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The Vulnerability of Canada to Volcanic Hazards

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Abstract. Western Canada lies in a zone of active tectonics and volcanism, but the dispersed population has witnessed few eruptions due to the remoteness of the volcanoes and their low level of activity. This has created a false perception that Canada's volcanoes are extinct.

There are more than 200 potentially-active volcanoes in Canada, 49 of which have erupted in the past 10,000 years. They occur in five belts, with origins related to tectonic environment. The minimum annual probability of a Canadian volcanic eruption is approximately 1/200; for an effusive (lava) eruption the probability is about 1/220, and for a significant explosive eruption it is about 1/3333. In-progress studies show that there have been earthquakes associated with at least 9 of the youngest Canadian volcanoes since 1975. A scenario of an eruption of Mt. Cayley (50.1°N, 123.3°W) shows how western Canada is vulnerable to an eruption. The scenario is based on past activity in the Garibaldi volcanic belt and involves both explosive and effusive activity. The scenario impact is largely a result of the concentration of vulnerable infrastructure in valleys.

Canadian volcanoes are monitored only by a regional seismic network, that is capable of detecting a $M > 2$ event in all potentially-active areas. This level of monitoring is probably sufficient to alert scientists at or near eruption onset, but probably insufficient to allow a timely forecast of activity. Similarly the level of geological knowledge about the volcanoes is insufficient to create hazard maps. This will improve slightly in 2002 when additional monitoring is implemented in the Garibaldi volcanic belt. The eruption probabilities, possible impacts, monitoring limitations and knowledge gaps suggest that there is a need to increment the volcanic risk mitigation efforts.

Key words: volcano, eruption, earthquake, monitoring, hazard, vulnerability, Canada

1. Introduction

Canada has been spared the almost ceaseless volcanism of places such as Japan or Indonesia, but it has not escaped volcanic hazards. We are part of a line of subduction zones and transform faults referred to as the *Pacific Ring of Fire* (Figure 1). The different tectonic environments in western Canada have produced five young volcanic regions (Section 2.3, Figure 2), containing volcano types from stratovolcanoes and calderas to monogenetic cinder cones.

The number and diversity of young Canadian volcanoes contrasts dramatically with our level of knowledge regarding their origins, histories, current status and hazards. Major reasons for this are the large area, remoteness, and numbers of

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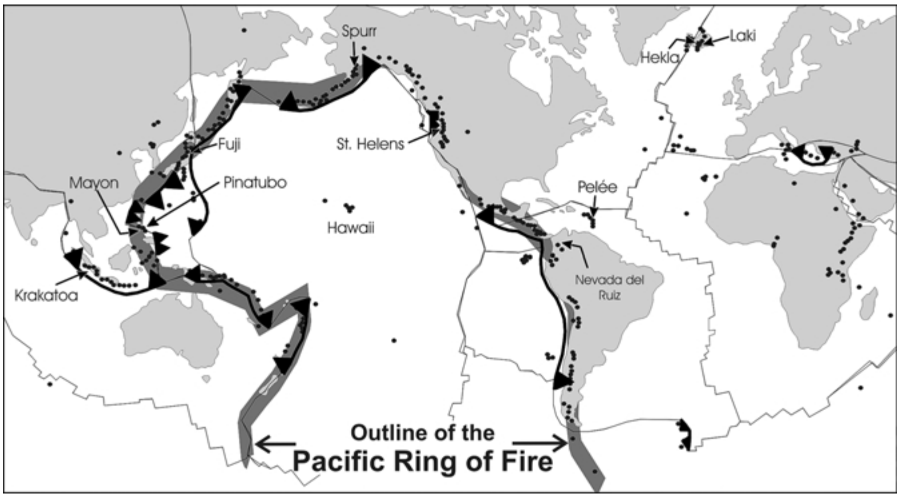

Figure 1. Plate tectonic framework for Canadian volcanoes, part of the Pacific Ring of Fire. Labelled volcanoes are locations of prominent historical eruptions; thin lines are divergent tectonic margins, heavy lines with teeth are subduction margins, the black dots are volcanoes, and the dark gray band indicates the Ring of Fire.

volcanoes to cover by a small group of workers. The Garibaldi belt volcanoes have received the most attention (Bye *et al.*, 2000; Green, 1990; Green *et al.*, 1988; Hickson *et al.*, 1999; Kelman *et al.*, 2001; Mathews, 1958; Stasiuk *et al.*, 1994) yet even these are inadequately understood. Mt. Edziza, a large volcanic complex which includes a caldera and which has produced more than 8 million years of nearly continuous volcanic activity, was the focus of geological work by Souther (1992), but has since received little attention. Other centres have been the focus of single regional studies.

The belief that a natural hazard is negligible is typical worldwide wherever it has not yet been experienced by a population, even in the face of scientific data to the contrary. In Canada, this lack of experience is a result of a short human history and the characteristically low frequency of volcanic activity. Over the last five decades researchers have accumulated enough information to show that the level of hazard from our volcanoes is deserving of increased attention. In this paper we discuss the distribution of volcanoes and their hazards in Canada, use an eruption simulation to show how western Canada is vulnerable to volcanic hazards, and discuss current needs to deal with the hazards.

