A to have been affected by 8 small Holocene eruptions, leading to a total of 2 huge + 4 large + 4 medium + 8 small eruptions = 18 eruptions, which would suggest an annual probability of ash fall in Zone A of about 1 in 550. However, this is speculative.

²⁷ There have been 7 Holocene eruptions from Mount St. Helens whose eruptive volumes place them in the medium size category (Carey et al., 1995), including the 1980 eruption. It is likely that many of them deposited ash at a sufficient range to have fallen in Canada, provided the right wind direction.

found in the Klondike goldfields and adjacent areas of the Yukon (Preece et al., 2011). There are also numerous proximal tephras known at British Columbian volcanoes, and it is possible that they have accompanying distal tephra deposits that have not yet been identified (Souther, 1970; Read et al., 1989; Souther, 1992; Villeneuve et al., 1998; Edwards and Russell, 1999; Edwards et al., 2000, 2002; Russell and Hauksdóttir, 2001). Finally, there is evidence in southeastern Alaska and the adjacent ocean for several Holocene tephras and cryptotephras from Alaska's Mount Edgecumbe and Aniakchak, as well as two tephras similar to (but of different age from) the White River Ash (Riehle et al., 1992; Eastwood et al., 2004; Payne et al., 2008; Addison et al., 2010). These tephras, and other Holocene Alaskan tephras, may continue into northwestern British Columbia, and most probably represent eruptions smaller than VEI 5, since the tephra deposits are not thick or widespread. These data indicate that there could easily be more than a dozen tephra layers associated with medium or small eruptions ($VEI \leq 5$) in British Columbia or the Yukon.

3.10 Map preparation

Ash Hazard Zone D (lowest hazard)

Around each volcano, we drew an ellipse of eccentricity 0.6, with the long axis oriented due east (090°) and the volcano on the westmost focus for Canadian and Alaskan volcanoes, and the long axis oriented at 026° (northeast) and the volcano on the southwestmost focus for volcanoes in Washington and Oregon. The distance from the volcano to the opposing edge of the ellipse (the eastern or northeastern edge) is D_x , the maximum dispersal range and, for Ash Hazard Zone D, is 1600 km. Once all ellipses were drawn, we connected their boundaries with a smoothed line, forming a continuous zone around the volcanoes. Where the smoothed line met the American border, we stopped following the ellipse boundaries and followed the border, truncating the ash hazard zone at the border rather than continuing into the United States. Where

the smoothed line reached the ocean, it was extended out into the ocean for 100 km and then drawn parallel to the coast at a distance of 100 km. After the Ash Hazard Zone was drawn, the ellipses were deleted. The area formed is Ash Hazard Zone D.

Ash Hazard Zone D depicts the area with a 1 in 5000 estimated annual probability of receiving ash fall. This does not mean that the annual probability of receiving ash fall is 1 in 5000 for every point within the area – this is the annual probability that some unspecified point anywhere within the area will receive ash fall. During an ash fall event, ash is unlikely to cover all of a particular ash hazard zone.

Ash Hazard Zone C

We followed the procedure outlined for Ash Hazard Zone D, but made the maximum dispersal distance, D_x , equal to 800 km. Ash Hazard Zone C depicts the area with an approximately 1 in 1700 annual probability of receiving ash fall. This does not mean that the annual probability of receiving ash fall is 1 in 1700 for every point within the area – this is the annual probability that some unspecified point anywhere within the area will receive ash fall. During an ash fall event, ash is unlikely to cover all of a particular ash hazard area.

Ash Hazard Zone B

We followed the procedure outlined for Ash Hazard Zone D, but made the maximum dispersal distance, D_x , equal to 400 km. Ash Hazard Zone B depicts the area with an approximately 1 in 1000 probability of receiving ash fall. This does not mean that the annual probability of receiving ash fall is 1 in 1000 for every point within Ash Hazard Zone B – this is the annual probability that some unspecified point anywhere within the area will receive ash fall. During an ash fall event, ash is unlikely to cover all of a particular ash hazard area.

Ash Hazard Zone A (highest hazard)

We followed the procedure outlined for Ash Hazard Zone D, but made the maximum dispersal distance, D_x , equal to 200 km. Ash Hazard Zone A depicts the area with a greater than 1 in 1000 probability of receiving ash fall. This does not mean that the annual probability of receiving ash fall is greater than 1 in 1000 for every point within the area – this is the annual probability that some unspecified point anywhere within the area will receive ash fall. During an ash fall event, ash is unlikely to cover all of a particular ash hazard area. Note the distinction between Ash Hazard Area A and B: the hazard in Area A is greater than the hazard in Area B because it is closer to the volcanoes, but we have not quantified how much greater.

There is a break in the ash fall hazard zone continuity for zones A and B in central British Columbia, indicating a lower ash fall hazard in this region. This is not an artifact of the procedure used to generate the Volcanic Ash Fall Susceptibility Map but a real feature of the volcanic geography of British Columbia. The volcanoes most likely to produce significant ash are located in southwest B.C., Washington, and Alaska. In central B.C., volcanoes are either pre-Holocene or are of compositions less likely to generate significant ash, and none of the Anahim Volcanic Belt volcanoes was assigned a high ash hazard ranking.

Areas outside Ash Hazard Zones A, B, C, and D do not have annual ash fall probabilities of zero, however, we estimate the annual probability to be less than 1 in 5000.

We have prepared two simplified versions of the Preliminary Volcanic Ash Fall Susceptibility Map that will be easily reproducible for page-size documents or Power Point presentations (Figure 5, Figure 6). They are suitable for

presentations or documents that focus less on the technical aspects of evaluating ash fall hazards and more on the emergency planning aspects.

