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Annotated Bibliography of References Relevant to Volcanic Hazards in Canada

M.C. Kelman

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ABSTRACT

This annotated bibliography of references about Canadian volcanoes was compiled as an accompaniment to the Preliminary Volcanic Ash Fall Susceptibility Map of Canada (Open File 7679, Kelman, 2015). It is prefaced with an introduction to volcanic hazards, volcanism in Canada, hazards from volcanoes outside Canada’s borders that could impact Canadian territory, and a brief discussion about volcano monitoring as it applies to Canada.

The bibliography is a list of references about Pleistocene and Holocene volcanoes in Canada, organized by volcanic region. Each entry consists of a bibliographic reference plus either an abstract, brief summary, or introduction. The bibliography lists published papers, books, monographs, theses, and manuscript reports. Conference abstracts are in most cases only included when their information is unavailable elsewhere. Maps are only included if they depict volcanic hazards or contain significant information not available in other publications. Reports not accessible to the general public (e.g. internal reports from within Natural Resources Canada) and nontechnical brochures are not included. References about volcanic ash layers in Canada are only included if they are for Holocene events and contain specific information about the style, timing, or magnitude of eruption of a Canadian volcano, or chemical information about its tephra that is useful in identifying it. References about ash layers in Canada that originated from American eruptions are not included, with the exception of some references about the two White River ash deposits, which are included because their source is so close to the Canadian border and because most ash deposition occurred within Canada. Some references about landslides or debris flows not directly associated with eruptions are included because the fracturing and hydrothermal alteration of rock that contribute to slope failures are related to volcanic activity, and because similar mass movements could also occur during eruptions. References from before 1950 are non-comprehensive because many of them are difficult to obtain; however, some pre-1950 references that contain important information not available in later publications are included.

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VOLCANISM IN CANADA

Introduction

The Geological Survey of Canada (GSC) has undertaken national-scale natural hazard assessments through its Public Safety Geoscience Program in order to produce first-order national-scale natural hazard susceptibility maps for Canada, and to prioritize key areas for future research. As part of this project, the Preliminary Volcanic Ash Fall Susceptibility Map of Canada was prepared (Kelman, 2015). Most volcanic hazards are not resolvable at a national scale, so by default, the map focuses on volcanic ash (tephra fragments smaller than 2 mm), which can be carried thousands of kilometres or more by wind. This annotated bibliography of references pertaining to Canadian volcanoes and volcanic hazards is complementary to the Preliminary Volcanic Ash Fall Susceptibility Map of Canada.

Canada contains at least 300[1] potentially active volcanoes, all located in British Columbia and the Yukon. "Potentially active" volcanoes are defined, in this case, as those with a known or suspected history of eruption since the start of the Pleistocene[2]. These volcanoes include cinder cones, shield volcanoes, stratovolcanoes, lava flows,

[1] The number of volcanoes is an estimate, because distinguishing discrete volcanoes is not always an unambiguous process: a large volcanic complex may have multiple distinct vents and overlapping deposits, which may be counted as separate volcanoes or as a single volcano, because the age of many volcanoes is an estimate based on field evidence (so they may or may not actually have erupted during the Pleistocene/Holocene), and because there are volcanic fields with multiple discrete vents or deposits which may or may not have been mapped and counted individually.

[2] The Pleistocene 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, I have used 1.8 million years BP as a cutoff for the start of the Pleistocene, according to the previous version of the geological time scale (Gradstein et al., 2004), because most of this bibliography was compiled prior to 2013. For the same reason, the beginning of the Holocene is taken as 10,000 BP, according to the previous version of the geological time scale (Gradstein et al., 2004), rather than 11,700 BP, which defines the start of the Holocene on the most recent geological time scale (Cohen et al., 2013). Using 10,000 BP as a starting date for compiling tephra data also has the advantage in that 10,000 BP was postglacial throughout most of western Canada (Fulton, 1971; Clague, 1980, 1981; Friele and Clague, 2002; Clague and James, 2002; Dyke et al., 2003; Dyke, 2004; Stroeven et al., 2010), so widespread tephra layers associated with large explosive eruptions are recorded across broad areas rather than being locally absent due to ice cover.

tuyas, domes, and other types of volcanic edifices, distributed in six volcanic regions (Figure 1). Seismic activity has been recorded in the vicinity of at least ten volcanic centres since 1985, including several with eruptive histories that include significant explosive events and go back hundreds of thousands of years or longer, and there have been at least three probably volcanogenic seismic swarms: at the west end of the Anahim Volcanic Belt (Milne, 1956), to the east of the Clearwater-Quesnel volcanic province (Rogers, 1981), and near Nazko cone, at the east end of the Anahim Volcanic Belt (Cassidy et al., 2008, 2011). This, plus the presence at many volcanoes of geothermal springs, geothermal anomalies, and volcanic rocks whose textures, structures, flow morphologies, degree of dissection, field relationships, and age[3] suggest they erupted during or after the last major glaciation, indicates that many of Canada's volcanoes are dormant and could erupt again.

On human time scales, eruptions in Canada are infrequent. Based on counts of known explosive and effusive (non-explosive) eruptions during the Holocene, Stasiuk et al. (2003) estimated the minimum annual probability of any type of volcanic eruption within Canada at approximately 1/200, the annual probability of an effusive eruption within Canada at about 1/220, and the annual probability of an explosive eruption within Canada at about 1/3333. Kelman (2015) estimated the probability of a major volcanic ash fall event in Canada at 1 in 1700 or greater, based on the record of six widespread Holocene ash layers within Canada, five originating in the conterminous United States or Alaska, all of which can be mapped hundreds or thousands of kilometres from the source[4]. This estimate of 1 in 1700 is the probability of an ash fall event larger than the

[3] Only a small number of volcanic deposits in British Columbia and the Yukon have had their Holocene or Pleistocene ages confirmed through radiometric dating (e.g. Aumento and Souther, 1973; Souther et al., 1987; Brooks and Friele, 1992; Leonard, 1995); at many localities, Holocene age is demonstrated principally by deposit preservation and the lack of evidence for glacial overriding.

[4] There are six widespread Holocene tephra layers mapped across western Canada: Mount St. Helens Yn (~4300 BP; Mullineaux et al., 1975; Mullineaux, 1996), Mount St. Helens Wn (~520 BP; Mullineaux et al., 1975; Mullineaux, 1996), White River north (~1800 BP) and east (~1150 BP) (Bostock, 1952; Lerbekmo et al., 1975; Clague et al., 1995), Bridge River (~2700 BP; Clague et al., 1995; Leonard, 1995), and Mazama (7300 BP; Hallett et al., 1997; Zdanowicz et al., 1999; Bacon and Lanphere, 2006). This anotated bibliography is not comprehensive with respect to Canadian tephra references because tephra layers are used as geochronological markers in a wide range of disciplines, including archaeology, anthropology, botany, ecology, zoology, palynology, and sedimentology, and in many publications, the tephra is mentioned only briefly and only with respect to its use as a chronological marker.

one resulting from the May 18, 1980 Mount St. Helens eruption. However, an important consideration is that volcanic deposits are often thin and may be poorly consolidated, so they erode rapidly, and the geologic record may not reflect the frequency, extent, and intensity of volcanic eruptions: smaller magnitude events are particularly likely to be underrepresented. Payne and Blackford (2008) counted many identifiable and unidentifiable crypotephras (volcanic ash layers not visible to the naked eye) at a single site in Alaska, and suggested that reliance on visible tephra layers will lead to an underestimate of the frequency of eruptions; numerous other cryptotephra studies suggest likewise. Any estimate of event frequency based on the geological record, especially the tephrochronological record, is almost certainly a minimum.

A useful concept for describing and comparing volcanic eruptions is the Volcanic Explosivity Index (VEI), created by Newhall and Self (1982). The VEI is a semi-quantitative scale of a volcano's explosivity, ranging from 0-8, and is based on eruption column height, volume of ejecta (tephra and pyroclastic flow debris), and qualitative observations of eruptive style[5]. The overall level of hazard posed by a volcano generally correlates with the magnitude of eruption. VEI gives some basis to compare historic and prehistoric eruptions. For example, the 2010 eruption of Eyjafjallajökull in Iceland was assigned a VEI of 4, while the 1980 eruption of Mount St. Helens, Washington had a VEI of 5, and the 1991 eruption of Mount Pinatubo in the Philippines had a VEI of 6. Of the six major Holocene eruptions recorded in western Canada, two had VEIs greater than 6, and four had VEIs from 5-6. Worldwide, the frequency of eruptions of different magnitudes follows a power law relationship, with each higher VEI about an order of magnitude less common than the next lower VEI (Simkin and Siebert, 1994; Siebert et al., 2010).

Because of the volcanic magnitude-frequency relationship, because there are a number of less-widespread Holocene tephra layers in Canada, and because many Canadian volcanoes have been only minimally studied, it is likely that numerous unrecognized smaller magnitude eruptions (VEI<5) occurred in Canada during the

[5] 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 paper, however, I use the VEI exclusively.

Holocene[6], and Kelman (2015) estimated the annual probability of ash fall from an eruption of this magnitude to be at least 1 in 1000. However, as we saw with the 2010 Eyjafjallajökull eruption, even a volcanologically small eruption (VEI 4) can produce enough ash to be regionally disruptive and costly: the International Air Transport Association (IATA) estimated the Eyjafjallajökull eruption cost the commercial airline industry 1.7 billion US dollars. A very large eruption, comparable to the 1912 Novarupta eruption in Alaska (at VEI 6, the world's largest eruption during the twentieth century), would be far more problematic and costly[7].

Kelman (2015) estimated that annual probabilities for major volcanic events affecting Canada (which include ash falls from volcanic eruptions outside Canada) were, for VEI≥6, 1/5000, for VEI=5-6, 1/1700, for VEI=4-5, 1/1000, and for VEI<4, greater than 1/1000. These probability estimates are minima, and the actual probabilities may be significantly greater. The impact of even a low magnitude eruption could be substantial, particularly if it occurred near a populated area or along one of the transportation corridors that link isolated parts of British Columbia and the Yukon.

[6] There are a number of tephra (volcanic ash) layers in Canada that are not widespread and whose source and age are unknown (Hallett et al., 2001; Foit et al., 2004; Lakeman, 2006; Preece et al., 2011), indicating that unrecognized explosive eruptions (probably VEI<5) have occurred in or near Canada. There are also numerous proximal tephras that have not been recognized beyond the immediate vicinities of their sources (Read et al., 1989; Souther, 1992; Villeneuve et al., 1998; Edwards and Russell, 1999, 2000; Edwards et al., 2002; Russell and Hauksdóttir, 2001). These minimally-studied distal and proximal tephras have not been included in estimates of the frequency of explosive eruptions in Canada (Kelman, 2015) because the magnitudes of the eruptions that produced them are unknown and because they have not been mapped and correlated over large distances. There are also numerous cryptotephra layers (ash layers not visible to the naked eye) found in and near Canada (e.g. Payne et al., 2008; Pyne-O'Donnell et al., 2012), which demonstrate how regionally variable ash deposition and preservation can be: one site in Newfoundland records at least 12 discrete cryptotephras, including 3 of the 6 widespread Holocene ash layers listed above, and some layers that are not correlated with any known eruptions (Pyne-O'Donnell et al., 2012). This supports the contention that eruption frequency estimates based on the tephrochronologic record are likely to be minima.