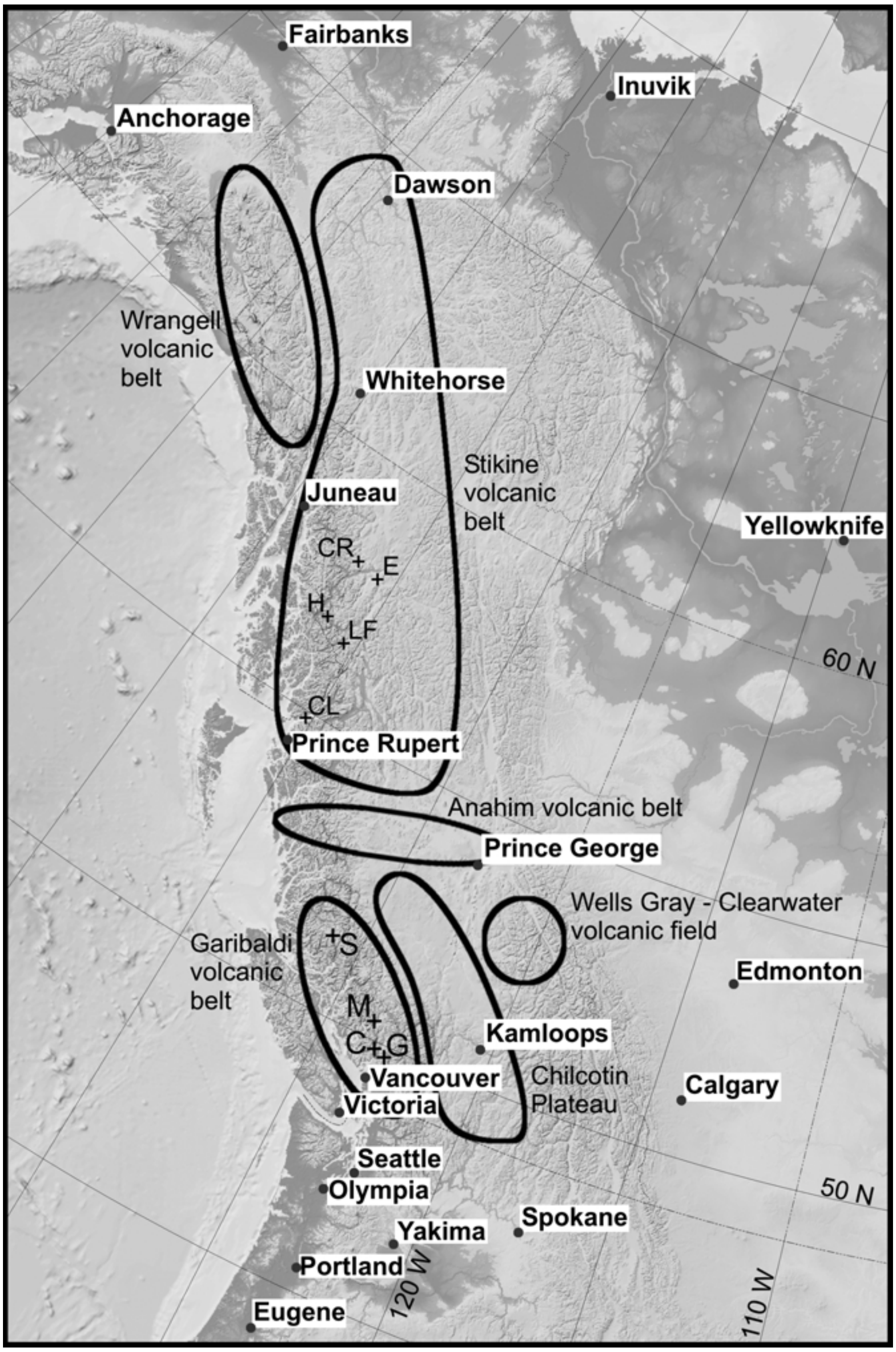

Figure 2. The 5 belts of young volcanoes in western Canada. Major cities are labelled. Only the volcanoes with associated seismicity in the past 15 years are shown ("+" symbols): G, Garibaldi; C, Cayley; M, Meager; S, Silverthrone, CL, Crow Lagoon; LF, Lava Fork; H, Hoodoo; E, Edziza; CR, Castle Rock.

2. Volcanic Hazards and Canada's Vulnerability

2.1. PHYSICAL BASIS FOR THE HAZARD

2.1.1. *Eruption Frequencies*

No volcanic disaster has been recorded in Canada, making it necessary to demonstrate that volcanic hazards are a societal concern. To determine if a hazard exists when it hasn't been experienced, one must infer or measure both the annual probability of occurrence of the hazardous process, and its likely future magnitude (intensity $\times$ area affected $\times$ duration). Note that earthquake magnitude (M) is different in meaning and method of calculation from the magnitude of an earthquake's hazard. If either the probability or the magnitude of a process is zero, there is no hazard; in all other cases the process should be given some consideration, especially if it may be deadly or destructive. For example, Cascadia subduction zone earthquakes of $M > 8$ occur infrequently (crudely 1 per 500 years) (Adams *et al.*, 2000). However, the magnitude of this hazard will be large, hence it influences the National Building Code of Canada, emergency response plans, and research priorities. In the case of a road over a drainage prone to frequent debris flows, the situation is worthy of at least small-scale research and mitigation efforts since there is a chance of fatality and a likelihood of road destruction. Conversely, ignoring these hazards would be irresponsible.

An assumption in estimating hazards is that natural phenomena, such as earthquakes of a particular size in a particular area, recur with a frequency which is statistically constant over long periods of time. For many phenomena, such as volcanoes, this assumption is based on monitoring experience and careful study and tabulation of past events. The assumption allows scientists to estimate hazard levels and make forecasts, and is rarely doubted when the phenomenon is experienced frequently. Someone who feels a few earthquakes each year probably would not doubt a forecast for a significant earthquake in the next six months. When the recurrence interval is longer than people's lives, and based on indirect evidence, forecasts are less plausible even though the concepts are identical.

Volcanic hazards in Canada can be split into those sourced from without, and those from within. The volcanoes of Alaska, Washington, and more distant locations present low-magnitude, high frequency hazards in Canada. Ash plumes from distant explosive eruptions drift across Canadian airspace numerous times each decade. Typically, by the time the plumes reach Canada, they are dilute and deposit vanishingly small amounts of ash, so they are hazardous mainly to aircraft (Section 2.2.1). Plans are in place to mitigate the risk (Section 3.1). Hazards resulting from the influence of large eruptions on climate (Rampino *et al.*, 1988) will not be discussed in detail due to their relative improbability.

To establish that the threat from domestic volcanoes is real requires using evidence from seismic and geologic records. Unfortunately there is insufficient geologic knowledge on Canadian volcanoes to make a detailed assessment. The reason for this is that most government geologic mapping in Canada is done for purposes of small-scale regional mapping (e.g., 1 : 250,000) whereas hazard mapping requires work at larger scale (> 1 : 25,000). In regional mapping, only prominent deposits or packages of deposits are mapped. Hazardous volcanic events may produce deposits only a few centimeters thick. In this paper prominent volcanic deposits produced over a known time interval are counted, resulting in minimum frequencies. These deposits can be split usefully into two categories allowing a relative magnitude to be crudely assigned: low magnitude, dominantly effusive (lava) eruptions, and high magnitude explosive (pyroclastic) eruptions. Both eruption types are destructive to any infrastructure or life on contact, but their ranges, intensities and durations are typically very different. Although the partition between relatively high and low magnitude events is conceptually useful, the real volcanic situation is more complex. For example many lava eruptions exhibit some explosive behaviour; some lava eruptions are so voluminous and long-lived that they are high-magnitude hazards; some explosive eruptions are so small and short-lived that they are low-magnitude; and small eruptions can produce secondary high-magnitude hazards.

An additional difficulty in calculating eruption frequencies is that, at the time of most of the mapping (pre-1990), radiometric dating methods were less developed. The results were particularly problematic for radiometric dates obtained on young rocks, that are most relevant to future eruptions.

Eruption frequencies based on reconnaissance or regional mapping and older dating methods are usually low by a factor of 2 to 10. A recent example comes from the Caribbean island of Dominica (Shepherd *et al.*, 2000) where reconnaissance studies pre-1990 indicated an eruption recurrence interval of about 10,000 years. Detailed hazard mapping, however, revealed previously undiscriminated deposits. These were dated using modern accelerator mass spectrometry methods and the recurrence interval was revised to 500–1000 years, a factor of 10 increase in the annual probability of eruption.

Canada's young volcanoes can be divided into five belts (Section 2.3, Figures 1 and 2), each of which displays numerically dominant types of eruptions. In addition their locations relative to developed areas vary; therefore it's useful to consider the hazards in terms of these belts. Table I shows the results for the 49 known eruptions in the region, within the last 10,000 years; 46 effusive and 3 explosive eruptions. The counted deposits are considered distinct eruptive episodes because their vent spacing is at least tens of kilometres. Even though the results are crude estimates, the minimum annual probabilities of eruption for western Canada and at least 4 of the volcanic belts (Stikine, Anahim, Wells Gray and Garibaldi) are greater than zero. Low-magnitude events (lava effusion) are most probable; given that these occur approximately every 200 years and the time since the last one is about 100 years, an eruption of this type within our lifetimes would not be surprising. This would most likely occur in a relatively remote area, but does not mean that the risk is negligible. Remote areas in western Canada are crossed by important networks of

Table I. Canadian volcanic eruption numbers and frequency for the holocene epoch

Belt	Holocene eruptions	Historic eruptions	Types[1]	Holocene average eruption frequency[2] (1/y)	Time since last eruption (YBP)
Garibaldi[3]	5	0		Total 1/2000	
			X, 2	X, 1/5000	X, 2350[8]
			E, 3	E, 1/3333	E, <10000
Chilcotin[4]	0	0	–	–	>10000
Wells Gray[5]	5	0	E, 5	E, 1/2000	<10000
Anahim[6]	5	0	E, 5	E, 1/2000	<10000
Stikine[7]	34	3		Total 1/290	
			X, 1	X, 1/10000	X, <10000
			E, 33	E, 1/300	E, 100[9]
Total	**49**	**3**		**Total 1/200**	
			X, 3	**X, 1/3333**	**X, 2350**
			E, 46	**E, 1/220**	**E, 100**

[1] X = dominantly explosive; E = dominantly effusive.
[2] Eruption frequency = number of eruptions/10,000 years.
[3] Mathews (1958), Hickson (1990), Souther and Yorath (1991).
[4] Souther and Yorath (1991).
[5] Hickson (1990).
[6] Souther (1992), Souther and Yorath (1991), Hickson (1990).
[7] Edwards and Russell (2001).
[8] Clague *et al.* (1995).
[9] Sutherland Brown (1969).

infrastructure linking communities, and are the source of economically-important natural resources. Both of these elements are vulnerable to volcanic hazards, especially large-magnitude secondary hazards that are probable in the region. The growth of communities and linking infrastructure means that the probability of impact is increasing with time.