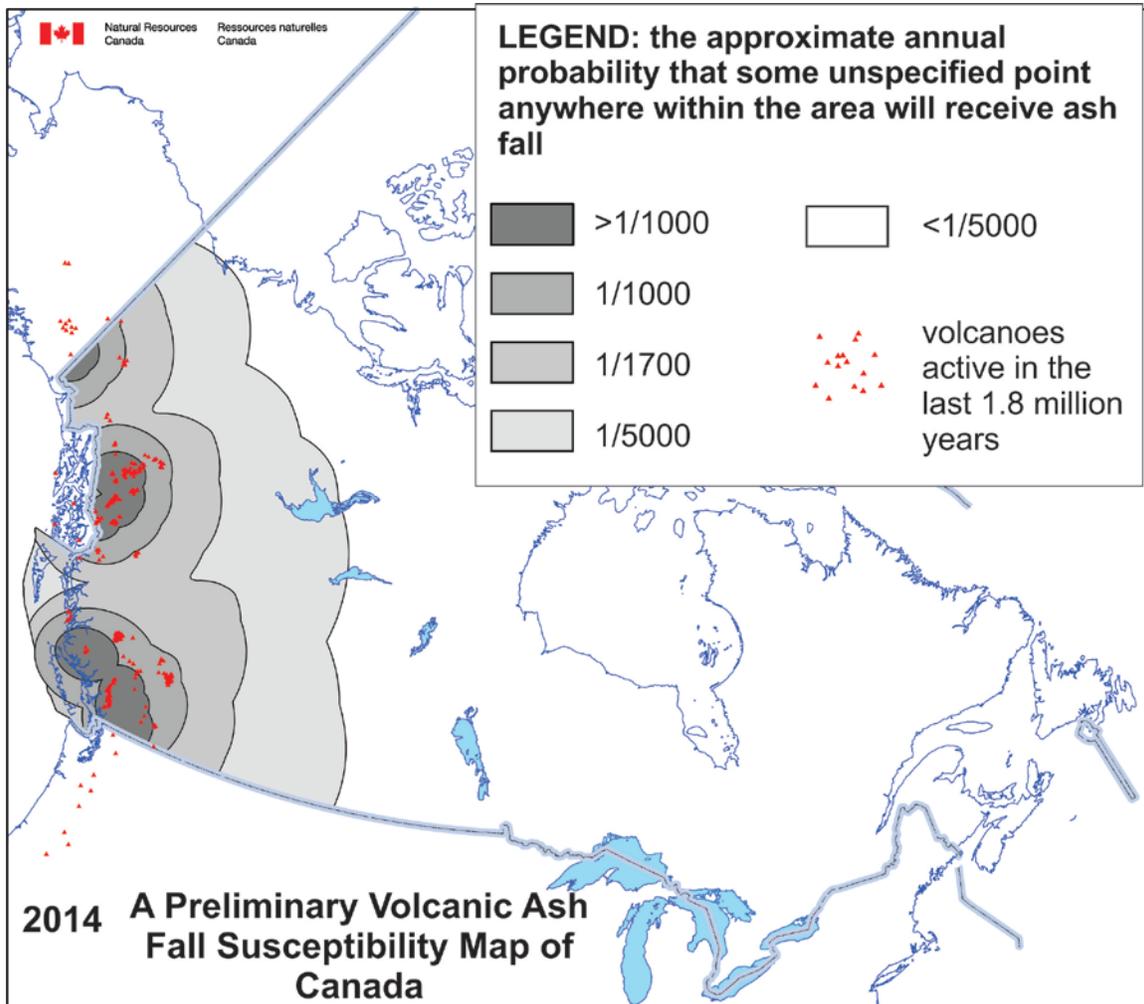


Figure 5. A simplified version of “A Preliminary Volcanic Ash Fall Susceptibility Map of Canada”, with ash fall probabilities given numerically.

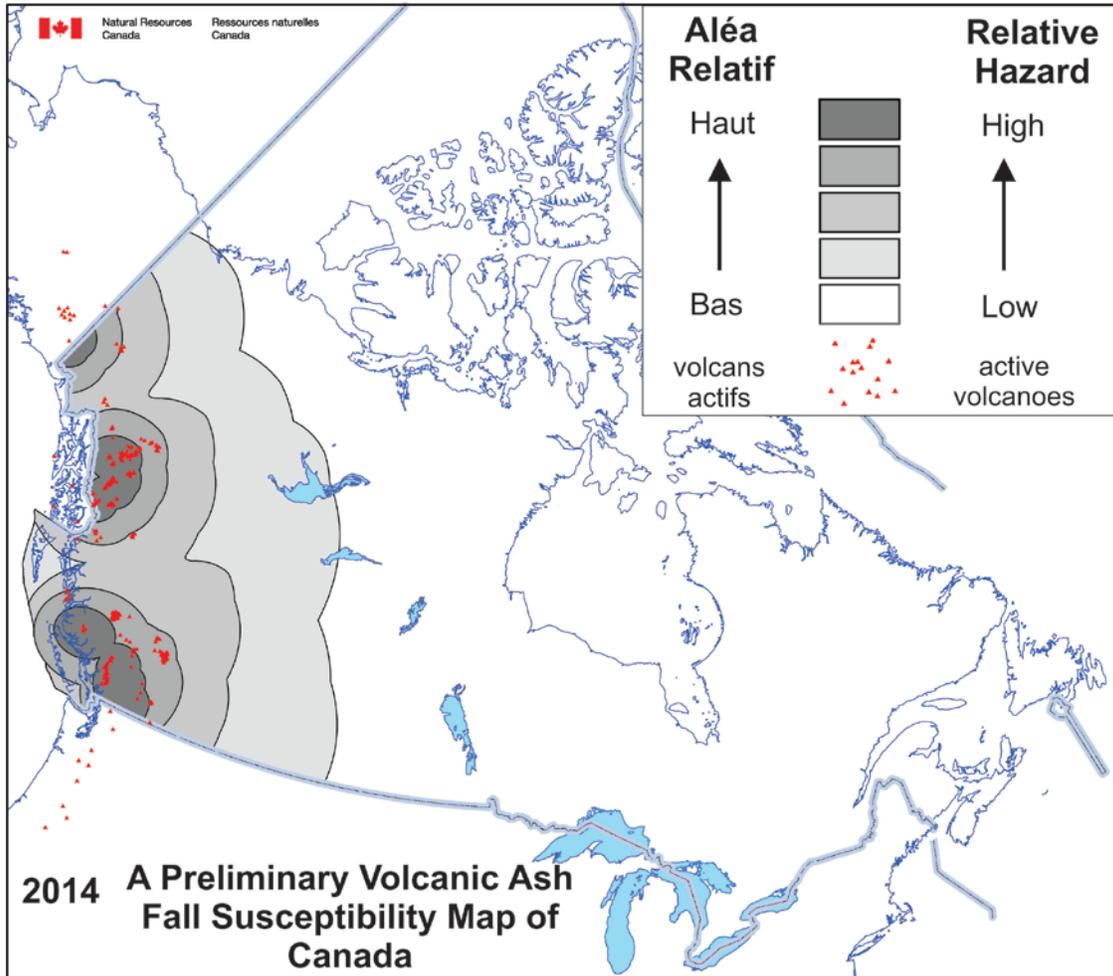


Figure 6. A simplified version of “A Volcanic Ash Fall Susceptibility Map of Canada”, with volcanic ash fall probabilities given descriptively rather than numerically.

4.0 Conclusions

The recurrence interval estimates on the Preliminary Volcanic Ash Fall Susceptibility Map are for explosive volcanic eruptions, range from 5000 years to less than 1000 years, and are probably minima because they are based principally on mapped tephra dispersals. The recurrence interval for all volcanic eruptions in Canada (including non-explosive eruptions dominated by flowing lava) is probably much less, and has been estimated to be as short as 1/200 (Stasiuk et al., 2003). Many episodes of volcanic unrest (seismicity, deformation, gas emissions) do not lead to eruption, but since it may be difficult to ascertain whether an eruption will occur until after significant unrest, the probability that targeted volcano monitoring will be required is likely to be much higher than the probability of an eruption. Even a small, non-explosive eruption could have significant local effects, and an explosive eruption similar to or larger than the 1980 Mount St. Helens eruption could scatter ash on much of British Columbia or the Yukon, and would have a huge impact on western Canada.

The Preliminary Volcanic Ash Fall Susceptibility Map provides a general picture of where the volcanic hazards in Canada are: ash fall hazard zones are explicitly defined and all other hazards fall within the areas covered by the map symbols. However, because of the long recurrence intervals between eruptions in Canada and the scarcity of information about most volcanoes, it is difficult to evaluate how realistic a depiction it is. There are a number of obvious shortcomings:

1. The Preliminary Volcanic Ash Fall Susceptibility Map is based on a very small set of eruptions which may not represent the most probable eruptive and weather conditions. Ash fall patterns are highly dependent on eruptive and weather conditions, so the stratigraphic record of huge and large Holocene eruptions in western North America may not be representative. However, because the ash fall record reflects actual eruptions, it is preferred over VATD modelling as a guide to future ash fall hazards in spite of the uncertainties involved.

2. The Volcanic Ash Fall Susceptibility Map does not take into account regional variations in eruption frequency. Eruptions in Alaska are much more frequent than eruptions in any part of Canada (i.e., there have been numerous historical eruptions in Alaska but none in Canada), and the Garibaldi Volcanic Belt is less frequently active than other segments of the Cascade Volcanic Arc such as the segment containing Mount St. Helens (Scott, 1990; Sherrod and Smith, 1990; Hickson, 1994). However, the Volcanic Ash Fall Susceptibility Map assigns the same event probability to all volcanoes ranked as posing a “high” ash hazard. Thus, the map is imprecise with respect to regional event frequency variations or differences in eruptive frequency and magnitude between individual volcanoes.

3. The Volcanic Ash Fall Susceptibility Map does not reflect the possible clustering of eruptions in time: There is some evidence that rates of volcanism were elevated during the early Holocene due to unloading of the lithosphere resulting from deglaciation of the northern hemisphere (Zielinski et al., 1994, 1996), and Huybers and Langmuir (2009) similarly noted a two- to six-fold increase in subaerial volcanism between 7000 and 12,000 BP, and attributed it to decompressional melting of the mantle resulting from deglaciation. (However, data from the Andes contradict this theory for arc settings, as they do not indicate elevated eruption rates in the early postglacial period [Watt et al., 2013].) Regardless, the data for volcanic regions of Canada are too sparse to evaluate whether eruption rates have varied throughout the Holocene.