[7] Ash from the Novarupta eruption fell as far away as Seattle, Washington, (~2500 km; Fierstein, 2012; Payne and Symeonakis, 2012), and associated dust and sulphurous aerosols were detected over California, Europe, and northern Africa within two weeks. The Novarupta ash has been identified in ice cores collected in Greenland (Fierstein and Hildreth, 2001).

Volcanic Hazards: A Brief Overview

A volcano is an opening in the earth's crust through which lava, volcanic ash, and gases escape. Beneath a volcano, liquid magma containing dissolved gases rises through cracks and channels in the earth's crust. As the magma rises, pressure decreases, allowing dissolved gases to form bubbles. How the magma behaves when it reaches the surface (where it is called lava) depends in part on its chemical composition. Lavas with a low silica (SiO_2) content tend to have low viscosities and flow freely, allowing gases to escape readily, while lavas with a high silica content have high viscosities and are more resistant to flow, so that gases cannot escape gradually[8].

Basalt contains the least silica, so basaltic lava typically has a low viscosity and is fairly fluid, allowing it to flow freely in effusive eruptions[9]. A low viscosity lava with lots of gas typically forms fire-fountains (a style of eruption seen in both Hawaii and Iceland) (Figure 2a). Small fire-fountain eruptions produce cinder cones (like Nazko cone in central British Columbia). When low viscosity lava contains less gas, however, it erupts in outpouring flows (rivers of lava) (Figure 2b). Repeated fire-fountain and lava flow eruptions over long time periods form gently sloping shield volcanoes like Anahim Peak in central British Columbia or the volcanoes that make up the Hawaiian Islands. Effusive eruptions generally pose a lower eruption hazard than explosive eruptions because their effects are more local; they do not generate large quantities of ash.

Andesite, dacite, and rhyolite lavas are progressively higher in silica and progressively more viscous, so gases cannot escape gradually. When high-silica lavas contain lots of trapped gas, the pressure builds up and is released in explosive

[8] Viscosity depends on a number of interrelated factors. Although silica content is important, other factors affecting viscosity include magma temperature, crystal content, abundance of bubbles, and dissolved volatile content. Viscosity, gas content, and interrelated factors such as rate of bubble formation, rate of magma ascent, and eruption conduit diameter control eruption style.

[9] Although most explosive eruptions of basaltic 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; Nye et al., 2002). Even with lower-viscosity magmas, eruptions may still be explosive if magma ascent is very rapid and gas overpressures persist near the earth's surface.

eruptions that produce ash (tiny particles of shattered rock[10]) (Figure 2d). Rocks from such eruptions are termed *pyroclastic*. The 1980 eruption of Mount St. Helens was this type of eruption. If high-silica lavas contain little trapped gas, however, they may ooze slowly onto the surface to pile up as steep-sided lava domes (Figure 2c). Some andesite, dacite, or rhyolite volcanoes experience both effusive and explosive activity, alternating explosive eruptions with long periods of dome-building, forming stratovolcanoes like Mount St. Helens (Washington state) and Mount Garibaldi (southwest British Columbia). Explosive eruptions can create significant far-reaching hazards, particularly ash.

A volcano is said to be erupting while material (lava or pyroclastic debris) is being emitted. Eruptions can last minutes to years, depending on how "eruption" is defined[11]. Many volcanoes experience repeated eruptions closely spaced in time, forming cycles. Periods of inactivity may be less than a year or many thousands of years.

Volcanoes pose numerous types of hazard, depending on lava composition, gas content, and other factors (Figure 3a, b):

Eruptions of low-viscosity lava (commonly but not exclusively basalt) typically produce some or all of the hazards shown in Figure 3(a). Eruptions of silica-rich lava (most commonly rhyolite or dacite) may produce some or all of the hazards shown in Figure 3(b). The type, intensity, and extent of a hazard will vary depending on lava composition and gas content, and on other factors such as eruption rate, eruption duration, volume of erupted material, the presence of water, snow, or ice, structural instabilities of the volcano, local topography, and weather. Some volcanoes may erupt more than one composition of lava, and the hazards associated with a volcano may vary over time. The effects of most volcanic hazards are usually restricted to within a few tens of kilometres of a volcano: exceptions are lahars (volcanic mudflows and debris flows), which may travel many tens of kilometres or more downstream, and

[10] The term for all fragmental material produced by explosive eruptions is *tephra*. The term *ash* is reserved for tephra less than 2 mm in size. Ash particles may measure less than a thousandth of a millimeter.

[11] The definition of an individual "eruption" is often used somewhat flexibly: On a short time scale, a single explosion might be referred to as an eruption (especially if it is not followed by further eruptive activity), while in other cases, a series of explosions over a short time period might be considered a single eruption. On a longer time scale, the growth of a lava dome or persistence of a lava lake, over months or years, might be considered a single eruption.

volcanic ash, which can be carried thousands of kilometres by wind. Therefore, stratovolcano eruptions tend to have much more widespread effects than those of cinder cones, and are more likely to interfere with aviation (Figure 3c). The different volcanic hazards are described below.

Lava

Lava (molten rock) can erupt as fire fountains, flows, and domes. Fire fountains occur when lava of low viscosity is ejected into the air, breaking into globs that may solidify as they fall to the ground. Lava flows travel down volcano slopes along relatively predictable paths that depend primarily on topography, and are typically less than tens of kilometres long. The approximately 10,000 year-old Ring Creek flow from Opal cone, near Squamish in southwest British Columbia, is one Canadian example (Brooks and Friele, 1992). Lava flows can also form natural dams, which may be unstable and vulnerable to future landsliding, as is the case at the southwest British Columbia landform known as The Barrier (Mathews, 1952). Lava domes are steep mounds of viscous lava. Domes can be dangerous due to the possibility of collapses which may produce pyroclastic density currents. Buildings and infrastructure in the path of lava are likely to be damaged or destroyed, but since lava moves relatively slowly, fatalities are rare. Lava also has the potential to ignite forest fires, but rarely poses a direct hazard to areas distant from a volcano.

Pyroclastic density currents

Pyroclastic density currents (PDC's; pyroclastic flows and surges) are hot avalanches of rock, ash, and gas that travel down volcano slopes at typical speeds of greater than 10 m/s, sometimes more than 100 m/s (Moore, 1967; Fisher, 1979; Wilson and Head, 1981), with temperatures as high as 660°C (Suzuki-Kamata et al., 1992). Pyroclastic density currents are most likely to occur at volcanoes with lavas of intermediate to high silica content, and occur when high eruptive columns collapse or from laterally-directed explosions or the collapse of lava domes. They may interact with snow or ice, resulting in the formation of lahars. PDC's typically travel downslope, following topography, but may surmount significant topographic obstacles if momentum is sufficient. Most pyroclastic density currents are restricted to within a few kilometres of a volcano, although in very large caldera-forming eruptions they may travel more than 100 km. Pyroclastic surges (also called blasts) are of lower density than pyroclastic flows, may travel at extremely high speeds, and are more likely than pyroclastic flows to surmount topographic obstacles. Pyroclastic density currents can be very dangerous in the immediate vicinity of a volcano, as they usually incinerate, disaggregate, and/or bury everything in their paths. They can also deposit significant unconsolidated sediment in valleys, contributing to the hazard from debris flows, lahars, floods, dams, outburst floods, and river aggradation (e.g. at El Chichón, 1982; Macías et al., 2004).

Phreatic explosions

Water that percolates into hot volcanic deposits or into rocks heated by nearby magma, or magma that contacts groundwater, can result in rapid conversion of liquid water to steam. This sudden increase in volume, when in a confined space, can cause steam venting, rock fracturing, or phreatic explosions (Sheridan and Wohletz, 1981). These are similar to other volcanic explosions but don't involve new magma and don't produce significant eruption columns; however, they may be followed by much larger eruptions of juvenile material. Undersea volcanoes can also produce large phreatic explosions.

Lahars and jökulhlaups

Lahars are hot or cold mixtures of water and volcanic debris that form when lava, pyroclastic flows, or heated volcanic gases come into contact with water, ice, snow, or loose wet sediments, or when water mixes with poorly consolidated volcanic debris, and may be triggered by sudden rapid mass movements (landslides and flank collapses). Typical lahar speeds on volcano slopes are 15-30 km/h, but speeds as high as 180 km/h have been reported (Rodolfo, 2000). Because lahars may travel great distances rapidly down river channels, have the consistency of wet flowing cement (fluid when moving, solid when at rest), and may have particles ranging from flour-sized to house-sized, they can damage, destroy, or bury people, animals, vegetation, and structures tens of kilometres or more from a volcanic vent. Lahars may cause catastrophic damage even far from a vent. For example, the disastrous 1985 lahar from Nevado del Ruiz, Colombia, destroyed the town of Armero 74 km from the volcano. The prehistoric Osceola Mudflow from Mount Rainier, Washington, traveled more than 120 km (Vallance and Scott, 1997). Deposition by lahars of large amounts of unconsolidated sediment contributes to the hazard from debris flows, floods, dams, dam outburst floods, and river aggradation. Lahars in unconsolidated volcanic debris may continue for many years after an eruption, posing a significant hazard to people and property and a serious ongoing economic issue.

Melting of large amounts of glacial ice by eruptions can also lead to catastrophic releases of large volumes of water as *jökulhlaups*. These are especially common in Iceland, where many volcanoes are located under glaciers.

Landslides, sector collapses, flank collapses, and debris avalanches

Landslides, debris avalanches, and sector or flank collapses (collapses of large portions of a mountain) can occur at volcanoes with or without accompanying eruptions. Large mass movements are common at volcanoes because the rocks are fractured and hydrothermally altered (chemically and physically modified by heated fluids circulating through the rock), rendering the volcanoes structurally unstable, and the terrain may be steep; volcanic debris avalanches include some of the largest recent landslides on earth (e.g. Voight et al., 1981; Crandell et al., 1984). Landslides and other mass movements at volcanoes are very dangerous because, during or soon after an eruption, they may incorporate water and transform into lahars, and runout distances may be tens of kilometres. Large mass movements associated with eruptions can be highly destructive, as was the case with the May 18, 1980 Mount St. Helens eruption, in which a large landslide depressurized the volcano and triggered a powerful laterally-directed blast (Voight et al., 1981; Glicken, 1990). Landslides often fill valleys, blocking drainage pathways, which can lead to upstream flooding and, in some cases, catastrophic outburst floods when a landslide dam is rapidly breached and destroyed. For example, the 2350 BP eruption of Mount Meager, B.C., produced a landslide that dammed the Lillooet River, resulting in a large outburst flood when the dam broke (Evans, 1992; Cordey, 1999; Hickson et al., 1999). One of Canada's largest historic landslides occurred in August 2010 at Mount Meager, and also resulted in the temporary damming of the Lillooet River, although this was not associated with an eruption (Roche et al., 2011; Guthrie et al., 2012).