2.1.2. *Historic Seismicity*

Volcanoes are one of the few hazards that typically exhibit clear precursor activity (Tilling, 1989). The most common precursors are shallow seismicity and ground surface deformation, commonly interpreted to result from magma movement or changing reservoir pressure. Many volcanoes go through multiple episodes of precursor activity years before erupting; these episodes are referred to as “periods of unrest”. The interpretation of precursor activity leads intuitively to the ideas that more restless volcanoes are most likely to erupt. This means that when a volcano begins to exhibit precursor activity, the annual probability of eruption increases and so does the level of hazard. A result of these ideas is that it is worthwhile to geophysically monitor volcanoes in order to forecast the hazards. In Canada the only monitoring is done by the regional seismic network, which was set-up primarily to address hazards from tectonic earthquakes, but also to provide a regional capability for detecting eruptions. It is probably not sufficiently sensitive to monitor the precursor activity in a way that would allow forecasts (Section 3). However, at least two possible volcano-seismic swarms have been detected in B.C.: to the east of the Wells Gray-Clearwater volcanic field (Rogers, 1981), and at the south end of the Stikine volcanic belt (Milne, 1956). In addition, basic results are available from a recently-initiated study of the Geological Survey of Canada (GSC) earthquake catalogue, which show that some seismicity has been detected near Canadian volcanoes. The counts of earthquakes are minima since most precursor-type microseisisms are likely to be smaller than the location magnitude threshold (Section 3), and unlocated but detected events are not catalogued in an easily accessible way. Nine volcanoes have had associated seismicity since 1985: Mt. Meager (17 events), Mt. Cayley (4), Garibaldi (3), Silverthrone (2), Wells Gray-Clearwater volcanic field (85), Crow Lagoon (4), Lava Fork (5), Mt. Hoodoo (8), Mt. Edziza (8) and Castle Rock (2). It is noteworthy that the seismic activity correlates with some of the most youthful volcanoes, and with long- lived centers with a history of significant explosive behaviour – including Edziza, Hoodoo, Cayley, Meager and Garibaldi. Beneath areas of monogenetic cinder cone activity, for example Lava Fork, Crow Lagoon and the Wells Gray-Clearwater field, the seismicity appears to be more dispersed. In a few cases earthquakes are clustered in time and space, suggestive of volcanic earthquake swarms. Although the existing data do not allow a clear conclusion (Section 3.1), these observations are further indications that some of Canada's volcanoes may be active, and that their associated hazards may be significant.

Besides volcanoes within Canada, there are significant inferred hazards from volcanoes just outside the border. In the south, in Washington state, Mt. Baker has shown activity in historic time (Gardner *et al.*, 1995). An explosive eruption there could send significant amounts of ash into B.C. and Alberta, and may send floods or mudflows into the Fraser River valley (Gardner *et al.*, 1995). To the north, in Alaska, Mt. Churchill has produced two large explosive eruptions in the past 2000 years (Lerbekmo *et al.*, 1975). Future activity would send more ash into Canada, and probably also floods and/or mudflows.

2.2. TYPES OF VOLCANIC HAZARDS

Volcanoes can produce many hazardous events, the type depending mainly on the magma composition. Basaltic eruptions tend to be dominated by effusive (lava) and weak explosive behaviour, and generally pose minimal hazards compared to explosive, high silica dacitic to rhyolitic eruptions. However, there are many exceptions to this rule. Eruptions and their secondary effects can be strongly influenced by environmental conditions and the eruption rate (mass/volumetric rate, or intens-

Table II. Volcanic explosivity index (VEI) of Mt. St. Helens and the deadliest eruptions since A.D. 1500 (modified from Tilling, 1989).

Eruption	Year	VEI	Estimated casualties
Pinatubo, Philippines	1991	6	450
Nevado del Ruiz, Columbia	1985	3	25 000
Mount St. Helens, USA	1980	5	57
Mount Katmai, USA	1912	6	0?
Mont Pelée, Martinique	1902	4	30 000
Krakatau, Indonesia	1883	6	36 000
Tambora, Indonesia	1815	7	92 000
Unzen, Japan	1792	3	15 000
Lakagigar (Laki), Iceland	1783	4	9 000
Kelut, Indonesia	1586	4	10 000

ity). In addition, volcano behaviour can change suddenly and significantly during an eruption.

The level of hazard depends on the style of the eruption (relevant to the area affected), the intensity, and the duration. Using these measures or proxies for them, eruption magnitude is calculated as a number from 0 to 8, called a Volcanic Explosivity Index (VEI) (Newhall and Self, 1982; Table II). For example, the eruption of Mt. St. Helens on May 18, 1980 expelled 1.4 km^3 of material and produced a plume up to 24 km high, corresponding to VEI 5. Eruptions with VEI 8 are analogous to great earthquakes ($M > 8$), and correspond to high-intensity explosive events which produce hundreds or thousands of cubic kilometres of magma. There is no direct relationship between the size of an eruption and the number of lives lost (Table II), but the economic loss sustained by a region is approximately proportional to the eruption size.

Only brief descriptions of the hazards relevant to western Canada are given below, including both primary volcanic hazards (produced directly by eruption processes) and the important secondary hazards. Table III lists these and additional hazards, and gives a ranking of their frequency of occurrence. More thorough discussions can be found in Blong (1984), Hoblitt *et al.* (1987), Tilling (1989), and Ewert and Swanson (1992).

2.2.1. *Airfall Tephra/Ballistic Projectiles*

Tephra is fragmented volcanic rock and accompanies nearly all explosive eruptions (Table III). It is a dominant hazard because it affects the largest areas. A wide range of particle sizes comprise tephra, from ash-sized (micrometres to millimetres) to

Table III. Volcanic-hazard summary (modified from Thorarinsson, 1979, and Blong, 1984.

Volcanic hazard	Frequency of adverse effect/damage/death distances (kilometres from volcanic vent)					
	<10	10–30	30-100	100–500	500–1000	>1000
	Short range		Mid range		Long range	Global
Seismic activity and ground deformation	C	C	VR			
Lava flows	F	C	VR			
Ballistic projectiles	C					
Tephra falls	VF	F	F	C	R	
Debris avalanches, edifice collapse, sector collapse	A	F	VR			
Pyroclastic flows, surges	A	F	R	VR		
Lahars, debris flows, and jokulhlaups	F	F	R	VR		
Tsunami	A	F	C	R	VR	
Atmospheric effects	C	C	R	VR	VR	
Acid rains and gases	F	F	R	R	VR	VR

A = Always; Very Frequent; F = Frequent; C = Common; R = Rare; VR = Very Rare.

block-sized (centimetres to metres). The eruption of gas- rich, high silica magmas (dacites and rhyolites) tend to produce the most explosive eruptions and the largest proportion of fine ash. When magma mixes with near-surface water or groundwater, it may lead to more explosive activity than in dry conditions and is called phreatomagmatic activity (Sheridan and Wohletz, 1981). In explosive eruptions producing large volumes of ash, as the fragmented material leaves the vent it entrains ambient air and rapidly heats it, causing a thermally buoyant plume (Wilson *et al.*, 1980). The plume rises into the atmosphere until it reaches air of the same density, and then spreads laterally and downwind while the cooled tephra settles. The resulting material forms a blanket that thins and fines away from the vent. The process of fragmenting magma causes electrical charging on ash and aerosols (Lane and Gilbert, 1992; Lane *et al.*, 1993), and frequently results in lightning (Sparks *et al.*, 1997, p. 338). Most of the gas in eruption columns is water vapour, that cools and may condense on the ash in the plume. Smaller amounts of other gases, especially sulphur dioxide, chlorine and fluorine, react with the water vapour to form acids which acidify the condensate. If the ambient air is humid, the air entrained into the plume adds to the condensing water. Wet, charged ash particles stick to each other, forming aggregates (Lane *et al.*, 1993). As a result, ash often falls as muddy, acidic droplets called accretionary lapilli. The dispersal of tephra is controlled by grainsize, density, wind and eruption column height (Carey and Sparks, 1986), and the height depends on the eruption rate (Wilson *et al.*, 1980). Tephra injected into the upper atmosphere can be carried downwind hundreds or even thousands of kilometres. Ash from the 2350 YBP eruption of Mt. Meager

(150 km north of Vancouver) was deposited as far as 800 km to the northwest, in Alberta (Nasmith *et al.*, 1967).