4. The boundaries of Ash Fall Hazard Zones B and A, and the recurrence intervals associated with them, are increasingly speculative and are not based on quantifiable evidence. (This is especially problematic because Zones A and B correlate with the most probable, smaller volume, events [VEI<5]. Although most fatalities are associated with eruptions of VEI>4 [Siebert et al., 2010], smaller eruptions still cause significant damage and, in certain instances, such as the 1985 VEI 3 eruption of Nevado del Ruiz, Colombia, may still be catastrophic.)

5. The exact boundaries of the Ash Hazard Zones on the map are somewhat arbitrary – had different D_x values been chosen, the boundaries would move, although the overall appearance of the map might stay the same. Viewers of the map may assign undue importance to whether a particular volcano falls on one side (or the other) of a boundary.

6. The boundaries of the Ash Hazard Zones represent “significant” ash fall, which we crudely defined as several millimetres. However, this is a rough estimate of thickness, since we have not mapped ash fall thicknesses. Additionally, whether an ash fall event is significant depends on a number of factors: the ash layer thickness, the size of the ash, the composition of the ash, the location where it falls, and the point of view of the observer. Crops, machinery, people with respiratory problems, and so on may all be affected to different degrees by the same ash fall event. Even a light dusting of ash (which would probably extend far beyond the limits of the defined Ash Fall Hazard Zones) might be problematic in some circumstances. We note that cryptotephra layers in Newfoundland and Nova Scotia have recorded a number of distant eruptions, including the eastern White River ash, Mount St. Helens Wn, and Mazama (Payne et al., 2008), and that the eastern White River Ash eruption is recorded as a cryptotephra layer in Greenland and northern Europe (Jensen et al., 2014); it seems likely that most of Canada would have received at least a visible dusting of ash from this event, even though this is not recorded (at least visibly) over most of Canada. The areas affected by fine ash may be much larger than the ash hazard zones defined on the Volcanic Ash Fall Susceptibility Map.

7. Basaltic cinder cones have been ranked as “low to negligible ash fall hazard”, and thus have no ash fall hazards depicted around them. While it is true that they are less likely to produce widespread ash fall events, the ash may still be locally to regionally significant: the 1943 eruption of the Parícutin cinder cone in Mexico

caused ash to fall as far away as Mexico City (~330 km away), and the local effects were significant (Luhr and Simkin, 1993).

8. The most uncertain parts of the map are zones A and B. Unfortunately, these represent the most probable events.

9. The choice of an ellipse for the shape of Ash Hazard Zones may not be realistic, and the placement of the volcanoes at the leftmost focus, and the orientation for the ellipses, may also not be realistic.

Future research that could improve later versions of the Volcanic Ash Fall Susceptibility Map should include detailed studies of eruption histories at Canadian volcanoes, especially those whose ash hazard was ranked as high, with an emphasis on establishing precise dates for explosive events, either through dating of proximal eruption products or through distal tephrochronology; lakes, bogs, and protected inlets may record ash layers that are not preserved in other settings. Unidentified tephra layers should be linked to source volcanoes, where possible. Collection and analysis of bog cores with cryptotephra would also be helpful in establishing a more detailed chronology of ash fall events in Canada. All this work will improve estimates of ash fall recurrence intervals and provide information about the return periods for events of different magnitudes. Detailed studies of past eruption histories will also allow for detailed mapping of areas that may be affected by volcanic hazards other than ash (e.g., pyroclastic flows, lahars). All of this information could be combined into volcano-specific hazard assessments.

It would also be of great benefit to future hazard assessments to depict Canadian lahar hazards at a local to regional scale. The three large Garibaldi Volcanic Belt volcanoes (Garibaldi, Cayley, and Meager) all have steep topography, hydrothermal alteration, and abundant water, making them unstable and prone to mass movements, and all three have significant histories of major non-eruptive

landslides and debris flows (Moore and Mathews, 1978; Read, 1981; Clague and Souther, 1982; Evans, 1987, 1990; Evans and Brooks, 1991; Hungr and Skermer, 1982; Cruden and Lu, 1992; Bovis and Jakob, 2000; Guthrie et al., 2012). Therefore, all three have a strong potential for producing lahars during future volcanic eruptions. Their proximity to southwest British Columbia's population centres and infrastructure increases the risk. It would be relatively easy to evaluate lahar hazards at these volcanoes using the program Laharz (Iverson et al., 1998; Schilling, 1998), and the results could then be depicted at a regional scale on future versions of the Volcanic Ash Fall Susceptibility Map of Canada (thus transforming it into a multiple hazard map), and at a local scale on volcano-specific hazard maps. Assessment of lahar hazards to Canada could be especially important for the area north of Mount Baker, Washington, because it has been more frequently active than any Canadian stratovolcano. Lahars that originate on the north side of Mount Baker and travel down the Nooksack River may cross a drainage divide at Everson, Washington into Canada (Pittman et al., 2003; Easterbrook and Donnell, 2007); numerous weather-related floods along the Nooksack River have crossed into Canada by this route (e.g. Klohn Leonoff, 1991; United States Army Corps of Engineers, 1991), and there is evidence that the Nooksack River itself actually drained northward into Canada for much of the Holocene (Pittman et al., 2003). A future flood (whether weather-related or lahar-related) could cause another avulsion, leading to reestablishment of drainage of the Nooksack northward into Canada (Klohn Leonoff, 1991), which could be disastrous. An evaluation of the lahar hazard from Baker would be a significant first step in understanding and dealing with hazardous events from Mount Baker that might affect Canada.

5.0 References

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Appendix I.

Canadian volcanoes that have erupted during the Pleistocene or Holocene, and American volcanoes whose hazards may affect Canada. Each volcano is assigned a hazard rank of low to negligible, moderate, or high.