Unlike other volcano-related hazards in Canada, landslides are relatively common, though all historic events have occurred in the absence of eruptions. Numerous large prehistoric and historic non-eruptive slides of volcanic material have been documented at Mount Garibaldi, Mount Cayley, and Mount Meager in southwestern British Columbia (Moore and Mathews, 1978; Read, 1981; Clague and Souther, 1982; Evans, 1987; Evans and Brooks, 1991; Jordan and Slaymaker, 1991; Hungr and Skermer, 1992; Cruden and Lu, 1992; Clague and Evans, 1994; Jordan, 1994; Bovis and Jakob, 2000; Roche et al., 2011; Guthrie et al., 2012), and it is likely that numerous undocumented mass movements have occurred at more isolated volcanoes. Landslides are likely to pose a significant hazard at these volcanoes during future eruptions.

Volcanic earthquakes

Volcanic earthquakes may be small preeruptive events detectable only by instruments, or larger events associated with explosive eruptions. Quakes large enough for humans to feel may damage property; however, most volcanic earthquakes are too small to pose a shaking hazard. Because seismic activity precedes most eruptions, especially when hundreds or thousands of years have elapsed since the last eruption, volcanic earthquakes are a key tool for detecting and monitoring volcanic unrest and forecasting eruptions. Eruptions at long-dormant volcanoes without significant precursory seismicity (weeks or more) are exceedingly rare and may only occur in very specific circumstances (Soosalu and Einarsson, 2002; Castro and Dingwell, 2009).

Tsunamis

Tsunamis are water waves (sometimes inaccurately called “tidal waves”) that can result from submarine earthquakes or, more rarely, from volcanic eruptions or the entry of landslides, mudflows, or pyroclastic flows into large bodies of water. About 5% of all historic tsunamis have been generated at volcanoes, including some of the most destructive tsunamis known (Nomanbhoy and Satake, 1995; Masson et al., 1998; Urgeles et al., 1999; Begét, 2000); two of the better-known examples are those produced by the eruptions of Krakatau in 1883 (Carey et al., 2000) and Santorini during the late Bronze Age (McCoy and Heiken, 2000). Volcanic tsunamis can threaten huge areas when volcanoes are located on islands or along coasts. Because no large Canadian volcanoes are located along coastlines or shorelines, the generation of volcanic tsunamis from land-based Canadian volcanoes is improbable. Nearby submarine volcanoes off Canada’s west coast; (about which very little is known) may be a potential source; however, volcanogenic tsunamis that affect Canada are more likely to originate at distant volcanoes. Tsunami hazards for Canada are tabulated and discussed in Clague et al. (2003) and in Leonard et al. (2010, 2012), so they are not discussed in detail here.

Volcanic gases and acid rain

Every magma contains dissolved gases which may exsolve (bubble out) from the lava. These gases are most commonly water vapour, carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen, hydrogen sulphide (H_2S), and carbon monoxide (CO). Volcanic gases may, within the volcanic plume or atmosphere, react to form aerosols (dispersions of liquid particles in a gas) such as hydrochloric acid (HCl), hydrofluoric acid (HF), and sulphuric acid (H_2SO_4). Volcanic gases are important constituents of volcanic plumes that may be transported great distances, with or without accompanying ash. Volcanic gas emissions may occur over wide areas or may be concentrated at fumaroles near volcanic vents, and may occur before, during, or after eruptions.

Volcanic gases are harmful in several ways. First, they may be irritating or poisonous or, if present in significant quantities, may block respiration of oxygen, thus posing a threat to people, animals, and vegetation (e.g. Grattan and Pyatt, 1994; Baxter, 2000; Delmelle et al., 2002; Thordarson and Self, 2003). Effects may be indirect: 40% of volcano-related deaths between 1600 and 1980 were caused by gases through the destruction of crops, which contributed to human starvation and disease (Williams-Jones and Rymer, 2000). Second, the release of sulphur dioxide may result in the formation of acid rain which can promote the leaching of heavy metals into drinking water (as has been observed in Hawaii), a phenomenon that could have long-term health effects (Wright and Pierson, 1992). Third, sulphur dioxide and sulphate aerosols may damage aircraft flying at cruising altitudes (Bernard and Rose, 1990; Casadevall et al., 1996; Miller and Casadevall, 2000). Finally, volcanic gases may affect climate (a complex and potentially long term indirect effect of volcanism that is discussed below).

Measurement of volcanic gas emissions is a useful tool for monitoring volcanoes and generating eruption forecasts (supported by seismic and deformation monitoring), especially as remote sensing methods for volcanic gas detection and measurement have improved in recent decades. Detection of SO_2 clouds is also useful for reducing volcanic ash hazards to aviation, because SO_2 is frequently accompanied by ash (Carn et al., 2008).

Tephra

The term *tephra* refers to all fragmental material ejected from a volcano. *Volcanic ash* comprises fragments smaller than 2 mm (which may be as small as thousandths of a millimetre), while larger fragments are called *bombs* and *blocks*. Large fragments may be ejected at high velocities (as high as 660 m/s), resulting in direct injuries or death (e.g. Baxter, 1990, 2000; Baxter and Gresham, 1997), and superheated ballistic projectiles can also ignite fires. However, the large size of volcanic blocks and bombs means that they typically fall to earth within a few kilometres of the vent.

Volcanic ash may be produced in large quantities during an explosive eruption. As the fragmenting material is ejected from the vent, the eruption column entrains ambient 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 it spreads laterally and downwind, dispersing tephra. 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 then 35 km). Volcanic ash is unlike the soft fluffy ash produced by burning wood; it 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).

Ash poses a serious threat to aircraft, even at low concentrations, because its abrasiveness can damage engine parts, windows, flight surfaces, and any protruding parts, its small size allows it to contaminate almost any part of an aircraft, and its melting temperature (about 1100°C) is below that of jet engines operating at normal thrust, so it can be ingested into engines and melted, causing severe damage (e.g. Casadevall, 1994; Guffanti et al., 2009, 2010; Prata and Tupper, 2009). Electrical charging of ash and aerosol particles may cause lightning within a volcanic plume, which could also affect aircraft and electrical equipment. On or near the ground, volcanic 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 (Blong, 1984; Brantley et al., 1992; Stewart et al., 2006), irritate or damage eyes, and pose a health risk to people with respiratory problems (e.g. Baxter, 2000; Horwell and Baxter, 2006). Heated and electrically charged ash particles may potentially interfere with radio communications (Gilbert and Lane, 1994). Cleanup of ash can be very tedious, time-consuming, and expensive, and ash may be resuspended during cleanup or many years after an eruption (e.g. Hadley et al., 2004). The release of large amounts of volcanic ash into the atmosphere, coupled with the effects of volcanic gases, may have long-term effects on climate (discussed below).

Due to its ability to be carried great distances by wind, volcanic ash may affect regions thousands of kilometres from the source, even when eruptions are comparatively small, as was prominently demonstrated during the 2010 eruption of Iceland’s Eyjafjallajökull (e.g. Davies et al., 2010). Ash dispersal patterns are challenging to predict, and depend on height of the eruption column, ash particle size, magma composition, eruption continuity (continuous versus punctuated), magma interaction with water (ice, snow, lakes, groundwater), eruption duration, and wind and weather conditions (e.g. Wilson et al., 1980; Mastin et al., 2009; Schwaiger et al., 2012). All of these variables can change with time, even during a single eruption. Thus, it is extremely challenging to predict in advance where ash from a hypothetical future eruption will be dispersed. 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; Cahill et al., 2010; Schwaiger et al., 2012).

Effects on ecology or climate

Large eruptions can cause severe to catastrophic local ecological damage due to the direct effects of lava, lahars, pyroclastic density currents, landslides, gases, and tephra (e.g. burial of vegetation or waterbodies by lava or debris). Vegetated zones often recover from light to moderate ash falls (<2.5 cm) by the next growing season, but recovery from very heavy ash falls may take years, decades, or longer (Cook et al., 1981; Neild et al., 1998; Thornton, 2000). The degree of damage to plants is widely variable between species, and how harmful an ash fall event is depends not only on ash thickness but on its chemical makeup, particle size, and the season during which it falls (e.g. Cronin et al., 1998). The degree of harm to animals also varies between species and with ash characteristics: insects may be killed by very fine ash, due to its abrasiveness (Thornton, 2000), while larger animals may not be significantly harmed, even if they ingest ash while feeding. If there is significant fluorine concentrated at the surface of ash, this may cause poisoning in livestock who ingest ash-covered vegetation (e.g. Cronin et al., 1998; Neild et al., 1998). Water percolating through highly fractured and chemically altered volcanic rocks can also leach toxic metals from the rocks, contaminating springs in a form of natural pollution (Bortleson et al., 1977).

Very large eruptions may also have complex regional to global atmospheric effects, both due to volcanic ash injection into the atmosphere and to the large amounts of gases emitted (e.g. Bekki et al., 1996; Bluth et al., 1997; Textor et al., 2003; Gao et al., 2008; Robock et al., 2009; Gavin et al., 2011; Ayris et al., 2013). The conversion of SO_2 to sulphuric acid and the formation of sulphate aerosols can cause reflection of solar radiation back into space, leading to atmospheric cooling, while volcanic CO_2 has been postulated to cause warming, although the effect may not be significant relative to anthropogenic CO_2 (Gerlach, 2011). The climatic effects of volcanism have been demonstrated by decreases in global temperatures after several large historic eruptions, including the 1991 eruption of Mount Pinatubo in the Philippines, which injected about 20 million metric tonnes of SO_2 into the stratosphere, cooling the earth's surface by as much as 1.3°C during the following three years (McCormick and Veiga, 1992; Long and Stowe, 1994), and there is evidence that very large ancient eruptions had even more significant effects on climate and thus on human civilizations (e.g. Pang, 1991; Fedele et al., 2002; Machida and Sugiyama, 2002; Thordarsson et al., 2009). It is postulated that very large eruptions can contribute to extinctions (e.g. Ambrose, 1998; Courtillot; 1999; Rampino and Ambrose, 2000; Rampino and Self, 2000; Courtillot and Thordarsson, 2005). However, it is also worthwhile to note that climate changes resulting from large eruptions are complex, and while some regions may experience negative effects, other regions may experience positive effects (Neumann, 1990; Grattan, 2006). It is also unclear just how severe the climatic effects of some huge eruptions, such as the 74,000 BP Toba eruption, were; they may not have been as devastating as originally believed (e.g. Eastwood et al., 2002; Oppenheimer, 2002). Due to the areas (possibly global) and long time periods involved, and the scale, complexity, and uncertainty of climate effects, they are outside the scope of this annotated bibliography.

Volcanoes have some long-term positive effects, such as influencing soil development (e.g. Ping, 2000), and producing raw materials for industry and commerce (e.g. Dehn and McNutt, 2000), and they are often associated with geothermal resources (e.g. Souther, 1980; Arnórsson, 2000). Many valuable ore deposits are hosted within ancient volcanic rocks.

Volcanic Regions Within Canada

Canada’s young volcanoes can be divided into six belts whose geographies are related to the regional tectonics of northwestern North America: the Garibaldi Volcanic Belt, the Clearwater-Quesnel volcanic province, the Anahim Volcanic Belt, the Northern Cordilleran volcanic province, the Wrangell Volcanic Belt, and the Chilcotin Group basalts. A list of Canadian volcanoes with evidence for eruption during the last 1.8 million years (Pleistocene to Holocene) is given in Appendix 1. Volcano locations are shown in Figure 1.