Ash can pollute water supplies, disrupt transportation, and collapse buildings, especially when it falls wet. Inhaled ash, although not toxic in the short term, can aggravate respiratory conditions such as asthma and bronchitis. Silicosis has been attributed to long term exposure to volcanic ash (Vollmer *et al.*, 1986). Thick accumulations of ash can damage plants, especially smaller crops. Livestock may die from ingesting large quantities of ash-coated vegetation (Baxter, 1992). Ash damages mechanical equipment by abrasion; and electrical equipment because it is abrasive, often electrically charged or electrically conductive (if wet), and a thermal insulator (causing overheating).

While suspended, ash can affect aircraft. Ash plumes appear similar to meteorological clouds, making them difficult to avoid during flight. Jet engines operate above magmatic temperatures, hence ingested ash melts clogs air intake vents and coats the turbines, causing engine failure. Ash also abrades the exterior of the aircraft, "frosting" cockpit windows and damaging navigation, communications and hydraulic systems. In 1982 a Boeing 747 jet flew into a plume from Galunggung volcano (Johnson and Casadevall, 1994). It was severely damaged and temporarily lost power in all four engines, but the pilots managed to restart the engines and make an emergency landing. Since then the number of encounters has been growing (Casadevall, 1992, 1993, 1994; Anonymous, 1993a, b).

Blocks or magma droplets too large or dense to be entrained in the plume are shot on approximately ballistic trajectories, and are called ballistic ejecta or volcanic bombs (Sparks *et al.*, 1997, pp. 386– 390). In significant explosive eruptions, ballistics may reach 3–5 km from the vent, depending on size, cross-wind strength, and whether the column is laterally-directed. Ballistics are extremely destructive to whatever they hit, and usually land hot enough to ignite vegetation or houses.

2.2.2. *Pyroclastic flows*

Pyroclastic flows are hot, dense avalanches of gas and rock particles with a broad range in size, but usually dominantly ash. The most common variety results from collapse of explosive eruption columns. They can also result from disintegration of the front of a lava flow or lava dome or laterally-directed explosive eruptions. Pyroclastic flows originating from column collapse or lateral blasts can have considerable momentum and speed (50–150 km/h), and may travel great distances. Very large eruptions have produced pyroclastic flows that extend 100 km from the volcano. During the 2350 YBP eruption of Mt. Meager, small pyroclastic flows extended down the Lillooet River a distance of 7 km (Stasiuk *et al.*, 1994). In general, pyroclastic flows are gravity-driven and hence controlled by topography, but highly mobile flows can overtop topographic barriers hundreds of metres high (Yokoyama, 1974). Pyroclastic flows deposit large volumes of unconsolidated material in valleys, leading to damming, flooding, outburst floods, debris flows and river aggradation. All pyroclastic flows are extremely destructive.

2.2.3. *Pyroclastic surges*

Pyroclastic surges are a special type of pyroclastic flow, which are more dilute, turbulent and mobile but still contain gas and rock debris. Their deposits are distinct from typical pyroclastic flows. They are generated by violent explosions, early in eruptions or near the vent. Speeds over 360 km/h have been measured (Moore, 1967; Fisher, 1979; Wilson and Head, 1981). Due to their lower density and greater speed, surges are better able to overtop topographic barriers and cross bodies of water than pyroclastic flows. Surges are extremely destructive.

2.2.4. *Lava Flows*

Lava flows are among the least hazardous processes associated with a volcanic eruption because they are usually slower and affect smaller areas than explosive eruptions. However, if they occur near populated areas they can be destructive. High-silica compositions (dacites, rhyolites) tend to form thick (50–500 m) lobes or domes due to their high viscosity and eruption conditions (Stasiuk and Jaupart, 1997). These often generate dense pyroclastic flows due to the collapse of the flow front, as observed on Montserrat, West Indies (Cole *et al.*, 1998). Lava flows normally travel at speeds of a few kilometres per hour or less. Structures in the path of a lava flow are usually destroyed or encased. The narrow, deeply incised drainages of British Columbia allow small lava flows to dam rivers and cause upstream flooding. In southern British Columbia an anomalously long, dacitic lava flow was erupted at the end of the last ice age from Opal Cone near Mt. Garibaldi. It flowed 20 km along the valley, reaching 3 km from the present town of Squamish (Mathews, 1958). Numerous very long (>10 km) basaltic lava flows have also been recorded in the Cordillera. One of the longest (22.5 km) is from Tseax Cone in central BC, which dammed the Nass River (Sutherland Brown, 1969). Lava eruptions may have durations of many years.

2.2.5. *Catastrophic Landslides*

Catastrophic landslides may remove large portions of volcanoes. If the collapse is associated with a volcanic eruption it can cause a larger magnitude eruption than would otherwise be expected, due to sudden depressurization. This was the case in the May 18, 1980 eruption of Mount St. Helens, where the landslide triggered a violent laterally-directed blast (Voight *et al.*, 1981). Landslides associated with eruptions are favoured by steepened slopes due to ground deformation, heightened steam venting and vigorous, sustained shaking due to shallow seismicity.

There is considerable landslide threat in the Garibaldi volcanic belt (Read, 1981; Clague and Souther, 1982; Evans and Brooks, 1991). Many Canadian volcanoes, already poorly-consolidated and hydrothermally altered, are perched on basement rocks with steep paleo-relief. These conditions have led to many failures not associated with eruptive activity (Evans, 1990; Hungr and Skermer, 1992). Examples from southwestern British Columbia include the Dusty Creek (Clague and Souther, 1982; Evans, 1990; Hungr and Skermer, 1992) and Avalanche Creek landslides (Cruden and Lu, 1992) at Mount Cayley; collapse of the Barrier Lava (Moore and Mathews, 1978, Fig. 7); and almost yearly small landslides, and less frequent large ones, at Mt. Meager. A large landslide at Mt. Meager killed 4 people in 1975 (Jordan *et al.*, 1986; Evans, 1987, 1992). Although not directly related to eruptive activity, these would not occur in the absence of the volcanoes and so can be considered secondary volcanic hazards.

Landslides are confined to valleys, and so often block drainages. This produces upstream flooding, sometimes catastrophic outburst floods, and long term river bed aggradation.

2.2.6. *Lahars/Debris Flows*

A lahar – an Indonesian word for mudflow – is a slurry of water and dominantly volcanic rock particles, generated on volcanoes during or associated with volcanic eruptions (Cas and Wright, 1988, pp. 323–328). The suspended particles, if dominantly fine material such as volcanic ash, lead to viscous mudflows that behave like wet concrete. Lahars commonly suspend a broad range of particle sizes, from ash up to blocks as large as houses, and are more generally described as volcanic debris flows. If the source material for the debris flow is young, still-hot material, the flow may be dangerously hot. Volcanic debris flows are extremely destructive, but are confined to valleys. They are most common and most voluminous as a result of eruptions on snow- or ice-clad volcanoes.

Debris flows pose a significant secondary volcanic hazard as they can occur days, weeks, or years following an eruption. Vast areas may be covered by unconsolidated tephra, which is easily remobilized by rainfall or rapid snow/ice melting. Debris flows of comparable volumes generated in volcanic materials appear to have much longer run-out distances than those generated in nonvolcanic materials, apparently because of a greater percentage of fine particles (Jordan, 1990). Jordan *et al.* (1986) and Jordan (1990) recorded many large postglacial debris flows unrelated to eruptions at Mt. Meager, that nevertheless originated from the volcano's deposits. These debris flows can be considered secondary volcanic hazards. Debris flows move large amounts of sediment into drainages and hence lead to secondary flooding and river aggradation.