volcano	*state or province	latitude (degrees)	longitude (degrees)	volcano type	age of most recent activity	ash hazard rank
Abbot Creek Cone	BC	52.610	-121.160	cinder cone or other small volcano	Pleistocene	low to negligible
Adzich	BC	56.745	-129.736	cinder cone or other small volcano	Pleistocene	low to negligible
Alice Arm A	BC	55.417	-129.475	cinder cone or other small volcano	Pleistocene	low to negligible
Alice Arm B	BC	55.464	-129.342	cinder cone or other small volcano	Pleistocene	low to negligible
Alixton Creek	BC	51.800	-122.140	lava flow(s)	Pleistocene	low to negligible
Alkali Lake	BC	51.729	-122.306	lava flow(s)	Pleistocene	low to negligible
Arctic Lake 2	BC	57.370	-130.725	cinder cone or other small volcano	Holocene	low to negligible
Ash Mountain	BC	59.271	-130.512	cinder cone or other small volcano	Pleistocene	low to negligible
Badman Point	BC	59.032	-131.097	cinder cone or other small volcano	Pleistocene	low to negligible
Bell Irving Northeast	BC	56.936	-129.493	cinder cone or other small volcano	Pleistocene	low to negligible
Bell-Irving River	BC	56.900	-129.622	cinder cone or other small volcano	Pleistocene	low to negligible
Bell-Irving River East North	BC	56.893	-129.546	cinder cone or other small volcano	Pleistocene	low to negligible
Bell-Irving River East South	BC	56.887	-129.551	cinder cone or other small volcano	Pleistocene	low to negligible
Big Timothy	BC	52.102	-120.931	lava flow(s)	Pleistocene	low to negligible
Black Tusk	BC	49.975	-123.043	stratovolcano, caldera, or dome(s)	Pleistocene	low to negligible
Blackfly Tuya	BC	59.108	-130.864	cinder cone or other small volcano	Pleistocene	low to negligible
Boss Mountain	BC	52.167	-120.567	cinder cone or other small volcano	Pleistocene	low to negligible
Browns Lake	BC	51.420	-122.240	lava flow(s)	Pleistocene	low to negligible
Buck Hill Mountain/ Buck Hill cone	BC	51.801	-119.977	cinder cone or other small volcano	Pleistocene	low to negligible
Cache Hill	BC	57.541	-130.548	cinder cone or other small volcano	Holocene	low to negligible
Camp Hill	BC	57.590	-130.785	cinder cone or other small volcano	Holocene	low to negligible
Canyon Creek Cones	BC	56.358	-130.716	volcanic field	Holocene	low to negligible
Caribou Tuya	BC	59.236	-130.566	cinder cone or other small volcano	Pleistocene	low to negligible
Castle Rock	BC	57.840	-130.208	cinder cone or other small volcano	Pleistocene	low to negligible
Cauldron Dome	BC	50.156	-123.319	cinder cone or other small volcano	Pleistocene	low to negligible
Chakatah Creek Peak	BC	59.250	-131.033	cinder cone or other small volcano	Pleistocene	low to negligible
Charnaud Creek	BC	51.338	-126.139	cinder cone or other small volcano	Holocene	low to negligible
Cheakamus Valley flows	BC	50.230	-123.170	lava flow(s)	Pleistocene	low to negligible
Cinder Cliff	BC	57.746	-130.549	cinder cone or other small volcano	Holocene	low to negligible
Cinder Cone	BC	49.972	-123.007	cinder cone or other small volcano	Pleistocene	low to negligible
Cinder Mountain	BC	56.565	-130.647	cinder cone or other small volcano	Holocene	low to negligible
Cocoa Crater	BC	57.656	-130.708	cinder cone or other small volcano	Holocene	low to negligible
Coffee Crater	BC	57.637	-130.670	cinder cone or other small volcano	Holocene	low to negligible
Cone Glacier	BC	56.559	-130.665	cinder cone or other small volcano	Holocene	low to negligible
Cottonwood Peak	BC	59.377	-130.233	cinder cone or other small volcano	Pleistocene	low to negligible
Cracker Creek	BC	59.699	-133.317	cinder cone or other small volcano	Holocene	low to negligible
Craven Lake	BC	56.913	-129.369	cinder cone or other small volcano	Pleistocene	low to negligible
Crow Lagoon source	BC	54.700	-130.230	cinder cone or other small volcano	Holocene	low to negligible
Crows Bar	BC	52.008	-123.675	lava flow(s)	Pleistocene	low to negligible

volcano	*state or province	latitude (degrees)	longitude (degrees)	volcano type	age of most recent activity	ash hazard rank
Dark Mountain	BC	58.636	-129.439	cinder cone or other small volcano	Pleistocene	moderate
Dark Mountain North	BC	58.510	-129.630	cinder cone or other small volcano	Pleistocene	low to negligible
Dark Mountain South	BC	58.570	-129.490	cinder cone or other small volcano	Pleistocene	low to negligible
Dark Mountain West	BC	58.630	-129.490	cinder cone or other small volcano	Pleistocene	low to negligible
Dog Creek	BC	51.587	-122.258	lava flow(s)	Pleistocene	low to negligible
Dome Mountain	BC	58.456	-129.637	cinder cone or other small volcano	Pleistocene	low to negligible
Dragon Cone/ Dragon Head Cone	BC	52.258	-120.022	cinder cone or other small volcano	Holocene	low to negligible
Dufferin Island	BC	52.200	-128.333	cinder cone or other small volcano	Holocene	low to negligible
Eanastick Meadow	BC	49.799	-122.929	cinder cone or other small volcano	Pleistocene	low to negligible
Elaho Alpine Volcanics	BC	50.419	-123.465	cinder cone or other small volcano	Pleistocene	low to negligible
Elaho Side Valley	BC	50.494	-123.507	cinder cone or other small volcano	Pleistocene	low to negligible
Elaho Valley 1	BC	50.351	-123.587	cinder cone or other small volcano	Pleistocene	low to negligible
Elaho Valley 2	BC	50.409	-123.576	cinder cone or other small volcano	Pleistocene	low to negligible
Elaho Valley 3	BC	50.431	-123.571	cinder cone or other small volcano	Pleistocene	low to negligible
Elaho Valley 4	BC	50.463	-123.573	cinder cone or other small volcano	Pleistocene	low to negligible
Elaho-Meager East	BC	50.545	-123.534	cinder cone or other small volcano	Pleistocene	low to negligible
Elaho-Meager West	BC	50.545	-123.557	cinder cone or other small volcano	Pleistocene	low to negligible
Ember Ridge N	BC	50.077	-123.239	cinder cone or other small volcano	Holocene	low to negligible
Ember Ridge NE	BC	50.072	-123.215	cinder cone or other small volcano	Holocene	low to negligible
Ember Ridge NW	BC	50.076	-123.256	cinder cone or other small volcano	Holocene	low to negligible
Ember Ridge SE	BC	50.046	-123.222	cinder cone or other small volcano	Holocene	low to negligible
Ember Ridge SW	BC	50.046	-123.252	cinder cone or other small volcano	Holocene	low to negligible
Ember Ridge W	BC	50.067	-123.261	cinder cone or other small volcano	Holocene	low to negligible
Enid Creek Cone	BC	58.382	-129.524	cinder cone or other small volcano	Pleistocene	low to negligible
Eve Cone	BC	57.813	-130.676	cinder cone or other small volcano	Holocene	low to negligible
Fiftytwo Ridge	BC	51.924	-119.891	cinder cone or other small volcano	Pleistocene	low to negligible
Fingal Island	BC	52.096	-128.446	cinder cone or other small volcano	Holocene	low to negligible
Flatiron	BC	51.878	-120.047	lava flow(s)	Pleistocene	low to negligible
Flourmill cones	BC	52.056	-120.317	cinder cone or other small volcano	Holocene	low to negligible
Gabrielse Cone	BC	59.442	-130.378	cinder cone or other small volcano	Holocene	low to negligible
Gage Hill/ Gauge Hill (spelling?)	BC	52.069	-120.018	cinder cone or other small volcano	Pleistocene	low to negligible
Glacier Dome	BC	57.731	-130.620	cinder cone or other small volcano	Pleistocene	low to negligible
Glacier Pikes	BC	49.879	-122.979	cinder cone or other small volcano	Pleistocene	low to negligible
Grain Creek Cone	BC	52.623	-121.148	cinder cone or other small volcano	Pleistocene	low to negligible
Grizzly Butte Vent	BC	59.084	-130.923	cinder cone or other small volcano	Pleistocene	low to negligible
Hanceville	BC	51.954	-123.138	lava flow(s)	Pleistocene	low to negligible
Heart Peaks 1	BC	58.621	-131.984	cinder cone or other small volcano	Pleistocene	moderate
Heart Peaks 10	BC	58.566	-131.952	cinder cone or other small volcano	Pleistocene	low to negligible
Heart Peaks 11	BC	58.576	-131.919	cinder cone or other small volcano	Pleistocene	low to negligible
Heart Peaks 12	BC	58.599	-131.945	cinder cone or other small volcano	Pleistocene	low to negligible
Heart Peaks 2	BC	58.608	-131.998	cinder cone or other small volcano	Pleistocene	low to negligible
Heart Peaks 3	BC	58.606	-132.014	cinder cone or other small volcano	Pleistocene	low to negligible
Heart Peaks 4	BC	58.608	-132.058	cinder cone or other small volcano	Pleistocene	low to negligible