Garibaldi Volcanic Belt

The Garibaldi Volcanic Belt (GVB) is the northern extension of the Cascade Volcanic Arc of the northwestern United States, which includes well-known volcanoes such as Mount St. Helens, Mount Rainier, and Mount Baker. The GVB formed as a result of eastward subduction of the oceanic Juan de Fuca plate beneath the continental North American plate off the west coast of Vancouver Island (Green et al., 1988; Guffanti and Weaver, 1988; Rohr et al., 1996; Green and Harry, 1999). At the north end of the GVB lies the older Pemberton Volcanic Belt, whose northernmost centre, in the Franklin Glacier area, is dated at 6.8 million years (Baadsgaard et al., 1961; Richards and White, 1970; Richards and McTaggart, 1976; Wanless et al., 1978), although Pleistocene to Holocene volcanic rocks may also be present (Read, 1979; Lawrence, 1979). Volcanism shifted from the Pemberton Volcanic Belt to the Garibaldi Volcanic Belt about 3 million years ago (Barr and Chase, 1974; Green et al., 1988).

The GVB includes the stratovolcanoes Mount Garibaldi, Mount Meager, and Mount Cayley, the Bridge River volcanics, and the Silverthrone volcanic field (Green et al., 1988), as well as the American volcanoes, Mount Baker and Glacier Peak (Guffanti and Weaver, 1988)[12]. Large explosive volcanoes like these are typical of subduction zones, but in Canada's GVB, overall extrusion rates are lower than in central and southern parts of the Cascade Range and eruptions are less frequent (Scott, 1990; Sherrod and Smith, 1990). Many small volcanic centres are closely spaced but not coincident, resulting in complex volcanic fields rather than large central edifices. Many small centres within these fields record interactions between lava and ice.

The GVB contains some of the most potentially explosive young volcanoes in Canada and, because of its proximity to the population centres of southwest B.C., contains those volcanoes most likely to have significant impacts on people and infrastructure. The last major explosive eruption in Canada took place at the GVB's Mount Meager about 2350 years ago (Clague et al., 1995; Leonard, 1995), scattering ash as far as Alberta. A similar explosive eruption today in the Garibaldi Volcanic Belt could produce pyroclastic density currents, lahars, landslides, explosions, volcanic ash, and volcanic gases, and would cause significant damage to areas within a few tens of kilometres of the volcano. Road travel along southwest B.C.'s Sea to Sky corridor would probably be disrupted, and volcanic ash would likely result in major disruptions of air traffic on the west coast (Hickson and Edwards, 2001; Stasiuk et al., 2003). Fortunately, large eruptions are very infrequent in the GVB and, if an eruption occurred, it might be a relatively small lava eruption which would have more limited effects.

A hazard to Canada also exists from Mount Baker, which is located in Washington state, about 24 km south of the Canadian border. Mount Baker does not have a history of major explosive eruptions, although ash-producing eruptions are definitely possible and could deposit ash on Canadian soil, depending on wind conditions. Mount Baker has a long history of debris flows and lahars (Gardner et al., 1995), and this is the primary hazard it poses to Canada. A lahar from Mount Baker

[12] Although Mount Baker and Glacier Peak are included in the Garibaldi Volcanic Belt based on their tectonic affinity and chemistry, they are not discussed at length here because they lie outside Canada's borders. Mount Baker is discussed briefly because it is so close to the Canadian border and may pose a significant lahar hazard to Canada.

could travel downstream via the North Fork or Middle Fork Nooksack River into the lower Nooksack River, overspill a small drainage divide at Everson, Washington, and travel north into Canada via the Sumas River and Johnson Creek, eventually entering the Fraser River. At least fourteen weather-related floods have overspilled the Nooksack River at Everson during the last seventy years (Klohn Leonoff, 1991; Houser, 1997; Kerr Wood Leidal, 2005), and it is likely that a large Nooksack lahar would do the same (Cameron, 1989; Kovanen and Easterbrook, 1999; Easterbrook and Donnell, 2007). This would pose a major threat to the Abbotsford-Sumas Prairie region of southwestern British Columbia. Additionally, there is evidence that the Nooksack River flowed away from Mount Baker and north into Canada, rather than west via the Sumas River, for much of the Holocene (Cameron, 1989; Pittman et al., 2003; Hutchings and Campbell, 2005; Collins and Montgomery, 2011), and there is a possibility that a major flood (whether caused by weather or volcanic activity) could cause another channel avulsion that would reestablish northward flow of the Nooksack River into Canada (Klohn Leonoff, 1991, 1993; Pittman et al., 2003; Hutchings et al., 2007), with severe consequences such as significant changes in the path of the Sumas River and the volume of water it carries.

Clearwater-Quesnel volcanic province

The Clearwater-Quesnel volcanic province[13] (CQVP) is a region of central British Columbia that lies about 250 km inboard of the Garibaldi Volcanic Belt. It includes the Wells Gray – Clearwater volcanic field and the young cones near Quesnel Lake and has been active since about 3.5 million years ago (Hickson, 1987). Volcanism in this region has been attributed to thinning crust and the presence of crust-penetrating structures (Hickson, 1987; Souther, 1991; Souther and Yorath, 1991; Hickson et al., 1995). However, Madsen et al. (2006) have suggested that the volcanism in this region results

[13] This is not a formal name but is used here so that the volcanoes of the Quesnel Lake area may be included with those of the Wells Gray-Clearwater volcanic field. The name was first used by Souther (1991).

from asthenospheric upwelling facilitated by displacement, with extension, along the subducted extension of the Nootka Fault[14].

The CQVP includes numerous small basaltic volcanoes such as Pyramid Mountain, Dragon cone, and Mosquito Mound in the Wells Gray-Clearwater region, as well as the Quesnel cones, which are probably Pleistocene to Holocene in age (Fiesinger and Nicholls, 1977; Campbell, 1978; Kelman, unpublished data). Throughout the period of volcanism, the region has been covered with thick glacial ice at least three times, resulting in many unusual volcanoes with evidence for eruptions beneath ice or lava-ice contact, although there are also subaerial volcanic deposits emplaced between glacial events (Hickson, 1987). The volcanoes of Wells Gray Park have a long history of effusive activity, typically relatively quiet fire-fountaining of lava and the emission of lava flows which, due to their low viscosity, have in some cases flowed several kilometres (Hickson, 1987). The most recent eruption in the CQVP took place about 400 years ago at Kostal cone.

Although it is difficult, in the absence of unrest, to predict what an eruption would be like, a future eruption in the Well Gray area would most likely be similar to past eruptions, involving a small volume of non-explosive lava (Hickson and Edwards, 2001). Such an eruption would have primarily local effects, and might involve lava flows, small explosions, poisonous gases, small lahars, and minor local volcanic ash. The most widespread damage could potentially be caused by lava flows that disrupted, dammed, or rearranged local river drainages or ignited forest fires, or by more violent explosions that would occur if lava erupted into a lake or otherwise in contact with water (Sheridan and Wohletz, 1981). However, such explosions would still be small relative to those that can occur at large stratovolcanoes like Mount St. Helens.

Anahim Volcanic Belt

The Anahim Volcanic Belt (AVB) is a roughly east-west chain of alkaline basaltic and peralkaline silicic volcanoes stretching across central British Columbia, from the west coast just north of Vancouver Island to the Interior Plateau near Quesnel (Bevier et

[14] The Nootka Fault is the boundary between the subducting Juan de Fuca and Explorer plates off the west coast of Vancouver Island.

al., 1979; Rogers, 1981; Souther, 1984, 1986). The oldest volcanoes, near the west end of the belt, erupted about 14.5 million years ago, while the youngest dated rocks are Holocene in age. Because most of the volcanoes get younger from west to east, it has been theorized that they formed due to the North American continent sliding westward over a hot spot (Bevier et al., 1979; Rogers, 1981; Souther et al., 1987). However, it has also been postulated that the AVB formed due to shear melting of the upper mantle due to the edge effect from the subducted Juan de Fuca plate (Stacey, 1974; Madsen et al., 2006), or due to continental rifting. Volcanoes of the AVB include the Ilgachuz and Itcha Ranges, shield complexes built up over long time periods (Stout and Nicholls, 1983; Souther and Souther, 1994), and Nazko cone, the youngest volcano in the belt, which last erupted about 7200 years ago (Souther et al., 1987). Numerous other small postglacial cones are scattered along the AVB. Some of these, including the small volcanoes of the Milbanke Sound group (Baer, 1973; Souther, 1986; Souther, 1990) at the extreme western end of the AVB, do not follow the eastward-younging trend.

The most likely eruption scenario for the Anahim Volcanic Belt would be a cinder cone eruption, which could have significant local effects due to lava, fires, gases, lahars, ash, and ballistic projectiles; however, ash would not be scattered to more distant localities. A challenge to monitoring is that the next eruption may occur at a new site rather than at an existing cone (e.g. Connor et al., 2000), as was the case with Mexico’s Parícutin eruption in 1943 (Luhr and Simkin, 1993). The 2007 seismic swarm near Nazko cone, which was interpreted as an injection of magma into the lower crust (Cassidy et al., 2008; Hickson et al., 2009; Cassidy et al., 2011), is a reminder that this area is still volcanically active.

Northern Cordilleran volcanic province

The Northern Cordilleran volcanic province (NCVP), which includes volcanoes previously assigned to the Stikine Volcanic Belt[15], is a broad area of Neogene to

[15] The name *Stikine Volcanic Belt* was originally defined by Jack Souther (Geological Survey of Canada) for a group of young volcanic deposits centered around the Stikine River in northwest British Columbia. As more rocks in the Cordillera were mapped and dated, the Stikine Volcanic Belt was expanded to include volcanic deposits further and further from the original Stikine

Holocene volcanism (<23 million years old), alkalic and bimodal in composition (though dominated by mafic rocks), which stretches from just north of Prince Rupert, British Columbia into the Yukon Territory. It is the most active volcanic region in Canada, containing more than 100 volcanoes, including the youngest volcanoes known in Canada, at Lava Fork and Tseax cone (Sutherland Brown, 1969; Elliott et al., 1981; Hauksdóttir et al., 1994). The NCVP most likely formed due to transtensional stresses in the western Canadian Cordillera after subduction of the Farallon and Nazca plates, with eruptive events governed by periods of compression and tension of the continental margin related to subtle changes of the motions of the Pacific plate relative to the North American plate (Souther, 1977; Edwards and Russell, 1999, 2000; Madsen et al., 2006). It has also been postulated that subduction of a triple junction, leading to formation of a slab window and mantle upwelling, has played a role in NCVP tectonics (Hole et al., 1991; Thorkelson and Taylor, 1989), with the present-day slab window underlying the NCVP (Madsen et al., 2006). Coupled loading and unloading of the crust by ice sheets may have influenced the timing of NCVP volcanism (Grove, 1974; Hamilton et al., 1997; Edwards and Russell, 1999).