2.2.7. *Volcanic Gases and Acid Rain*

Volcanoes produce large quantities of gases, mostly H_2O, but also significant amounts of CO_2, CO, SO_2, HF, and Cl and N compounds (Thorarinsson, 1979; Baxter *et al.*, 1982; Baxter, 1992). Loss of life and damage has been attributed to each of these gases. SO_2 from Laki Volcano in Iceland in 1783 damaged crops and killed livestock and people. Many more died of starvation (Thorarinsson, 1979). SO_2 has produced a number of problems including increased incidents of acute asthma and bronchitis (Baxter *et al.*, 1982). Fluorine killed and disfigured livestock after the 1845 Hekla eruption and again in 1970 (Thorarinsson, 1979). Acid rain from volcanic clouds can damage crops. In Hawaii, the increased acidity of water collected in cisterns leaches heavy metals into drinking water, the long term health effect of which has not yet been assessed (Wright and Pierson, 1992).

The only known deaths resulting from a volcanic eruption in Canada occurred along the Nass River in northern B.C. about 240 years ago (Sutherland Brown, 1969). The native people of the area lived in villages along the banks of the river, down slope from the erupting volcano, Tseax cone. Legend describes about 2000 people as having died of “poison smoke” (Barbeau, 1935, p. 223). The most likely cause was asphyxiation from carbon dioxide.

Volcanic gases, and particularly SO_2, condense to aerosols during eruption. Many tons of these particles can be injected into the upper atmosphere in a single eruption. Aerosol particles are smaller than ash and so remain suspended for years after virtually all the ash has settled. In the months following an eruption, the aerosols spread through the stratosphere and scatter sunlight, reducing the solar energy input to the lower atmosphere and causing climate cooling. The 1991 eruption of Mt. Pinatubo, Philippines, caused an average global-scale lower atmosphere cooling of about 0.5 °C for 14 months (Sparks *et al.*, 1999, pp. 516–518). Much larger-magnitude but infrequent eruptions in the distant past are thought to have led to prolonged darkness and extreme cooling of large regions (Rampino *et al.*, 1998).

2.2.8. *Phreatic Explosions*

When water percolates into rock heated by nearby magma, or into still-hot volcanic deposits, it may be rapidly heated and flash to steam. The accompanying volumetric increase within a confined space can cause violent steam venting, hydrothermal fracturing or sudden, brief phreatic explosions (Sheridan and Wohletz, 1981). These eruptions behave similarly to pyroclastic eruptions but are not associated with the eruption of fresh magma; in fact, the deposits are made up completely of bedrock fragments rather than primary ash and pumice. Phreatic explosions do not produce sustained eruption columns, but they can generate widely dispersed tephra blankets and pyroclastic surges.

2.2.9. *Groundwater Contamination*

A secondary hazard at volcanoes is contamination of ground and surface water. Highly fractured or porous volcanic deposits are more susceptible to weathering by percolating groundwater than most plutonic and metamorphic rocks. In addition, commonly-associated acidic thermal springs can chemically leach toxic metals from the rocks, leading to natural pollution in streams (Bortleson *et al.*, 1977).

2.3. SPATIAL DISTRIBUTIONS

The tectonic environments in western Canada have produced five belts of volcanoes (Figure 2), described in more detail in Souther (1977) and Souther and Yorath (1991). Edwards and Russell (2001) call the large northwestern belt the Northern Cordillera Volcanic Province (NCVP), but this paper will use the name originally given by Souther (1977) to a more restricted area: the Stikine volcanic belt.

The Garibaldi and Wrangell volcanic belts owe their origin to subduction, and comprise stratovolcanoes that range in composition from basalt to dacite. Stratovolcanoes are long-lived centers that tend to form snow- and ice-clad peaks in Canada. They range in eruption style from small-magnitude lava flows to significant pyroclastic eruptions. In addition, the presence of snow/ice at the time of any activity is likely to produce volcanic debris flows in drainages that source on the volcano. The Garibaldi belt lies within the most densely developed part of BC. The Wrangell belt volcanoes are relatively remote and so create less risk, except for Mount Churchill (in Alaska, at the Yukon border). Based on past activity, this volcano presents one of the highest hazards to Canada of any volcano, having had the two largest-volume explosive eruptions in North America in the last 2000 years (Lerbekmo *et al.*, 1975; McGimsey *et al.*, 1992). These two eruptions blanketed more than half of Yukon Territory with ash, including the location of Whitehorse and Dawson. Some drainages from Mt. Churchill lead into the White River, and it is likely that future eruptions would impact this valley. The White River valley is the location of the Alaska Highway.

The Stikine volcanic belt owes its origin to shear-related crustal extension, the Chilcotin Plateau to back-arc extension, and the Anahim volcanic belt to a mantle plume or hot spot. Deep faults and crustal dynamics appear to have formed the Wells Gray-Clearwater volcanic field. In all these areas the characteristic behaviour is small-volume, cinder cone and fluid lava eruptions. However, there are exceptions, for example explosive eruptions of high-silica magma at Hoodoo Mountain and Mt. Edziza in the Stikine volcanic belt, as well as at least one large-volume lava flow from Tseax Cone. Lava flows may be important because they and any secondary effects follow valleys, which may contain infrastructure.

2.4. SOCIO-ECONOMIC VULNERABILITY

A major explosive eruption would have a significant impact independent of its exact location in western Canada, due to the likely source regions (northwestern or southwestern Canada) and the winds that tend to move ash eastward, over populated areas. Figure 4 shows the path for a plume from a small eruption of Mt. Spurr, tracked by satellite. The pattern of ash spreading for an eruption in the Garibaldi belt is demonstrated by the Cayley eruption scenario (Section 2.5). These two cases show very different dispersion patterns, because they are dependent on evolving wind patterns. They demonstrate the importance of using real-time simulations rather than statistically-averaged wind patterns to predict airborne ash hazards. Any

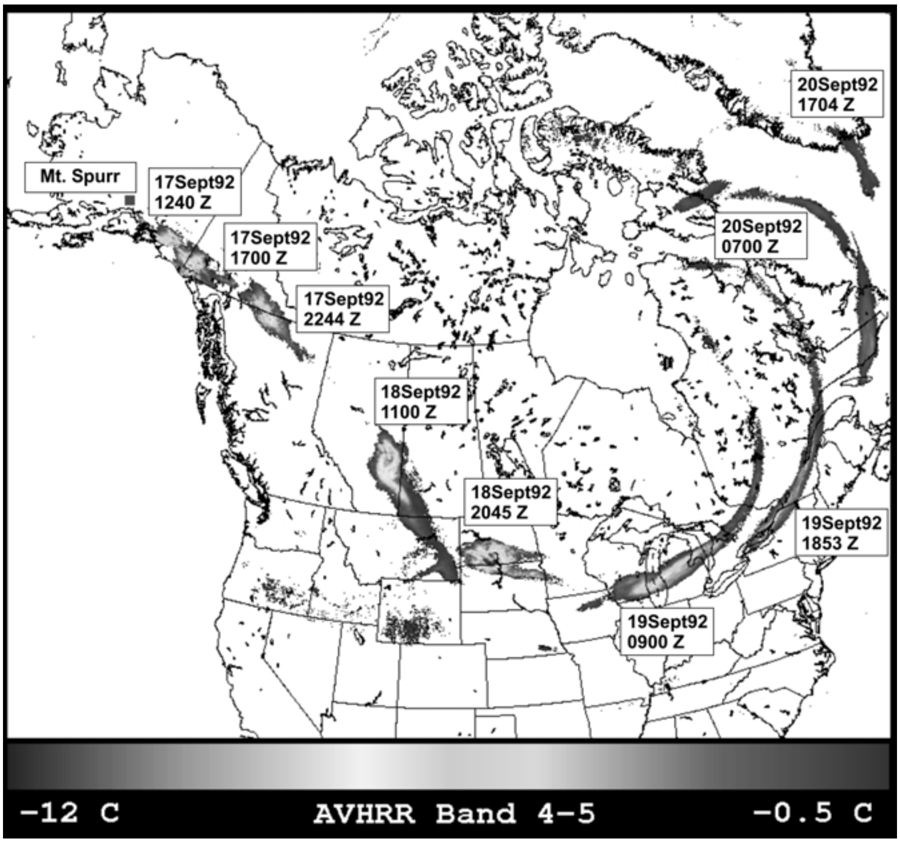

Figure 3. Compilation of AVHRR satellite images showing the 1992 Mt. Spurr ash plume from a minor eruption, and how it passed over most of Canada's major zones of development. Adapted from an image provided by the Canadian Meteorology Centre's Volcanic Ash Advisory Centre.

airborne ash would interrupt local air traffic as well as the multitude of east-west national and north-south international flights. Such interrruptions represent important economic losses to an active international air traffic region, and also disruptions of operations in an area reliant on local air traffic for essential transportation.