volcano	*state or province	latitude (degrees)	longitude (degrees)	volcano type	age of most recent activity	ash hazard rank
Heart Peaks 5	BC	58.584	-132.010	cinder cone or other small volcano	Pleistocene	low to negligible
Heart Peaks 6	BC	58.587	-131.997	cinder cone or other small volcano	Pleistocene	low to negligible
Heart Peaks 7	BC	58.553	-132.033	cinder cone or other small volcano	Pleistocene	low to negligible
Heart Peaks 8	BC	58.549	-132.001	cinder cone or other small volcano	Pleistocene	low to negligible
Heart Peaks 9	BC	58.559	-131.961	cinder cone or other small volcano	Pleistocene	low to negligible
Helmet Peak	BC	52.356	-128.366	cinder cone or other small volcano	Holocene	low to negligible
Hoan Creek	BC	55.345	-129.296	cinder cone or other small volcano	Pleistocene	low to negligible
Hoodoo Mountain	BC	56.772	-131.296	stratovolcano, caldera, or dome(s)	Holocene	high
Hyalo Ridge	BC	52.121	-120.356	cinder cone or other small volcano	Pleistocene	low to negligible
Ice Peak	BC	57.716	-130.636	cinder cone or other small volcano	Pleistocene	low to negligible
Icefall Cone	BC	57.724	-130.598	cinder cone or other small volcano	Pleistocene	low to negligible
Icefield Ridge	BC	57.204	-129.376	cinder cone or other small volcano	Pleistocene	low to negligible
Ida Ridge	BC	51.799	-119.939	cinder cone or other small volcano	Pleistocene	low to negligible
Ishkloo Cone	BC	52.671	-121.178	cinder cone or other small volcano	Pleistocene	low to negligible
Iskut River Cone	BC	56.707	-130.606	cinder cone or other small volcano	Holocene	low to negligible
Isspah Butte/Metah Mountain	BC	59.100	-131.317	cinder cone or other small volcano	Pleistocene	low to negligible
Itcha 1	BC	52.535	-124.799	cinder cone or other small volcano	Pleistocene	low to negligible
Itcha 10	BC	52.531	-124.716	cinder cone or other small volcano	Holocene	low to negligible
Itcha 11	BC	52.541	-124.781	cinder cone or other small volcano	Pleistocene	low to negligible
Itcha 12	BC	52.636	-124.695	cinder cone or other small volcano	Holocene	low to negligible
Itcha 13	BC	52.598	-124.806	cinder cone or other small volcano	Holocene	low to negligible
Itcha 14	BC	52.576	-124.488	cinder cone or other small volcano	Holocene	low to negligible
Itcha 15	BC	52.734	-124.564	cinder cone or other small volcano	Holocene	low to negligible
Itcha 16	BC	52.583	-124.859	cinder cone or other small volcano	Holocene	low to negligible
Itcha 17	BC	52.741	-124.983	cinder cone or other small volcano	Holocene	low to negligible
Itcha 18	BC	52.703	-124.956	cinder cone or other small volcano	Holocene	low to negligible
Itcha 19	BC	52.510	-124.702	cinder cone or other small volcano	Holocene	low to negligible
Itcha 2	BC	52.789	-124.424	cinder cone or other small volcano	Pleistocene	low to negligible
Itcha 4	BC	52.823	-124.563	cinder cone or other small volcano	Pleistocene	low to negligible
Itcha 5	BC	52.820	-124.746	cinder cone or other small volcano	Pleistocene	low to negligible
Itcha 6	BC	52.803	-124.842	cinder cone or other small volcano	Pleistocene	low to negligible
Itcha 7	BC	52.641	-124.444	cinder cone or other small volcano	Holocene	low to negligible
Itcha 8	BC	52.610	-124.582	cinder cone or other small volcano	Pleistocene	low to negligible
Itcha 9	BC	52.493	-124.829	cinder cone or other small volcano	Pleistocene	low to negligible
Itcha Mountain	BC	52.718	-124.829	shield volcano	Pleistocene	low to negligible
Iverson Creek	BC	59.499	-130.289	cinder cone or other small volcano	Pleistocene	low to negligible
Iverson Creek West	BC	59.569	-130.102	cinder cone or other small volcano	Pleistocene	low to negligible
Jack's Jump	BC	52.125	-120.057	cinder cone or other small volcano	Pleistocene	low to negligible
Jacques Lake	BC	52.474	-121.162	cinder cone or other small volcano	Pleistocene	low to negligible
Kana Cone	BC	57.901	-130.626	cinder cone or other small volcano	Holocene	low to negligible
Kawdy Mountain	BC	58.881	-131.235	cinder cone or other small volcano	Pleistocene	low to negligible
Kawdy Mountain South	BC	58.863	-131.150	cinder cone or other small volcano	Pleistocene	low to negligible
Keda Cone	BC	57.607	-130.686	cinder cone or other small volcano	Holocene	low to negligible
Kelowna	BC	49.950	-119.650	lava flow(s)	Pleistocene	low to negligible
King Creek	BC	56.492	-130.659	cinder cone or other small volcano	Pleistocene	low to negligible
Kitasu Hill	BC	52.498	-128.723	cinder cone or other small volcano	Holocene	low to negligible

volcano	*state or province	latitude (degrees)	longitude (degrees)	volcano type	age of most recent activity	ash hazard rank
Klastline - Buckley Lake	BC	57.861	-130.758	cinder cone or other small volcano	Pleistocene	low to negligible
Klastline cone	BC	57.789	-130.517	cinder cone or other small volcano	Pleistocene	low to negligible
Klastline Middle	BC	57.868	-130.605	cinder cone or other small volcano	Pleistocene	low to negligible
Klinkit Creek Peak	BC	59.469	-131.212	cinder cone or other small volcano	Pleistocene	low to negligible
Klinkit Lake Peak	BC	59.483	-131.000	cinder cone or other small volcano	Pleistocene	low to negligible
Kostal Cone	BC	52.189	-119.939	cinder cone or other small volcano	Holocene	low to negligible
Lambly Creek	BC	49.935	-119.529	lava flow(s)	Pleistocene	low to negligible
Lava Fork	BC	56.419	-130.768	cinder cone or other small volcano	Holocene	low to negligible
Leon Creek	BC	50.969	-121.926	lava flow(s)	Pleistocene	low to negligible
Level Mountain North	BC	58.463	-131.450	cinder cone or other small volcano	Pleistocene	moderate
Level Mountain SE	BC	58.386	-131.297	cinder cone or other small volcano	Pleistocene	low to negligible
Level Mountain SW	BC	58.371	-131.473	cinder cone or other small volcano	Pleistocene	low to negligible
Little Bear Mountain	BC	56.800	-131.300	cinder cone or other small volcano	Pleistocene	low to negligible
Little Eagle Peak	BC	58.520	-129.708	cinder cone or other small volcano	Pleistocene	low to negligible
Little Ring Mountain	BC	50.280	-123.315	cinder cone or other small volcano	Pleistocene	low to negligible
Llangorse Mountain #1	BC	59.368	-132.784	cinder cone or other small volcano	Pleistocene	low to negligible
Logan Ridge Volcanic Centre	BC	50.813	-123.408	cinder cone or other small volcano	Pleistocene	low to negligible
Logger's Lake Volcano	BC	50.063	-123.039	cinder cone or other small volcano	Pleistocene	low to negligible
Machmel River	BC	51.542	-126.330	cinder cone or other small volcano	Holocene	low to negligible
Mathews Tuya	BC	59.196	-130.436	cinder cone or other small volcano	Pleistocene	low to negligible
McLeod Hill	BC	52.015	-120.009	cinder cone or other small volcano	Pleistocene	low to negligible
Meehaz Mountain	BC	59.003	-131.451	cinder cone or other small volcano	Pleistocene	low to negligible
Mess Lake # 2	BC	57.456	-130.757	cinder cone or other small volcano	Holocene	low to negligible
Mess Lake # 3	BC	57.450	-130.798	cinder cone or other small volcano	Holocene	low to negligible
Mess Lake #1	BC	57.492	-130.733	cinder cone or other small volcano	Holocene	low to negligible
Meszah Peak	BC	58.479	-131.437	cinder cone or other small volcano	Pleistocene	low to negligible
Metahag Creek NE	BC	58.923	-131.097	cinder cone or other small volcano	Pleistocene	low to negligible
Metahag Creek NW	BC	58.976	-131.144	cinder cone or other small volcano	Pleistocene	low to negligible
Miszezula Lake	BC	49.814	-120.536	lava flow(s)	Pleistocene	low to negligible
Monmouth Creek	BC	49.693	-123.191	cinder cone or other small volcano	Pleistocene	moderate
Moraine Cone	BC	57.768	-130.613	cinder cone or other small volcano	Holocene	low to negligible
Mosquito Mound	BC	52.020	-120.183	cinder cone or other small volcano	Pleistocene	low to negligible
Mount Boucherie	BC	49.856	-119.571	lava flow(s)	Pleistocene	low to negligible
Mount Brew East	BC	50.037	-123.179	cinder cone or other small volcano	Pleistocene	low to negligible
Mount Brew West	BC	50.039	-123.206	cinder cone or other small volcano	Pleistocene	low to negligible
Mount Cayley	BC	50.120	-123.289	stratovolcano, caldera, or dome(s)	Pleistocene	high
Mount Downton	BC	52.706	-124.853	cinder cone or other small volcano	Pleistocene	low to negligible
Mount Edziza	BC	57.716	-130.635	stratovolcano, caldera, or dome(s)	Holocene	high
Mount Fee	BC	50.084	-123.245	stratovolcano, caldera, or dome(s)	Pleistocene	moderate
Mount Garibaldi	BC	49.851	-123.005	stratovolcano, caldera, or dome(s)	Pleistocene	high
Mount Hoadley	BC	55.331	-128.780	cinder cone or other small volcano	Pleistocene	low to negligible
Mount Josephine	BC	59.065	-130.703	cinder cone or other small volcano	Pleistocene	low to negligible
Mount Meager	BC	50.632	-123.504	stratovolcano, caldera, or dome(s)	Pleistocene	high