The NCVP includes numerous small volcanoes erupting alkaline basalt, but also includes several large, compositionally diverse central volcanoes (Mount Edziza, Level Mountain, Hoodoo Mountain) which have erupted more silica-rich (and therefore potentially explosive) compositions (Hamilton, 1981; Souther, 1992). The most recent eruption in Canada took place in the NCVP at Lava Fork about 120 years ago (Grove, 1974; Elliot et al., 1981; Souther, 1990). The only known volcanic fatalities in Canada occurred during the NCVP's Tseax cone eruption about 300 years ago (Sutherland Brown, 1969; Higgins, 2009), and were a result of "poisonous smoke", probably carbon dioxide, which causes asphyxiation (Hickson et al., 2007); this eruption is recounted in the oral histories of the Nisga'a people (Barbeau, 1935).

Volcanic Belt. (The Paleozoic "Stikine Assemblage" of volcanic and sedimentary rocks is also found in the Stikine region of British Columbia, but it is much older and unrelated to the Neogene to Recent volcanism, and this name duplication is a source of potential confusion.) Edwards and Russell (1999) redefined this broad area of volcanism as the *Northern Cordilleran volcanic province* (NCVP), and I have used this nomenclature. The name "Stikine Volcanic Belt" may still be used to refer to a subset of NCVP volcanoes located near the Stikine River, although this subset is not well-defined.

Wrangell Volcanic Belt

The Wrangell Volcanic Belt stretches more than 500 km across southern Alaska and into adjacent Canada, and lies at about 90° relative to the nearby Aleutian arc. It is located at the northern margin of the Pacific plate, where there is a west to east transition from normal subduction to flat-slab subduction to transform tectonics (Plafker et al., 1989; Chapman et al., 2008; Haeussler, 2008). Subduction of the Yakutat microplate in this region has produced the Wrangell volcanoes, which are dominantly large andesitic stratovolcanoes (Thorkelson and Taylor, 1989; Miller and Richter, 1994; Preece and Hart, 2004; Enkelmann et al., 2010). Volcanism commenced about 26 million years ago, has been migrating northward since about 14 million years ago (concomitant with a northwestward shift in plate convergence; Trop et al., 2012), and has continued into the Holocene, so the youngest, active volcanic centres lie in Alaska, not Canada (Kienle and Nye, 1990).

The Wrangell Volcanic Belt includes the large volcano Mount Wrangell, as well as Mounts Churchill and Bona, which have been postulated to be the source of the two large Holocene White River Ash eruptions that spread ash over thousands of square kilometres of northern Canada in eruptions about 1800 and 1150 years ago (Bostock, 1952; Lerbekmo et al., 1969, 1975; McGimsey et al., 1992; Clague et al., 1995; White and Donaldson, 2000). However, recent ice coring at Churchill-Bona indicates that the source is likely to be not Churchill but a vent beneath the nearby Klutlan Glacier (Mashiotta et al., 2004; Lerbekmo, 2008). Traces of the eastern lobe of the White River Ash are detected as far away as Newfoundland (Pyne-O'Donnell et al., 2012) and a visible ash layer has been mapped into the Northwest Territories, indicating a large eruption with significant long-reaching effects. At least two other Holocene tephra layers in southeast Alaska may have originated from the same source as the two large White River Ash deposits (Payne et al., 2008). None of the volcanoes in the Canadian portion of the Wrangell Volcanic Belt have been active during the Holocene. However, any future large explosive eruptions in the American portion of the Wrangell Volcanic Belt could deposit significant volcanic ash on Canada, just as the prehistoric White River

Ash eruptions did (Bostock, 1952; Lerbekmo et al., 1975; McGimsey et al., 1992; Clague et al., 1995; White and Donaldson, 2000).

Chilcotin Group basalts

The Chilcotin Group basalts comprise a zone of regionally extensive but discontinuous and thin, small-volume, flat-lying transitional to alkalic basaltic lava flows covering about 17,000 km^2 of British Columbia's Central Interior Plateau (Bevier, 1983 a, b; Mathews, 1989; Dohaney, 2009; Dohaney et al., 2010; Farrell, 2010; Andrews et al., 2011) and overlapping the Anahim Volcanic Belt in the north. Chilcotin volcanism is thought to be a result of extension of the crust behind the coastal subduction zone (back-arc extensional volcanism) (Bevier, 1983a, b) but likely involved subduction of a slab window whose edge is now situated near the northwest extent of the Chilcotin Plateau (Madsen et al., 2006; Andrews et al., 2010). Chilcotin eruptions commenced about 31 million years ago, although most eruptions happened 6-10 million years ago and 2-3 million years ago (Mathews, 1989), the latter erupting simultaneously with the early stages of Garibaldi Volcanic Belt activity. In addition there have been a few eruptions in the Pleistocene (11,700 to 1.8 million years ago). It is likely that most eruptions were small-volume, short-duration events from widely dispersed volcanoes across the Interior Plateau, with thin lava veneers on plateau surfaces and thick accumulations in valleys (Andrews et al., 2011). Many of these flows have now been eroded substantially. Figure 1 and Appendix 1 include only the Chilcotin flows that are of Pleistocene age (younger than 1.8 million years). The possibility of future Chilcotin volcanism is probably low but is not known.

Volcanic Hazards from the United States

Outside of Canada, several regions in the United States have the potential to directly affect Canada with one or more volcanic hazards. They are discussed briefly here, as an introduction, but are not included in the bibliography because this would have significantly increased its length.

The Cascade Volcanic Arc of Washington, Oregon, and California, is the southward continuation of the convergent margin that includes the Garibaldi Volcanic Belt, although a 90 km long non-volcanic gap separates the Garibaldi Volcanic Belt of southwestern British Columbia and northern Washington from the southern segments of the arc (Guffanti and Weaver, 1988). The American portion of this arc includes many volcanoes that have been repeatedly active during the last 10,000 years, including Mount St. Helens, which has erupted repeatedly throughout the Holocene and left two widespread ash layers within Canada (layer Yn, erupted around 4300 years ago [Mullineaux et al., 1975; Mullineaux, 1996], and layer Wn, erupted around 520 years ago [Mullineaux et al., 1975; Mullineaux, 1996]), and Mount Mazama, which experienced a massive eruption about 7300 years ago (Hallett et al., 1997; Zdanowicz et al., 1999; Bacon and Lanphere, 2006), forming modern Crater Lake and spreading ash over much of North America. The Mazama ash was so widespread that it is still present as a visible layer at sites in Saskatchewan (David, 1970), and traces of it have been found in Newfoundland (Pyne-O'Donnell et al., 2012). The principal hazard posed to Canada by volcanoes in the American Cascades is ash fall, since most volcanoes are far from the Canadian border. The exception to this is Mount Baker, which is considered part of the Garibaldi Volcanic Belt segment of the Cascade Arc and is discussed above, with the rest of the Garibaldi Volcanic Belt.

Other possible volcanic ash hazards to Canada from the conterminous United States could come from the Long Valley caldera or other young volcanoes of California and the American southwest. There is also the possibility of ash or other hazards from an eruption at the Yellowstone Plateau volcanic field, which has experienced some of the world's largest known eruptions: an eruption of more than 1000 km^3 (VEI 8), the Lava Creek eruption 640,000 years ago, formed the present caldera, which is 45 by 85 km in size (Lanphere et al., 2002), although no magmatic eruptions have occurred since the late Pleistocene (Christiansen et al., 2007). A major Yellowstone eruption would have widespread effects; however, the probability of such a huge eruption occurring within our lifetimes is extremely low, and there are currently no indications of preeruptive unrest at Yellowstone. Some researchers speculate, based on chemical evidence, that the Yellowstone Caldera is in the final stages of its magmatic cycle and is “dying”, and is thus unlikely to experience future large eruptions (Watts et al., 2012).

The other nearby source of volcanic hazards for Canada is Alaska. The Wrangell Belt (which continues into Canada) is discussed above. However, the Alaskan “panhandle” also contains numerous volcanoes that have been active in the Pleistocene to Holocene and might be considered as part of the Northern Cordilleran volcanic province, notably, the Mount Edgecumbe volcanic field (e.g. Riehle and Brew, 1984; Riehle, 1996; Addison et al., 2010), which produced widespread ash during the late Pleistocene, and at least two smaller, localized ash deposits during the Holocene (Riehle, 1996). At least 12 new volcanoes were also recently discovered in the Alaskan panhandle (Karl et al., 2011; Oskin, 2013). Aleutian volcanoes, including those of the Cook Inlet (Redoubt, for example), are another possible ash source, as numerous historical eruptions have occurred in this region. There is a long Quaternary record of Alaska-sourced ash falls in the Yukon (e.g. Preece et al., 2000, 2011).

It is also possible, though extremely improbable, that ash could fall on Canada from a more distant source, such as Iceland, however, a very large eruption combined with suitable wind conditions would be required. For Iceland, the most common eruption styles, the great distance from Canada, and the prevailing winds which tend to carry ash over Europe make any ash fall on Canada extremely unlikely, although low concentrations of ash could interfere with aviation in Canadian airspace. Even though the 2010 Eyjafjallajökull eruption (VEI 4) did not cause ash to fall on Canadian soil, the air travel disruptions that it produced give some idea of the possible problems that an explosive eruption in or near Canada might generate.

Volcano Monitoring Within Canada

Volcanic eruptions are almost always preceded by hours, days, weeks, months, or even years of precursory activity which reflects the movement or pressurization of magma. These signs of unrest include earthquakes, ground deformation, gas emissions, and heat anomalies, and they are readily detectable by volcano monitoring –

the systematic collection, analysis, and interpretation of observations and instrumental measurements at volcanoes before, during, and after eruptions. Although geologic mapping can establish the past behaviour of a volcano and is useful for producing hazard maps and long-term forecasts of volcanic behaviour (decades to centuries), monitoring is essential for generating short-term forecasts of impending eruptions. Monitoring changes in volcanic activity, especially in the size, type, and rate of seismic activity, is crucial, and any program aimed at mitigating volcanic hazards must include effective volcano monitoring (e.g. Ewert and Swanson, 1992; McNutt et al., 2000; Tilling, 2008; Donovan et al., 2012; Marzocchi et al., 2012; Zoback et al., 2013). Ideally, volcanoes with the potential to erupt would be monitored continuously, providing baseline information prior to unrest, but this is impractical for most volcanoes due to the expense and logistical challenges, and most of the world's potentially active volcanoes are not monitored regularly[16].

The most common indicator of volcanic unrest is unusual seismic activity (swarms of hundreds or thousands of small earthquakes, in most cases detectable only with seismometers). Deformation of the earth's surface (also usually only detectable with instruments) is another common volcanic precursor that can be used in monitoring, either through surveying methods (crack measurement, triangulation, leveling, Electronic Distance Measurement [EDM], campaign GPS, or gravity measurements), continuous direct monitoring (GPS stations, electronic tiltmeters, borehole tilt, or gravity measurements), or remote sensing (e.g. InSAR [Interferometric Synthetic Aperture Radar], photogrammetry, LIDAR [Light Detection and Ranging]). Volcanic gas emissions (especially water vapour, carbon dioxide, and sulphur dioxide) also provide information that can be used in eruption forecasting and analysis, and gases may be monitored with ultraviolet spectrometry (e.g. COSPEC, FLYSPEC, Mini-DOAS), LI-COR (infrared spectrometry), FTIR (Fourier Transform Infrared Spectrometry), direct gas sampling of fumaroles, on-site continuous monitoring using chemical sensors, or satellite remote sensing (OMI [Ozone Monitoring Instrument], OMPS [Ozone Mapping Profiler Suite], TOMS [Total Ozone Mapping Spectrometer], and other satellite

[16] It is noteworthy that of the 21 most explosive eruptions of the past 10,000 years worldwide, 17 erupted for the first time in recorded history (Simkin and Siebert, 1984), so it can be very challenging to prioritize monitoring of infrequently active volcanoes.

instruments). Thermal anomalies can be monitored with infrared cameras. Doppler radar and various satellites can monitor volcanic ash clouds. Stream gauges and other instruments can be used to monitor eruption-related changes in rivers and lakes. Infrasound sensors can be used to detect explosions. Acoustic flow monitors can detect lahars. Microgravity, resistivity, and magnetotelluric studies are also now becoming more common monitoring methods.