Volcanic eruptions of any type are likely to produce devastating effects on drainages to distances of tens of kilometers, especially in western Canada where the vent region is likely covered with snow and ice. Western Canada is particularly vulnerable to drainage-focused hazards because valleys have been the focus of development for transportation, communication and utilities infrastructure. Valleys are also most typically the location of communities and hydrological resources (fish and water for hydro-electricity, consumption, agriculture and industry). The most vulnerable corridors are the White River valley in Yukon Territory, from an eruption of Mt. Churchill, and the Vancouver-Pemberton corridor (containing Squamish and Whistler), which lies in the Garibaldi volcanic belt. Damage to these

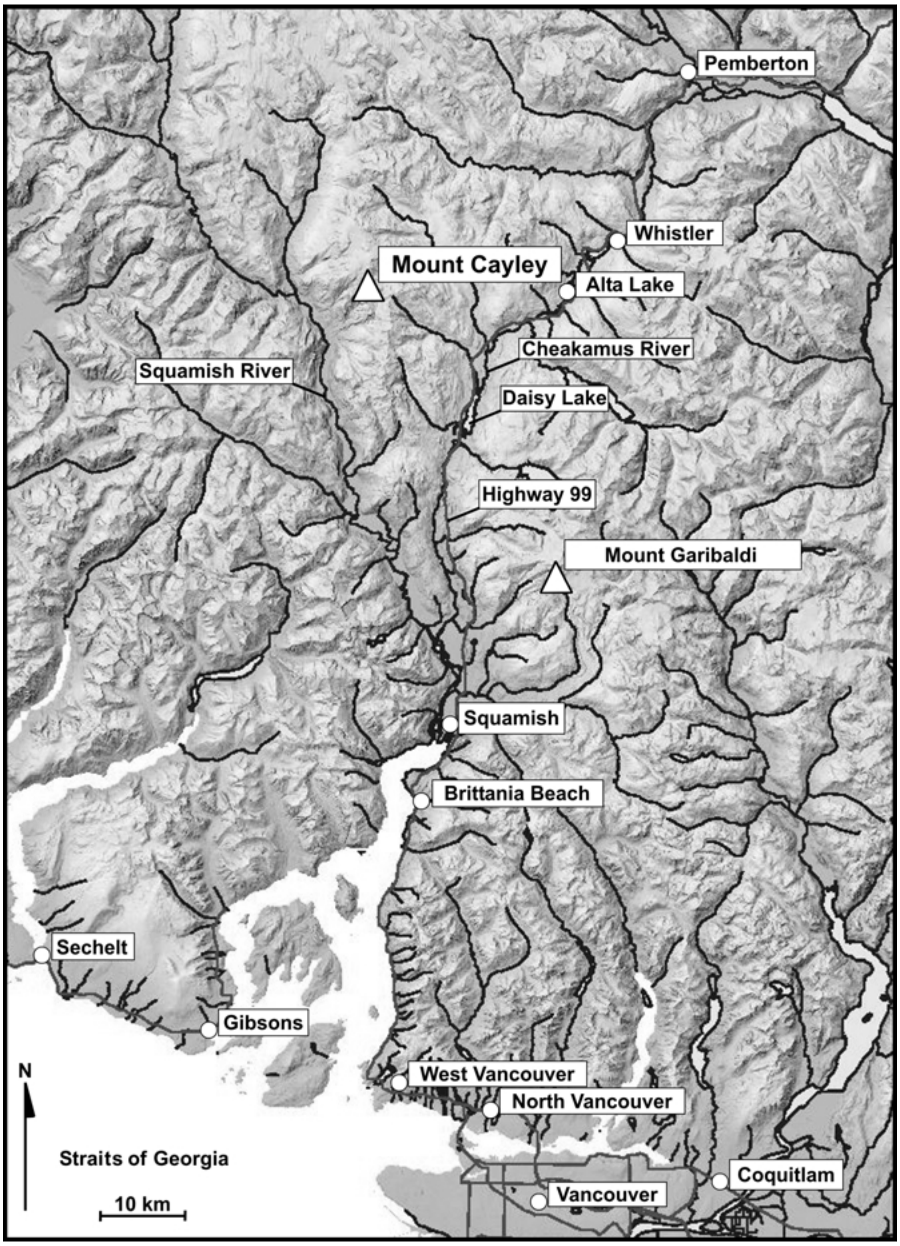

Figure 4. Plan view of southwest B.C. showing the major communities, roads, drainages and shaded topography. The Cheakamus River valley contains Highway 99, rail lines, power lines, power generating facilities, and communication lines, and is the major travel route between Vancouver, Whistler and Pemberton.

corridors is less critical for brief events such as earthquakes or landslides, since the period of cut-off is short and allows repair work to start quickly. Eruptions, however, may continue for weeks to decades. In addition, the secondary hazards (landslides, debris flows, flooding, aggradation) may be present for years after an eruption stops.

Growing populations and spreading development increase the risk posed by volcanoes. For example, in 1845 an eruption of Nevado del Ruiz (Colombia) destroyed the town of Armero, killing almost the entire population of about 1,400 people. Armero was rebuilt, and in 1985 a similar eruption destroyed it again but killed 25,000 people (Voight, 1989). Both the White River valley and the Vancouver-Pemberton corridor are experiencing rapid development.

2.5. ERUPTION SCENARIO: MT. CAYLEY

It is instructive to imagine what would happen if a geologically-plausible explosive eruption happened in western Canada. Mount Cayley, a stratovolcano 49 km from the town of Squamish and 93 km from downtown Vancouver (Figure 4), is the site of the scenario. It rises 2264 metres above the Squamish River, on the west side of the volcano, and 1844 m above the Cheakamus River, on the east side. The west side of the volcano has been the site of numerous landslides (Clague and Souther, 1982; Cruden and Lu, 1992; Evans and Brooks, 1991; Brooks and Hickin, 1991; Hungr and Skermer, 1992). The edifice comprises lava flows, thick lava breccias and pyroclastic flows. Hot springs occur high up on the west flank of the volcano. There have been shallow earthquakes near the volcano in the last 15 years, and seismic studies revealed a strong mid-crustal reflector beneath it consistent with a large, solidified, mafic, sill-like intrusion (Jones and Dumas, 1993; Hammer and Clowes, 1996). The eruptive scenario used is approximately equivalent, in terms of magnitude and sequence of events, to that at Mt. Meager 2350 years ago (Hickson *et al.*, 1999).

Significant precursor activity would be expected beneath the volcano weeks to years in advance, as magma breaks its way through the crust. The abundance of seismicity and the sensitivity of the existing regional network in this area would alert the GSC and probably trigger an expanded monitoring effort. As the magma nears the surface, the volcano would likely swell and the surface fracture, causing greatly increased vigour in the hotsprings, and the creation of new springs or fumaroles. Minor and possibly large landslides could occur and might temporarily block the Squamish River, as has happened in the past (Brooks and Hickin, 1991) without earthquake shaking and intrusion-related deformation. Eventually the near-surface magma may cause phreatic explosions and debris flows. By this time Highway 99 would be closed and Squamish would be at least partly, and probably wholly, evacuated.

If the local communities had emergency plans in place and the interpretation of monitored events was clear, response to the developing crisis well in advance of eruption would be straightforward and loss of life would be unlikely. Otherwise, the community would be vulnerable.