volcano	*state or province	latitude (degrees)	longitude (degrees)	volcano type	age of most recent activity	ash hazard rank
Mount Price/Clinker Peak	BC	49.918	-123.036	cinder cone or other small volcano	Holocene	low to negligible
Mud Lake Flow	BC	50.805	-123.379	cinder cone or other small volcano	Pleistocene	low to negligible
Nahta Cone	BC	57.308	-130.819	cinder cone or other small volcano	Holocene	low to negligible
Nanook Dome	BC	57.718	-130.618	cinder cone or other small volcano	Pleistocene	low to negligible
Nazko Cone	BC	52.928	-123.735	cinder cone or other small volcano	Holocene	low to negligible
Nichols Valley Flows	BC	50.951	-123.377	lava flow(s)	Pleistocene	low to negligible
Nicola (Chester)	BC	50.510	-120.699	lava flow(s)	Pleistocene	low to negligible
Nome Lake South	BC	59.544	-130.882	cinder cone or other small volcano	Pleistocene	low to negligible
Northwest Volcanic Remnant	BC	50.810	-123.451	cinder cone or other small volcano	Pleistocene	low to negligible
Nuthinaw Mountain	BC	58.790	-131.063	cinder cone or other small volcano	Pleistocene	low to negligible
Ochre Mountain Flow	BC	50.798	-123.365	cinder cone or other small volcano	Holocene	low to negligible
Opal Cone	BC	49.824	-122.976	cinder cone or other small volcano	Holocene	low to negligible
Outcast Hill	BC	57.390	-130.774	cinder cone or other small volcano	Pleistocene	low to negligible
Owl Creek North	BC	56.881	-129.701	cinder cone or other small volcano	Pleistocene	low to negligible
Owl Creek South	BC	56.854	-129.690	cinder cone or other small volcano	Pleistocene	low to negligible
Pali Dome East	BC	50.136	-123.269	cinder cone or other small volcano	Pleistocene	low to negligible
Pali Dome West	BC	50.137	-123.310	cinder cone or other small volcano	Pleistocene	low to negligible
Peak 1924	BC	59.034	-130.373	cinder cone or other small volcano	Pleistocene	low to negligible
Peak 2050	BC	59.401	-130.189	cinder cone or other small volcano	Pleistocene	low to negligible
Pharaoh Dome	BC	57.650	-130.600	cinder cone or other small volcano	Pleistocene	low to negligible
Pillow Creek	BC	52.021	-119.841	cinder cone or other small volcano	Pleistocene	low to negligible
Pillow Ridge	BC	57.755	-130.654	cinder cone or other small volcano	Pleistocene	low to negligible
Pointed Stick Cone	BC	52.236	-120.085	cinder cone or other small volcano	Holocene	low to negligible
Prentice Gulch	BC	51.632	-122.355	lava flow(s)	Pleistocene	low to negligible
Price Island	BC	52.442	-128.682	cinder cone or other small volcano	Holocene	low to negligible
Pyramid Mountain	BC	51.991	-120.105	cinder cone or other small volcano	Pleistocene	low to negligible
Quesnel Lake cone	BC	52.649	-120.988	cinder cone or other small volcano	Pleistocene	low to negligible
Quilchena Creek	BC	50.122	-120.509	lava flow(s)	Pleistocene	low to negligible
Rancheria River North	BC	59.716	-130.381	cinder cone or other small volcano	Pleistocene	low to negligible
Rancheria River South	BC	59.720	-130.178	cinder cone or other small volcano	Pleistocene	low to negligible
Ray Mountain	BC	52.250	-120.117	cinder cone or other small volcano	Pleistocene	low to negligible
Ridge Cone	BC	57.678	-130.626	cinder cone or other small volcano	Holocene	low to negligible
Ring Mountain	BC	50.222	-123.304	cinder cone or other small volcano	Pleistocene	low to negligible
Rochester Creek Northeast-North	BC	56.876	-129.507	cinder cone or other small volcano	Pleistocene	low to negligible
Rochester Creek Northeast-South	BC	56.859	-129.496	cinder cone or other small volcano	Pleistocene	low to negligible
Rochester Creek Southeast	BC	56.822	-129.549	cinder cone or other small volcano	Pleistocene	low to negligible
Rochester Creek Southwest	BC	56.822	-129.545	cinder cone or other small volcano	Pleistocene	low to negligible
Round Mountain	BC	49.765	-123.005	cinder cone or other small volcano	Pleistocene	low to negligible
Ruby Creek	BC	59.650	-133.351	lava flow(s)	Pleistocene	low to negligible
Ruby Mountain	BC	59.693	-133.374	cinder cone or other small volcano	Pleistocene	low to negligible