Periods of unrest that do not lead to eruption, like Canada's 2007 Nazko seismic swarm (Cassidy et al., 2008; Hickson et al., 2009; Cassidy et al., 2011), are not uncommon in volcanic regions, and numerous magmatic intrusions associated with unrest either stall at deep levels or become "failed eruptions" (i.e., magma stalls at less than 2-3 km depth before reaching the earth's surface [Moran et al., 2011]). Rapid magma ascent (cm/s to dm/s), high gas content, high gas pressure, decompression, high magma supply rate, and the presence of pathways leading to the surface would tend to promote eruption while slow ascent, degassing, low magma supply rate, and structural barriers would tend to hinder eruptions (Moran et al., 2011). However, unrest related to deep intrusions and "failed eruptions" still requires monitoring because it may not be clear what the outcome of unrest will be until considerable time has elapsed. Even with adequate volcano monitoring, there is always some uncertainty in volcanic eruption forecasts, and this poses a challenge for both volcanologists and emergency planning and response personnel. Unrest that is not followed by an eruption can still have significant psychological and economic impacts on communities near volcanoes.

In Canada, there is no ongoing monitoring at individual volcanoes because eruptions are so infrequent. NRCan's Canadian National Seismograph Network (CNSN) currently monitors the volcanic regions in British Columbia for earthquakes of approximately magnitude 2 or higher, although the magnitude threshold for earthquake detection in some areas is less than 2. Seismograph stations established in 1981 near Dease Lake (in the Northern Cordilleran volcanic province) and Whistler (in southwest British Columbia's Garibaldi Volcanic Belt [GVB]) substantially improved the seismic monitoring of some potentially explosive volcanoes. However, depending on the location, duration, and magnitude of volcanic seismicity, Canada's network may not be sufficiently sensitive to detect volcanic unrest in time for effective eruption forecasting. It is reassuring, however, to note that for closed volcanic systems which have not erupted in decades or centuries (like all of Canada's volcanoes), the lack of an available magma path to the earth's surface means that more significant preeruptive seismicity is probable: typically, the more work is required to bring magma to the surface, the more seismic activity is recorded (e.g. White and McCausland, 2013; Zoback et al., 2013). However, rapidly escalating activity over a short time period may, in very rare cases, still lead quickly to eruption (e.g. Basualto, 2008; Castro and Dingwell, 2009).

If volcanic unrest were detected in Canada, NRCan would respond by adding site-specific monitoring in order to determine what was happening. During the first days of the 2007 Nazko region seismic swarm, NRCan installed additional seismic stations, collected soil gas samples, and performed a physical reconnaissance of the area, and a rapid preliminary hazard assessment was done (Hickson et al., 2009). The swarm ended after two months, and was ultimately interpreted as being caused by the injection of magma into the lower crust (Cassidy et al., 2008, 2011). In the event of future unrest, NRCan would respond similarly, with the intensity of response correlating with any escalation in unrest, and would work closely with emergency planning agencies, the media, and the public to ensure that accurate hazard information was disseminated as it became available[17]. Such a reactive strategy (a flexible response to a developing volcanic crisis rather than targeted pre-unrest monitoring) is potentially workable, as was demonstrated during the large Mount Pinatubo eruption in 1991 in the Philippines, when unrest occurred at a previously unmonitored and understudied volcano (Newhall et al., 1996; Tilling, 2008); scientists and authorities installed additional monitoring equipment, prepared hazard maps, and evacuated people in response to escalating activity, and in spite of the size and unexpectedness of this eruption in a heavily populated area, the loss of life was small relative to the numbers of people at risk. However, not all volcanic crises, whether at monitored or unmonitored volcanoes, have been managed so successfully. Due to the scientific, logistical, and human challenges in monitoring a complex and changing situation, the margin of safety during a volcanic crisis, especially one in which activity escalates rapidly, may be narrow.

[17] The Interagency Volcanic Event Notification Plan (IVENP) provides a communications protocol for informing key agencies of the sudden onset of volcanic activity, ensuring that the aviation community is quickly made aware of potential ash hazards.

Conclusion

Canada’s volcanic hazard situation is uniquely challenging to manage for many reasons. Challenges inherent to any study of volcanoes are the difficulty in estimating eruption recurrence intervals (due to the underrepresentation of many volcanic events in the geological record), the difficulty in determining the age of many volcanic rocks (thus establishing that recent eruptions have occurred), the possibility that an eruption may last for years, the necessity to consider the large areas that may be affected by volcanic hazards (millions of square kilometres), and the existence of multiple volcanic hazards that operate at different ranges and time scales and can harm people and property in different ways. Problems specific to Canada’s geology and geography include the location of many volcanoes in remote areas, the lack of historical eruptions, and the presence of glaciers obscuring the summit areas of many volcanoes. Volcanological research is expensive, and Canada has only a small number of volcano researchers. There is competing pressures to study other, more frequent, natural hazards (earthquakes, landslides, severe storms, etc.). Finally, studies of volcanic hazards originating outside Canada necessitate coordinating with agencies outside Canada. All of these factors contribute to the paucity or lack of knowledge about most Canadian volcanoes. However, because volcanoes are among the few hazardous natural phenomena that exhibit precursory activity on time scales that can be used to take meaningful action, and because the consequences of even a small eruption could be significant, it would be irresponsible to ignore this potentially significant hazard. This annotated bibliography and the complementary map, A Preliminary Volcanic Ash Fall Susceptibility Map of Canada (Kelman, 2015), represent important steps in gaining a better understanding of volcanic hazards to Canada and being better prepared to deal with volcanic unrest within or near Canada.

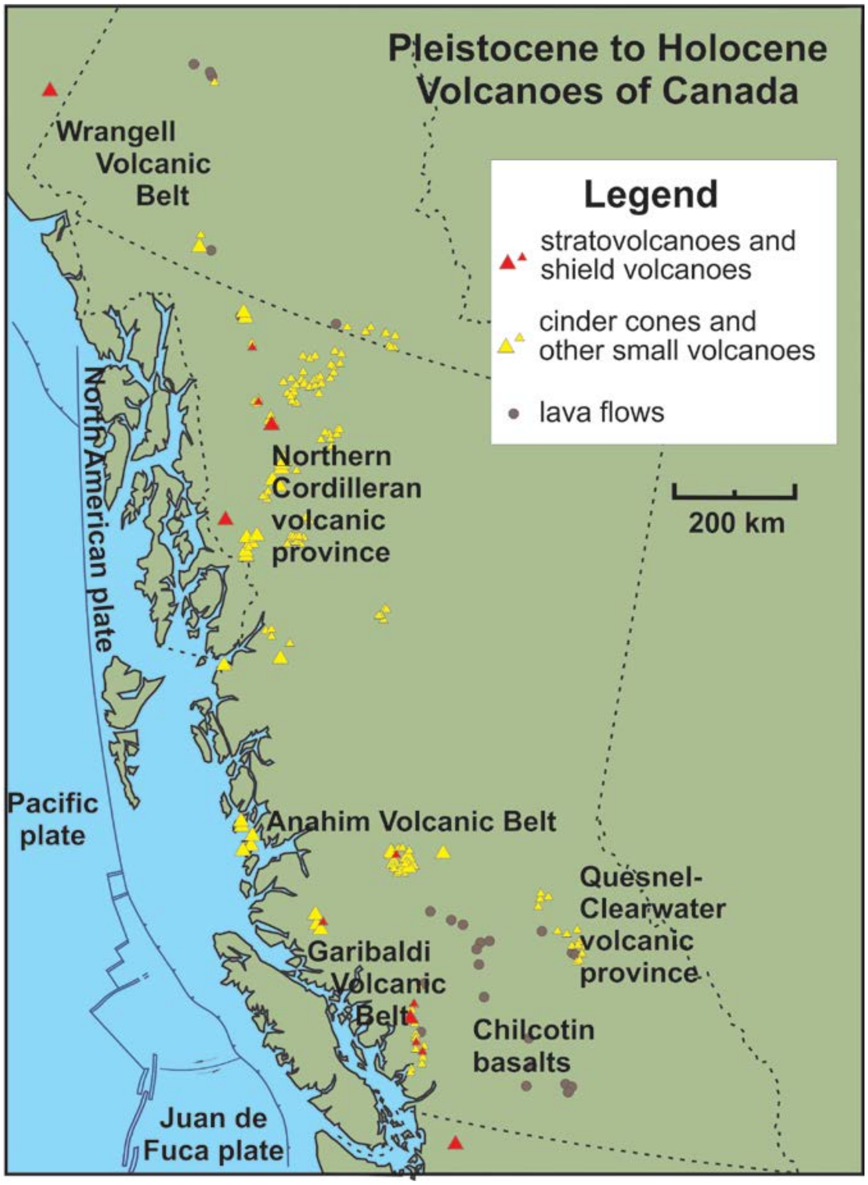

Figure 1. Map of Canadian volcanoes active in the last 1.8 million years. The six volcanic belts are shown: the Garibaldi Volcanic Belt, Quesnel-Clearwater volcanic province (Wells Gray-Clearwater volcanic field and Quesnel cones group), the Anahim Volcanic Belt, the Northern Cordilleran volcanic province (including the Stikine Volcanic Belt), the Wrangell Volcanic Belt, and the Chilcotin Group basalts (only flows of Pleistocene or younger age are shown). Note that American volcanoes are not shown, except for Mount Baker, Washington and Mount Churchill, Alaska. The Wrangell Volcanic Belt within Canada is mostly older than Pleistocene, so is minimally populated with volcanoes. Large symbols are for Holocene volcanoes and small symbols are for Pleistocene volcanoes.