In the run-up to eruption phreatic explosions might occur, during which, if not already, Squamish would be fully evacuated, Whistler would be at least considered for evacuation, and Highway 99 closed. As the magma reaches the surface it is likely to fragment, initiating a sustained explosive eruption that could reach 20 km height, and may be maintained for 12 hours. Figure 5 shows a possible spreading pattern for the plume, as modelled for the stated conditions by the Canadian Meterological Centre, using CANERM software for modelling dispersion and transport. Air traffic would be diverted from the area, and all airports covered by the plume would be closed (Vancouver, Victoria, Kamloops, Prince George, Seattle). Above the vent area, material from the eruption column would collapse to form pyroclastic flows, and would flow east and west into the Squamish and Cheakamus valleys. These would rapidly melt snow and ice in the summit area of Mt. Cayley, generating debris flows that cooould reach Squamish and Daisy Lake, damaging much infrastructure.

Based on the plume coverage, heavy ash falls would occur in the Vancouver area, the Fraser valley, Bellingham, Kamloops, Whistler and Pemberton. The ash would damage power and communications lines, satellite dishes, computer and other electrical equipment. Telephone, radio, cell phone and satellite communications would be cut off. Weak structures could collapse under the weight of the ash.

Thirty-six hours after the eruption began, the ash plume would spread to envelope most of the west coast from Seattle to Anchorage (Figure 5), causing all enclosed airports to be closed and all relevant flights to be diverted or cancelled. The plume would then sweep eastward and disrupt air traffic across Canada from Alberta to Newfoundland.

Ash from further, minor explosive activity could continue to fall lightly but persistently in the Whistler-Pemberton area for days, followed by weeks of viscous lava dome growth punctuated by small explosions. The explosions would generate short-lived plumes to elevations of 10 to 15 km, small pyroclastic flows to the Squamish and Cheakamus valleys, and ash plumes to the north and east.

Explosions might cease and be replaced by slow, continuous growth of a lava dome in the new crater. Rain and seasonal snow melt would regularly remobilize the tephra into lahars, and these would continue to threaten the Squamish and Cheakamus valleys. Months later, the lava dome could overtop the crater. The solidifying, spreading lava could then generate rockfalls and form a voluminous talus apron into the Squamish valley. As the lava dome spreads, it would periodically undergo gravitational collapse to generate dense pyroclastic flows into the Squamish and Cheakamus valleys. Ash elutriated from the pyroclastic flows would form plumes up to 10 km high, again dropping ash onto Pemberton and Whistler and causing disruptions to local air traffic. Infrequently, the lava dome might produce small explosions, ash plumes and pyroclastic flows. Squamish townsite would

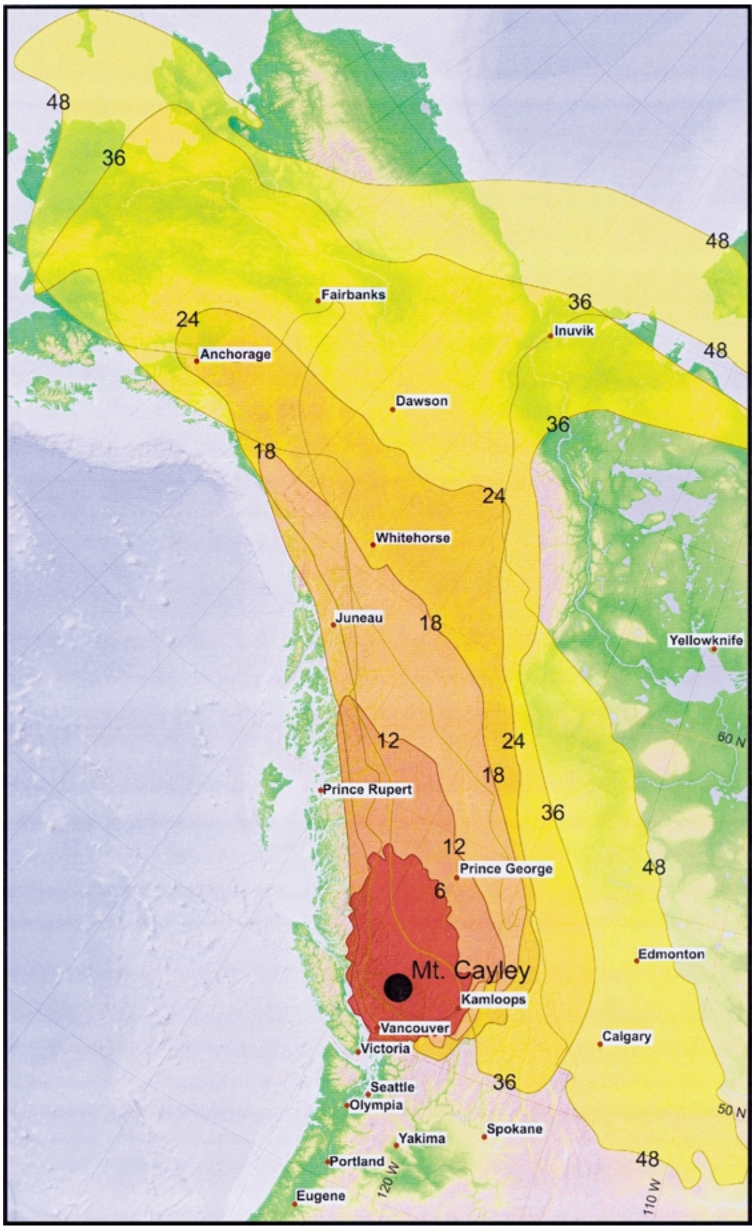

Figure 5. Canadian Meteorology Centre's Volcanic Ash Advisory Centre CANERM output for a 48-hour real-time 3-dimensional ash dispersion simulation, for a 12-hour eruption of Mt. Cayley on 6 June 2000 which produces an eruption column to 20 km height. The plume areal coverage is shown in different colours, at 6, 12, 18, 24, 36 and 48 hours after the onset of eruption. Major cities are labeled.

remain evacuated, Highway 99 would remain closed and unrepairable, and travel between Whistler/Pemberton and Vancouver would be forced to go via a much longer route to the east.

Eruptive activity itself could go on for years, followed by years of declining secondary activity. The cooling lava would intermittently spall sections to produce pyroclastic flows. The fragmental material on the slopes and in valleys would be periodically remobilised into debris flows. Significant structural mitigation would have to be built to reclaim use of the Highway 99 corridor and Squamish area.

3. Needs and Gaps

3.1. MITIGATION: HAZARD ASSESSMENTS AND MONITORING

The fact that there is some probability of Canada being impacted destructively by domestic or nearby volcanic eruptions argues that some type of mitigation programme is needed. Cost-benefit considerations are critical to dealing with natural hazards. However, a cost-benefit analysis requires accurate information about the hazard types, magnitudes and frequencies. These do not exist for Canada's volcanoes in the detail required.

Volcanic-hazard mapping, which reveals a volcano's eruption history in detail, provides an understanding of the hazardous activity that might be expected in the future and so is fundamental to a hazard assessment. No hazard maps have been made for any Canadian volcano, because the level of knowledge is insufficient. A broad volcanic hazards programme has not existed within the GSC. Most information has been accumulating in a slow, piecemeal way from the contributions of many workers. Modern knowledge is best developed at Mt. Meager (e.g., Stasiuk *et al.*, 1994; Hickson *et al.*, 1999; Stewart *et al.*, 2001) and is expected to greatly increase with the initiation of a short-term mapping and monitoring project in 2002. Knowledge at other volcanoes is less developed, but some work is being done at least at Mt. Churchill (McGimsey *et al.*, 1992; Richter *et al.*, 1995) and Mt. Cayley (Kelman *et al.*, 2001). A focused program cataloguing infrastructural vulnerability around all young Canadian volcanoes and rapid hazard evaluation at the nine volcanoes associated with recent seismicity (Section 2.2.2) would be a leap forward and would yield a fast and economic determination of priority areas for more work.