volcano	*state or province	latitude (degrees)	longitude (degrees)	volcano type	age of most recent activity	ash hazard rank
Salal Glacier Volcanic Centre	BC	50.784	-123.380	cinder cone or other small volcano	Holocene	low to negligible
Satah 1	BC	52.480	-124.696	cinder cone or other small volcano	Pleistocene	low to negligible
Satah 2	BC	52.476	-124.688	cinder cone or other small volcano	Pleistocene	low to negligible
Satah 3	BC	52.473	-124.676	cinder cone or other small volcano	Pleistocene	low to negligible
Satah 4	BC	52.441	-124.710	cinder cone or other small volcano	Pleistocene	low to negligible
Second Canyon Cone	BC	56.409	-130.720	cinder cone or other small volcano	Holocene	low to negligible
Sham Hill	BC	50.905	-123.508	cinder cone or other small volcano	Pleistocene	low to negligible
Sheep Track Bench	BC	51.784	-119.974	cinder cone or other small volcano	Pleistocene	low to negligible
Sheep Track Pumice	BC	57.647	-130.670	cinder cone or other small volcano	Holocene	low to negligible
Sidas Cone	BC	57.859	-130.628	cinder cone or other small volcano	Holocene	low to negligible
Silverthrone Caldera	BC	51.458	-126.083	stratovolcano, caldera, or dome(s)	Pleistocene	high
Sixty Mile	BC	64.050	-140.467	cinder cone or other small volcano	Miocene	low to negligible
Slag Hill	BC	50.190	-123.307	cinder cone or other small volcano	Pleistocene	low to negligible
Slag Hill Tuya	BC	50.203	-123.280	cinder cone or other small volcano	Pleistocene	low to negligible
Sleet Cone	BC	57.784	-130.553	cinder cone or other small volcano	Pleistocene	low to negligible
Snippaker Creek	BC	56.625	-130.872	cinder cone or other small volcano	Holocene	low to negligible
Snowshoe Lava Field 11	BC	57.618	-130.662	cinder cone or other small volcano	Holocene	low to negligible
Snowshoe Lava Field 2	BC	57.689	-130.662	cinder cone or other small volcano	Holocene	low to negligible
Snowshoe Lava Field 3	BC	57.638	-130.661	cinder cone or other small volcano	Holocene	low to negligible
Snowshoe Lava Field 4	BC	57.656	-130.690	cinder cone or other small volcano	Holocene	low to negligible
Snowshoe Lava Field 5	BC	57.646	-130.689	cinder cone or other small volcano	Holocene	low to negligible
Snowshoe Lava Field 6	BC	57.641	-130.699	cinder cone or other small volcano	Holocene	low to negligible
Snowshoe Lava Field 8	BC	57.625	-130.633	cinder cone or other small volcano	Holocene	low to negligible
Source Hill	BC	57.287	-130.813	cinder cone or other small volcano	Pleistocene	low to negligible
Southern Tuya	BC	59.206	-130.655	cinder cone or other small volcano	Pleistocene	low to negligible
Spanish Bonk	BC	52.137	-120.366	cinder cone or other small volcano	Pleistocene	low to negligible
Spanish Lake Centre	BC	52.068	-120.308	cinder cone or other small volcano	Holocene	low to negligible
Spanish Mump	BC	52.166	-120.336	cinder cone or other small volcano	Pleistocene	low to negligible
Sphinx Dome	BC	57.750	-130.567	cinder cone or other small volcano	Pleistocene	low to negligible
Sphinx Moraine	BC	49.929	-122.981	cinder cone or other small volcano	Pleistocene	low to negligible
Squamish Headwaters volcanic centre	BC	50.358	-123.390	cinder cone or other small volcano	Pleistocene	low to negligible
Storm Cone	BC	57.773	-130.639	cinder cone or other small volcano	Pleistocene	low to negligible
Swinton Creek	BC	58.523	-129.813	cinder cone or other small volcano	Pleistocene	low to negligible
Tadekho Hill	BC	57.354	-130.778	cinder cone or other small volcano	Pleistocene	low to negligible
Tanzilla Butte	BC	58.395	-129.856	cinder cone or other small volcano	Pleistocene	low to negligible
Tennena Cone	BC	57.679	-130.662	cinder cone or other small volcano	Holocene	low to negligible
Thaddeus Lake	BC	51.929	-122.822	lava flow(s)	Pleistocene	low to negligible

volcano	*state or province	latitude (degrees)	longitude (degrees)	volcano type	age of most recent activity	ash hazard rank
Thaw Hill	BC	57.275	-130.713	cinder cone or other small volcano	Pleistocene	low to negligible
The Big End Table	BC	49.881	-122.996	cinder cone or other small volcano	Pleistocene	low to negligible
The Black Hole	BC	50.397	-123.398	cinder cone or other small volcano	Pleistocene	low to negligible
The Gargoyles	BC	49.806	-122.998	cinder cone or other small volcano	Pleistocene	low to negligible
The Little End Table	BC	49.892	-123.006	cinder cone or other small volcano	Pleistocene	low to negligible
The Neck	BC	57.660	-130.590	cinder cone or other small volcano	Pleistocene	low to negligible
The Pyramid	BC	57.745	-130.560	cinder cone or other small volcano	Pleistocene	low to negligible
The Saucer	BC	57.630	-130.626	cinder cone or other small volcano	Holocene	low to negligible
The Table	BC	49.895	-123.015	cinder cone or other small volcano	Pleistocene	low to negligible
The Thumb	BC	56.163	-126.744	cinder cone or other small volcano	Pleistocene	low to negligible
The Thumb # 1	BC	56.112	-126.608	cinder cone or other small volcano	Pleistocene	low to negligible
The Thumb # 2	BC	56.183	-126.717	cinder cone or other small volcano	Pleistocene	low to negligible
The Thumb # 3	BC	56.298	-126.652	cinder cone or other small volcano	Pleistocene	low to negligible
The Thumb # 4	BC	56.296	-126.616	cinder cone or other small volcano	Pleistocene	low to negligible
The Thumb # 5	BC	56.295	-126.607	cinder cone or other small volcano	Pleistocene	low to negligible
The Thumb # 6	BC	56.290	-126.634	cinder cone or other small volcano	Pleistocene	low to negligible
Tom Mackay Creek	BC	56.707	-130.566	cinder cone or other small volcano	Pleistocene	low to negligible
Toozaza Peak	BC	59.508	-130.349	cinder cone or other small volcano	Pleistocene	low to negligible
Triangle Dome	BC	57.720	-130.650	cinder cone or other small volcano	Pleistocene	low to negligible
Tricouni Southeast Flow	BC	49.992	-123.219	cinder cone or other small volcano	Pleistocene	moderate
Tricouni Southeast Knob	BC	49.972	-123.175	cinder cone or other small volcano	Pleistocene	low to negligible
Tricouni SW	BC	49.990	-123.231	cinder cone or other small volcano	Holocene	low to negligible
Triplex Cone Centre	BC	57.798	-130.633	cinder cone or other small volcano	Holocene	low to negligible
Triplex Cone Northwest	BC	57.806	-130.652	cinder cone or other small volcano	Holocene	low to negligible
Triplex Cone Southeast	BC	57.794	-130.621	cinder cone or other small volcano	Holocene	low to negligible
Trudel Creek	BC	51.385	-126.225	cinder cone or other small volcano	Holocene	low to negligible
Tseax Cone	BC	55.111	-128.899	cinder cone or other small volcano	Holocene	low to negligible
Tsekone Ridge	BC	57.698	-130.698	cinder cone or other small volcano	Pleistocene	low to negligible
Tuber Hill	BC	50.910	-123.458	cinder cone or other small volcano	Pleistocene	low to negligible
Tuber Hill - East	BC	50.949	-123.402	cinder cone or other small volcano	Holocene	low to negligible
Tumeka Lake	BC	57.214	-129.473	cinder cone or other small volcano	Pleistocene	low to negligible
Tutsingale Mountain	BC	58.781	-130.878	cinder cone or other small volcano	Pleistocene	low to negligible
Tuya #1	BC	59.319	-130.234	cinder cone or other small volcano	Pleistocene	low to negligible
Tuya Butte	BC	59.133	-130.568	cinder cone or other small volcano	Pleistocene	low to negligible
Twin Cone	BC	57.809	-130.532	cinder cone or other small volcano	Pleistocene	low to negligible
Unnamed 3 miles S of Ash Mtn	BC	59.230	-130.514	cinder cone or other small volcano	Pleistocene	low to negligible
Upper Rochester Creek	BC	56.823	-129.369	cinder cone or other small volcano	Pleistocene	low to negligible
Volcanic Creek Cone	BC	59.758	-133.378	cinder cone or other small volcano	Holocene	low to negligible
Volcano Vent	BC	59.124	-130.923	cinder cone or other small volcano	Pleistocene	low to negligible
Walkout Creek	BC	57.576	-130.750	cinder cone or other small volcano	Holocene	low to negligible
Watts Point	BC	49.650	-123.217	cinder cone or other small volcano	Pleistocene	moderate