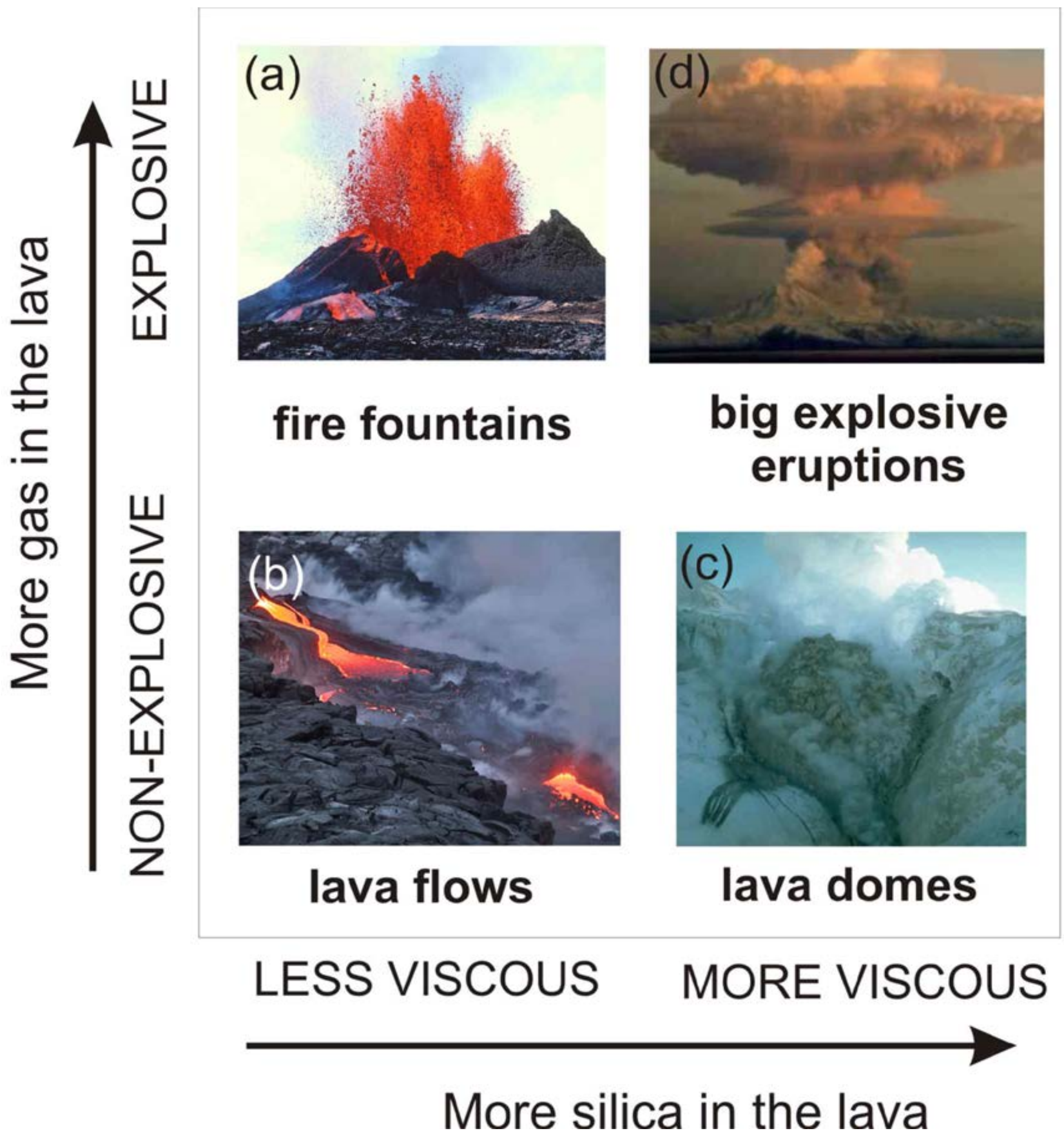

Figure 2. Relationship of magmatic silica (SO_2) content and gas content to eruptive style. Images are courtesy of: (a) and (b) Hawaii Volcano Observatory (HVO), (c) and (d) Alaska Volcano Observatory (AVO).

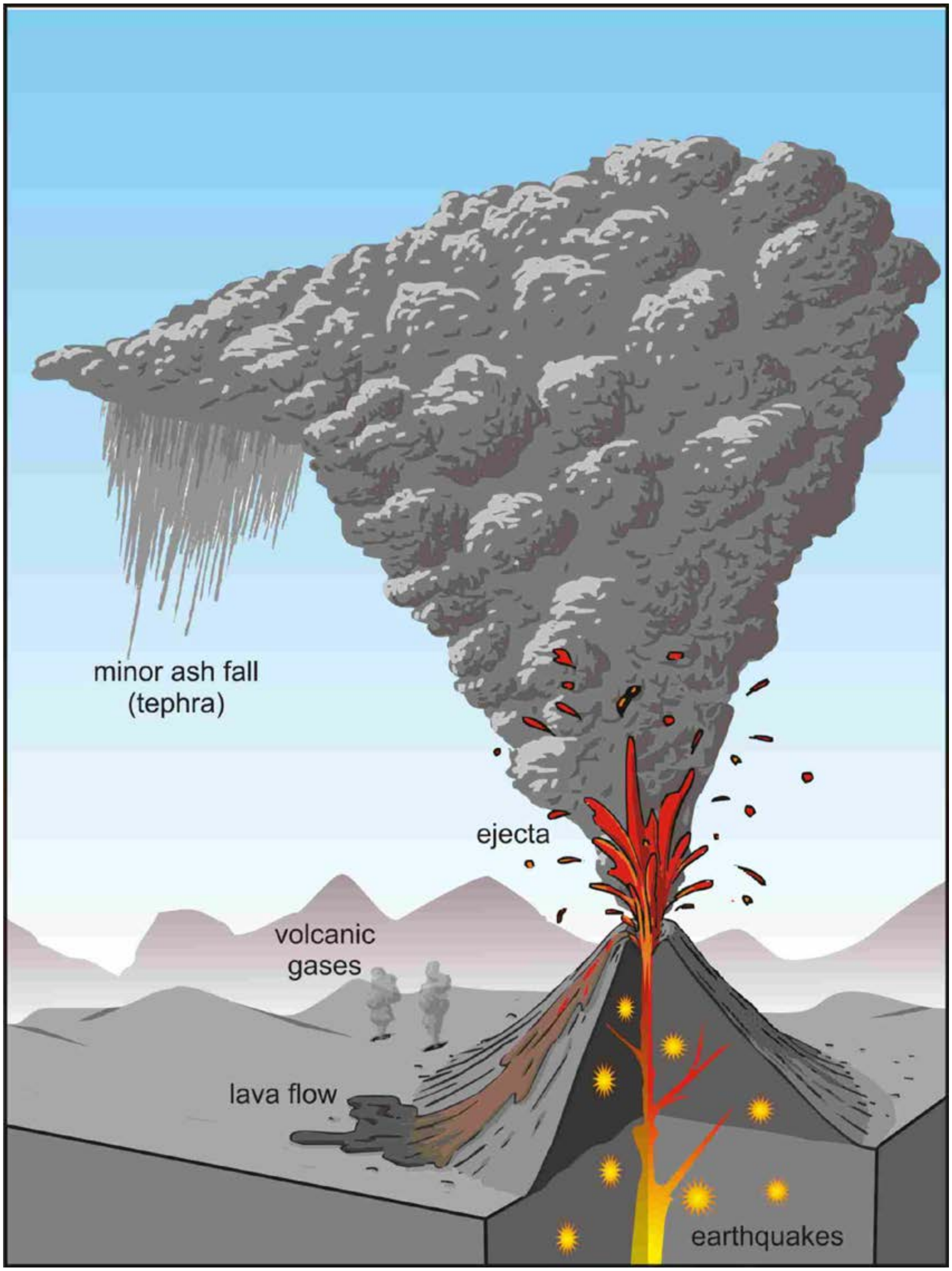

Figure 3. (a) Hazards associated with a cinder cone eruption: lava flows, ejecta (volcanic blocks and bombs), minor ash fall (tephra), volcanic gases, and earthquakes.

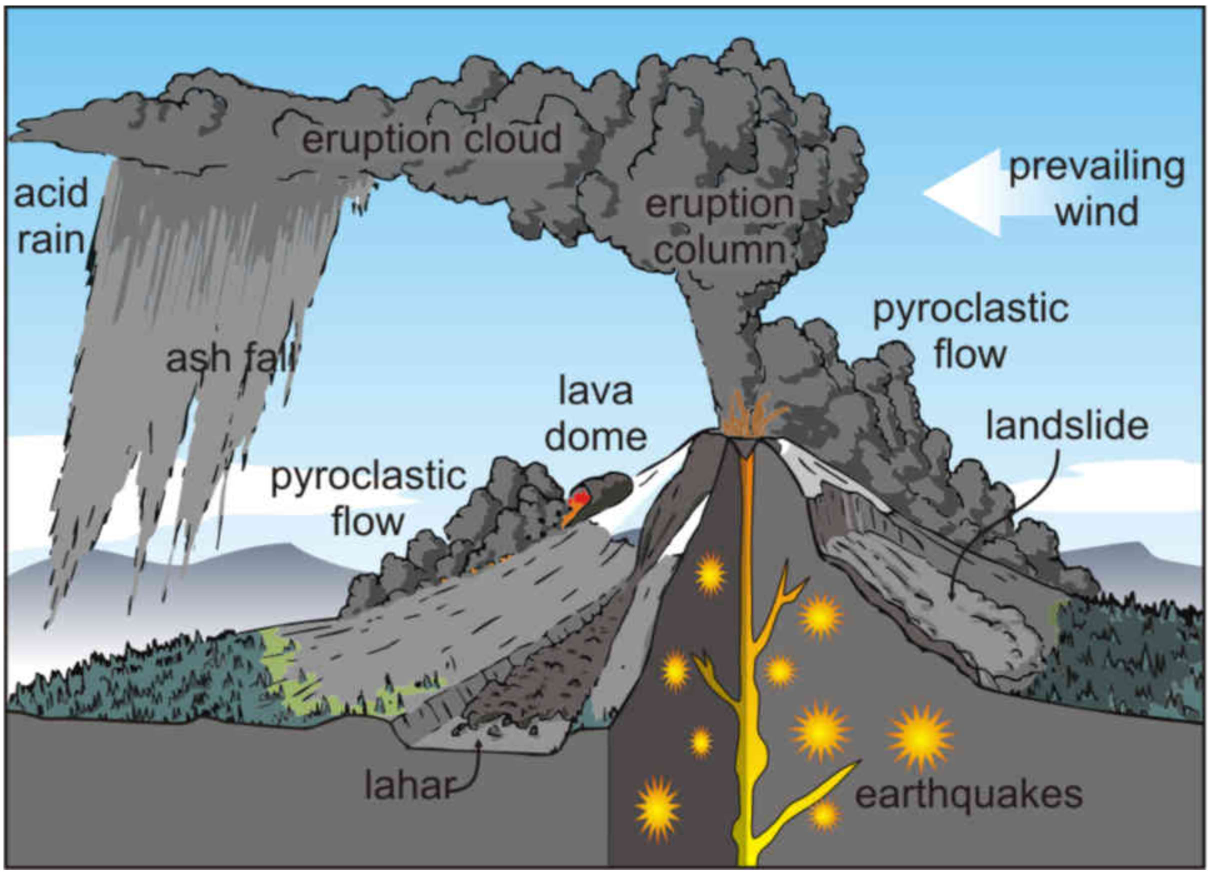

Figure 3. (b) Hazards associated with a large explosive volcanic eruption: lava domes, pyroclastic flows, landslides, lahars, volcanic ash (tephra), acid rain, earthquakes, and volcanic gases.