There has been a national network of seismometers in Canada since 1975, although it was sparse until 1985. Apart from a few brief seismic monitoring experiments by the GSC (Rogers, 1981), no volcano monitoring has been done in Canada at a level approaching that in other developed countries with historically-active volcanoes. Active or restless volcanoes are typically monitored using at least 3 seismographs all within about 15 km, and usually within 5 km, for improved sensitivity of detection and reduced location errors, especially for earthquake depth. Such monitoring gives the possibility of disciminating volcanic from tectonic events in advance of an eruption, providing a forecasting ability which is fundamental

Table IV. Distances to 3 nearest Canadian seismic stations for volcanoes with associated seismicity in the last 15 years.

Volcano	Latitude (N, degrees)	Longitude (W, degrees)	Distance to 3 nearest stations* (km)
Mt. Meager	50.63	123.50	58, 110, 115
Mt. Cayley	50.12	123.28	41, 52, 72
Mt. Garibaldi	49.84	123.00	25, 53, 69
Silverthrone	51.52	126.12	124, 129, 142
Wells Gray Field	51.99	120.10	59, 120, 121
Crow Lagoon	54.7	130.23	42, 137, 190
Lava Fork	56.42	130.85	230, 236, 279
Hoodoo Mountain	56.78	131.28	199, 281, 303
Mt. Edziza	57.72	130.63	88, 379, 386
Castle Rock	57.84	131.15	94, 353, 383

* Calculated using the positions of the 54 stations making up the western Canadian National Seismograph Network, in its 2000 configuration (including broadband, short period and B.C. Hydro stations).

to mitigating volcanic risk (Tilling, 1989). With increasing distance and decreasing numbers of instruments the forecasting ability is reduced because earthquake location accuracy decreases (especially the depth), and the network becomes less sensitive: both the smallest magnitude that can be reliably located and the smallest event that can be detected but not located, increase. At present no Canadian volcano has a seismograph closer than 15 km, and for most the distance is much larger (Table IV). The location errors in the Garibaldi and Wells Gray areas are a few kilometres, and in more remote northern areas they are up to 10 km. Most volcanoes are about 5 km in diameter. The location magnitude threshold in the Garibaldi volcanic belt and Wells Gray-Clearwater volcanic field is approximately M 1 to 1.5, and elsewhere it is M 1.5 to 2. At closely-monitored volcanoes both the located and detected events are catalogued and analysed in near real-time, to help interpretation. Unlocated events are not catalogued or analysed in western Canada in near real-time, nor in an easy-to-access manner.

In Canada it is conceivable that minor precursor swarms could go unnoticed, especially if no events were locatable; larger events in more significant swarms would be noticed but only a small subset of the swarm events would be located and catalogued; location errors would be sufficiently large that it would be difficult to interpret them with confidence as volcanic in nature, or even associate them with a particular volcano. For comparison, a recent (1998–2000) volcano-seismic swarm on the Caribbean island of Dominica was the most vigorous of the 12 that the island has experienced in 50 years of monitoring, in terms of numbers and magnitudes. More than 75% of the 2800 earthquakes where smaller than magnitude 1.5, more than 85% were smaller than magnitude 2, and only about 30% were locatable

(Shepherd *et al.*, 2000), despite a much denser network of seismographs (8, all closer than 15 km) compared to any Canadian volcano. As a result, for the known earthquakes near Canadian volcanoes (Section 2.1.2), no clear interpretation is possible. It may be that the earthquakes are volcanic in nature, or simply the result of motion along small, intra-crustal faults that are abundant in the region, perhaps locally weakened by recent volcanic activity or ongoing geothermal circulation. To reduce uncertainties in interpretation and forecasting, volcanologists attempt to apply a range of monitoring methods, such as high-precision GPS for measuring ground deformation. None of these have been applied yet to Canadian volcanoes. The current level of monitoring in western Canada, therefore, would probably not allow timely eruption forecasting. In the Garibaldi volcanic belt the seismic network sensitivity is probably sufficient that there would be warning time, but it is unclear whether it would come sufficiently early to evade a disaster. It is not known how long the period of pre-eruption seismicity would be, and it takes time for scientists to deploy additional instruments and methods, make interpretations, reach consensus and communicate the results; for community leaders to make decisions and plans and communicate with residents; and for residents to respond. From intuition and simple physical arguments, it is expected that brief precursor periods would be unlikely for volcanoes that erupt infrequently, as in western Canada, but there is no statistical data supporting this idea, and hence is an unsafe basis for dealing with poorly-understood hazardous processes. Ensuring that at least one instrument was within 15 km of each of the nine volcanoes with associated recent seismicity would probably resolve current needs.

The well-acknowledged, low-magnitude hazard to aircraft posed by airborne ash drifting into Canadian airspace led to the development in 1990 of a communication plan, called the Inter-Agency Volcanic Event Notification Plan (IVENP). The plan provides communication instructions to all groups likely to receive information about an eruption in Canada, in order to divert air traffic. The involved groups are the GSC, Provincial Emergency Program, Royal Canadian Mounted Police, Transport Canada, NAVCanada, Office of Critical Infrastructure Protection and Emergency Planning (OCIPEP), Environment Canada, Airline Pilots Association, and the Canadian Meteorology Centre's (CMC) Volcanic Ash Advisory Centre (VAAC). The CMC VAAC is one of eight VAACs covering the global airspace. It uses the reports of eruptions and plume locations, real-time weather data, and 3-dimensional modelling, to rapidly predict plume location. The plan includes protocols for eye-witnesses of eruptions in Canada to rapidly disseminate the observations, and for GSC seismologists and volcanologists to then attempt to confirm the event as an eruption. Clearly, it could be made more effective by improved monitoring. The IVENP is reviewed annually and is maintained by the GSC.

3.2. BASIC RESEARCH

There is a need for basic research to better understand all facets of Canada's volcanoes, to underpin and complement hazards work. Universities are the best-suited for basic research, but NSERC grants to university earth scientists have been cut significantly over the past few years. Typical one-season field programs (without student salaries) start at $15,000 – this is the average annual total amount of NSERC grants in the earth sciences, and is meant to cover all research costs including student salaries, conferences, publications, analyses and minor equipment. Before 1995, collaborative resource-pooling arrangements were possible between the GSC and universities, but the GSC withdrew this funding source, and the reduction in NSERC funding prevent the collective group from executing significant projects.

3.3. INSTITUTIONAL CAPABILITIES

From the early 1970s until 1987, the GSC employed one volcanologist. In 1987 a second was hired, but the retirement of the first in 1990 left the GSC with one for the next decade. In 2000, with the assistance of external funding, another was hired. The expansion of work at Mt. Meager permitted temporary hiring of a third. If funding were available for field work, current staff would take two to four years to complete a rapid evaluation of hazards and vulnerability for the 9 volcanoes with associated seismicity (Table IV).

The GSC owns an aging COSPEC (Correlation Spectrometer) for gas monitoring purposes. Other monitoring equipment, such as differential GPS, seismometers and surveying equipment, and people with the expertise to operate them, exist within the GSC but are committed to other programs of work. Satellite remote sensing images and analytical methods, such as interferometric synthetic aperture radar, are available from the Canadian Centre for Remote Sensing – like the GSC, part of Natural Resources Canada. Such images and techniques, however, are costly and again the personnel with the relevant expertise are already fully committed to other work.

3.4. EDUCATION

The main source of information about Canada's volcanoes for the public and decision-makers is the GSC, although university professors play an important educational role. The GSC is mandated to provide information, and so takes an active role in outreach. GSC scientists produce geoscience posters (e.g., Geoscape Vancouver poster; Turner *et al.*, 1996); design displays for science museums; give talks for schools, natural history groups and communities; take part in university course instruction and field trips; give media interviews; create and maintain websites (e.g., volcanocanada.com); take part in emergency awareness community days; and initiate and maintain information-exchange relationships with entities such as community town councils, the Provincial Emergency Program, and the Office of Critical Infrastructure Protection and Emergency Preparedness. Although active in outreach, GSC scientists have limited time and typically cannot take up all outreach opportunities. Outreach for the purposes of helping at-risk communities develop mitigation and response plans is precluded by the lack of detailed hazard assessments and limited resources.

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