volcano	*state or province	latitude (degrees)	longitude (degrees)	volcano type	age of most recent activity	ash hazard rank
West Kettle River	BC	49.091	-119.071	lava flow(s)	Pleistocene	low to negligible
West Vent	BC	59.126	-131.010	cinder cone or other small volcano	Pleistocene	low to negligible
Wetalth Ridge	BC	57.313	-130.783	cinder cone or other small volcano	Pleistocene	low to negligible
White Creek Cone	BC	52.549	-124.852	cinder cone or other small volcano	Pleistocene	low to negligible
White Horse Bluff	BC	51.889	-120.117	lava flow(s)	Pleistocene	low to negligible
Whitetop Mountain	BC	52.649	-124.559	cinder cone or other small volcano	Pleistocene	low to negligible
Williams Cone	BC	57.781	-130.600	cinder cone or other small volcano	Holocene	low to negligible
Alligator Lake North Cone	YT	60.414	-135.415	cinder cone or other small volcano	Holocene	low to negligible
Alligator Lake South Cone	YT	60.396	-135.426	cinder cone or other small volcano	Holocene	low to negligible
Big Creek	YT	60.160	-129.708	cinder cone or other small volcano	Pleistocene	low to negligible
Black Creek Flow	YT	62.812	-137.563	lava flow(s)	Pleistocene	low to negligible
Fort Selkirk Vent	YT	62.773	-137.417	lava flow(s)	Pleistocene	low to negligible
Holbrook Creek	YT	62.812	-138.109	lava flow(s)	Pleistocene	low to negligible
Ibex Mountain	YT	60.547	-135.527	cinder cone or other small volcano	Pleistocene	low to negligible
Miles Canyon	YT	60.400	-135.000	lava flow(s)	Pleistocene	low to negligible
Ne Ch'e Ddhawa	YT	62.744	-137.276	cinder cone or other small volcano	Pleistocene	low to negligible
Rancheria River flows	YT	60.093	-130.641	lava flow(s)	Pleistocene	low to negligible
Volcano Mountain	YT	62.926	-137.380	cinder cone or other small volcano	Holocene	low to negligible
Watson Lake 1	YT	60.074	-128.826	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 10	YT	60.053	-128.835	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 11	YT	60.071	-128.746	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 2	YT	60.081	-128.913	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 3	YT	60.242	-129.124	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 4	YT	60.162	-129.688	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 5	YT	60.208	-129.146	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 6	YT	60.217	-129.150	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 7	YT	60.250	-128.833	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 8	YT	60.250	-129.617	cinder cone or other small volcano	Pleistocene	low to negligible
Watson Lake 9	YT	60.117	-130.283	cinder cone or other small volcano	Pleistocene	low to negligible
Wolverine Eruptive Centre	YT	62.674	-137.373	cinder cone or other small volcano	Pleistocene	low to negligible
Wolverine West	YT	62.716	-137.273	cinder cone or other small volcano	Pleistocene	low to negligible
Aniakchak	AK	56.906	-158.209	stratovolcano, caldera, or dome(s)	Holocene	high
Augustine	AK	59.363	-153.435	stratovolcano, caldera, or dome(s)	Holocene	high
Behm Canal-Rudyard Bay	AK	55.320	-131.051	cinder cone or other small volcano	Holocene	low to negligible
Black Peak	AK	56.551	-158.787	stratovolcano, caldera, or dome(s)	Holocene	high
Blue Mountain-Gas Rocks	AK	57.705	-156.847	stratovolcano, caldera, or dome(s)	Holocene	high
Bona-Churchill	AK	61.419	-141.715	stratovolcano, caldera, or dome(s)	Holocene	high
Capital Mountain	AK	62.424	-144.113	stratovolcano, caldera, or dome(s)	Pleistocene	low to negligible
Chiginagak	AK	57.133	-156.991	stratovolcano, caldera, or dome(s)	Holocene	high
Dana	AK	55.642	-161.216	stratovolcano, caldera, or dome(s)	Holocene	high
Drum	AK	62.116	-144.640	stratovolcano, caldera, or dome(s)	Pleistocene	moderate
Duncan Canal	AK	56.500	-133.102	cinder cone or other small volcano	Holocene	low to negligible
Dutton	AK	55.187	-162.274	stratovolcano, caldera, or dome(s)	Holocene	high
Edgecumbe	AK	57.051	-135.761	stratovolcano, caldera, or dome(s)	Holocene	high

volcano	*state or province	latitude (degrees)	longitude (degrees)	volcano type	age of most recent activity	ash hazard rank
Emmons Lake	AK	55.341	-162.073	stratovolcano, caldera, or dome(s)	Holocene	high
Fisher	AK	54.669	-164.352	stratovolcano, caldera, or dome(s)	Holocene	high
Gordon	AK	62.131	-143.088	cinder cone or other small volcano	Pleistocene	low to negligible
Griggs	AK	58.357	-155.104	stratovolcano, caldera, or dome(s)	Holocene	high
Hayes	AK	61.599	-152.420	stratovolcano, caldera, or dome(s)	Holocene	high
Iliamna	AK	60.032	-153.092	stratovolcano, caldera, or dome(s)	Holocene	moderate
Jarvis	AK	62.023	-143.620	stratovolcano, caldera, or dome(s)	Pleistocene	high
Kaguyak	AK	58.611	-154.025	stratovolcano, caldera, or dome(s)	Holocene	high
Katmai	AK	58.279	-154.953	stratovolcano, caldera, or dome(s)	Holocene	high
Kialagvik	AK	57.202	-156.747	stratovolcano, caldera, or dome(s)	Holocene	high
Mageik	AK	58.195	-155.254	stratovolcano, caldera, or dome(s)	Holocene	high
Martin	AK	58.169	-155.357	stratovolcano, caldera, or dome(s)	Holocene	high
Novarupta	AK	58.265	-155.159	stratovolcano, caldera, or dome(s)	Holocene	high
Prindle Volcano	AK	63.720	-141.622	cinder cone or other small volcano	Pleistocene	low to negligible
Redoubt	AK	60.485	-152.744	stratovolcano, caldera, or dome(s)	Holocene	high
Sanford	AK	62.213	-144.130	stratovolcano, caldera, or dome(s)	Pleistocene	moderate
Shishaldin	AK	54.755	-163.971	stratovolcano, caldera, or dome(s)	Holocene	high
Skookum Creek	AK	62.400	-143.132	stratovolcano, caldera, or dome(s)	Pleistocene	low to negligible
Spurr	AK	61.299	-152.254	stratovolcano, caldera, or dome(s)	Holocene	high
Tanada Peak	AK	62.302	-143.506	shield volcano	Pleistocene	low to negligible
Tlevak Strait - Suemez Island	AK	55.250	-133.302	volcanic field	Holocene	low to negligible
Trident	AK	58.234	-155.103	stratovolcano, caldera, or dome(s)	Holocene	high
Ugashik-Peulik	AK	57.750	-156.370	stratovolcano, caldera, or dome(s)	Holocene	high
Veniaminof	AK	56.198	-159.393	stratovolcano, caldera, or dome(s)	Holocene	high
Wrangell	AK	62.006	-144.019	shield volcano	Holocene	moderate
Crater Lake	OR	42.930	-122.120	stratovolcano, caldera, or dome(s)	Holocene	high
Hood	OR	45.374	-121.695	stratovolcano, caldera, or dome(s)	Holocene	high
Newberry	OR	43.722	-121.229	stratovolcano, caldera, or dome(s)	Holocene	high
South Sister	OR	44.103	-121.768	stratovolcano, caldera, or dome(s)	Holocene	high
Adams	WA	46.206	-121.490	stratovolcano, caldera, or dome(s)	Holocene	high
Baker	WA	48.777	-121.814	stratovolcano, caldera, or dome(s)	Holocene	high
Glacier Peak	WA	48.112	-121.113	stratovolcano, caldera, or dome(s)	Holocene	high
Rainier	WA	46.853	-121.760	stratovolcano, caldera, or dome(s)	Holocene	high
St. Helens	WA	46.200	-122.183	stratovolcano, caldera, or dome(s)	Holocene	high

*BC = British Columbia; YT = Yukon; AK = Alaska; OR = Oregon; WA = Washington

Appendix II.

Data sources for Holocene tephra compilation map for western Canada, Figure 2.

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