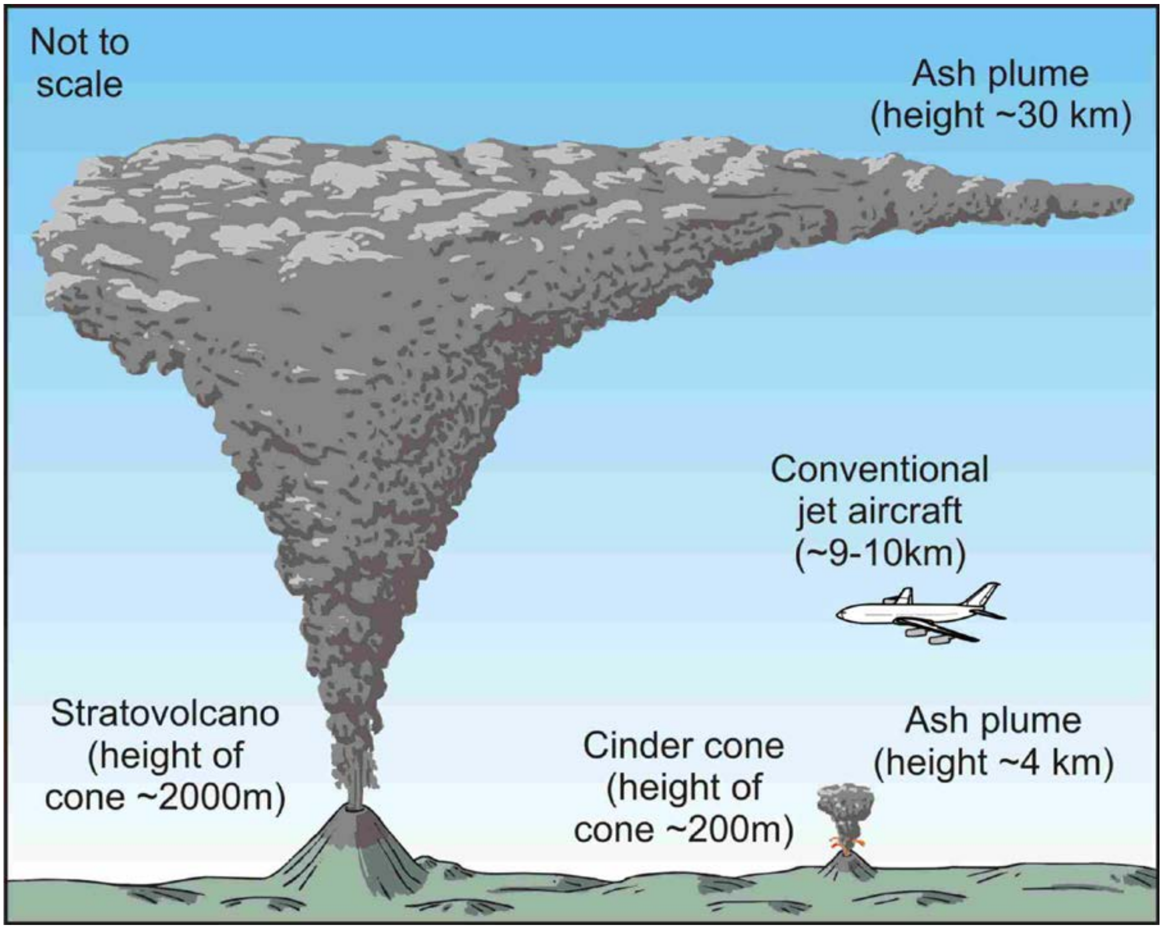

Figure 3. (c) Relative scale of a large explosive eruption versus a cinder cone eruption. The ash plume from a large stratovolcano eruption may be 30 km high or more, while the plume from a cinder cone eruption is typically less than 4 km. This, plus the significantly greater quantity of ash that may be ejected during the former, means that explosive stratovolcano eruptions tend to have much more widespread effects than cinder cone eruptions, and pose a much greater threat to aviation.

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Abstract: In 2008, a Vibroseis seismic reflection survey was acquired by Geoscience BC across the eastern part of the volcanic-covered Nechako basin in central British Columbia, where Cretaceous sedimentary rocks have been exhumed along a NNW trend. Good signal penetration through the volcanic cover is indicated by lower crustal reflections at 8-12 s, which were recorded by the entire seismic survey. Comparison of the 2008 seismic survey with data from a previous survey indicates that the lack of reflectivity in the earlier surveys is generally representative of the subsurface geology. The seismic data show that 1700 and 2900 m thick sub-basins are present at the northern and southern ends of this trend, but the intervening Cretaceous rocks are discontinuous and relatively thin. The creation of a passive-roof duplex by Campanian or later low-angle thrusting is inferred within the thickest Cretaceous strata, but elsewhere faulting is likely related to Eocene extension or transtension. Seismic reflections are also recorded from folded volcanic stratigraphy, the base of the surface volcanic rocks, an underlying volcaniclastic stratigraphy, and intrusions projecting into a Quaternary volcanic cone. Seismic interpretation is complemented by coincident audiofrequency magnetotelluric surveys, from which faulting is inferred at offsets in a regional conductor. No regionally extensive stratigraphy can be identified within the seismic data, and the central Nechako basin appears to be a complex network of small, deformed sub-basins, rather than a single large basin.

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Abstract: Volcanism in association with large quantities of ice manifests itself in a variety of morphological forms developed under differing physical conditions. These physical conditions include the location, amount, thickness, and type of confining ice, the location and quantity of trapped water, and the surrounding topography. Ice in the form of thick continental ice sheets, thinner alpine glaciers or even perennial accumulations of snow can influence the resulting morphological form of the volcano. The chemical composition of the erupting magma, effusion rate and total erupted volume will also affect the shape of the resulting edifice. Quaternary volcanoes influenced by many of these factors are found in western Canada. The morphological forms range from tuyas to subglacial mounds to stratovolcanoes. This paper provides a review of ice-contact volcanism and volcanic products formed in these environments using Canadian examples for illustration.

Madsen, J.K., Thorkelson, D.J., Friedman, R.M., and Marshall, D.D., 2006. Cenozoic to Recent plate configurations in the Pacific Basin; ridge subduction and slab window magmatism in western North America; Geosphere, v. 2, no. 1, p. 11-34.

Abstract: Forearc magmatic rocks were emplaced in a semicontinuous belt from Alaska to Oregon from 62 to 11 Ma. U-Pb and ^{40}Ar-^{39}Ar dating indicates that the magmatism was concurrent in widely separated areas. Eight new conventional isotope dilution-thermal ionization mass spectrometry (ID-TIMS) U-Pb zircon ages from forearc intrusions on Vancouver Island (51.2±0.4, 48.8±0.5 Ma, 38.6±0.1, 38.6±0.2, 37.4±0.2, 36.9±0.2, 35.4±0.2, and 35.3±0.3 Ma), together with previous dates, indicate that southwestern British Columbia was a particularly active part of the forearc. The forearc magmatic belt has been largely attributed to ridge-trench intersection and slab window formation involving subduction of the Kula-Farallon ridge. Integration of the new and previous ages reveals shortcomings of the Kula-Farallon ridge explanation, and supports the hypothesis of two additional plates, the Resurrection plate (recently proposed) and the Eshamy plate (introduced herein) in the Pacific basin during Paleocene and Eocene time. We present a quantitative geometric plate-tectonic model that was constructed from 53 Ma to present to best account for the forearc magmatic record using ridge-trench intersection and slab window formation as the main causes of magmatism. The model is also in accord with Tertiary to present inboard magmatic and structural features.

Manthei, C.D., Ducea, M.N., Girardi, J.D., Patchett, P.J., and Gehrels, G.E., 2010. Isotopic and geochemical evidence for a recent transition in mantle chemistry beneath the western Canadian Cordillera; Journal of Geophysical Research, v. 115, no. B2, 1 p.

Abstract: New petrologic, geochemical, and isotopic data are reported from a suite of mafic dike and lava flow samples collected from sites within the western Canadian Cordillera. Samples range in age from Eocene to Quaternary and document a significant transition in mantle chemistry that occurred sometime after 10 Ma. Eocene to late Miocene basalts emplaced as dikes within the Coast Mountains Batholith contain abundant hornblende, are enriched in large ion lithophile

elements (LILE) (Ba, Rb, K), have negative high field strength element (HFSE) (Nb, Ta) anomalies, and were likely derived from lithospheric mantle $^{87}Sr/^{86}Sr$ = 0.70353-0.70486; epsilon$_{Nd}$ = +2.5 to +5.7) that was stabilized after the cessation of arc magmatism in the area. By contrast, Quaternary lava flows have lower LILE concentrations, positive Nb-Ta anomalies, and were likely generated by upwelling asthenosphere ($^{87}Sr/^{86}Sr$ = 0.70266-0.70386; epsilon$_{Nd}$ = +7.4 to +8.8) or at least a mantle source with different chemical and isotopic characteristics. A regional comparison of mafic rocks from western Canada that are also Eocene to Quaternary in age indicates that the transition in mantle chemistry after 10 Ma was pervasive and widespread and was not limited to the present study area. This transition occurred approximately 40 Ma after the cessation of Cordilleran arc magmatism in central British Columbia, suggesting that large-scale transitions in mantle chemistry beneath magmatic arcs may occur on the order of tens of millions of years after the final subduction of oceanic lithosphere, in this case as a result of lithospheric thinning by continental extension.

Mathews, W. H., 1947. 'Tuyas,' flat-topped volcanoes in northern British Columbia; American Journal of Science, v. 245, no. 9, p. 560-570.

Abstract: Several flat-topped, steep-sided volcanoes, here named '*tuyas*', situated in northern British Columbia, consist of nearly horizontal beds of basaltic lava resting on outward-dipping beds of fragmental volcanic rocks. It is concluded that (1) these 'tuyas' were formed by volcanic eruptions into several 'intraglacial' lakes thawed through the Pleistocene Cordilleran ice-sheet by volcanic heat; (2) the levels of these lakes were maintained by rocky spillways along the course of drainage of their meltwaters toward the ice-front; and (3) the lavas capping the mountains were extruded from the volcanoes after they had been built above the lake levels, and the outward-dipping beds were formed by the aqueous chilling of the lava when it reached the water's edge.

Mejia, V., Barendregt, R.W., and Opdyke, N.O., 2002. Paleosecular variation of Brunhes age lava flows from British Columbia, Canada; Geochemistry, Geophysics, Geosystems – G^3, v. 3, no. 12, 14 p.

Abstract: Brunhes age lava flows have been sampled for paleosecular variation studies from several volcanic fields of southern British Columbia (Silverthrone, Garibaldi Lake, Mt. Meager, Clearwater-Wells Gray Park and Kelowna area). A total of 52 lava flows were sampled and 7 to 10 samples were drilled at each site. Previous radiometric studies indicate that the ages of these lava flows range from 2.3 to 760 ka. Stepwise thermal demagnetization (14 to 21 steps) was carried out for all the samples in each site and AF demagnetization was performed on one sample per site. Forty-five sites were selected based on rigorous criteria (alpha$_{95}$ ≤ 5°) to calculate a mean direction (D = 356.9°, I = 70.2°, alpha$_{95}$ = 2.8°) that is statistically indistinguishable from the direction of the dipole field at the area (I = 68.3°). Virtual geomagnetic poles (VGPs) do not show the far-sided effect and the angular standard deviation is 17.5°, a value in agreement with the paleomagnetic field dispersion for that latitude. These high quality results are expected to improve the time averaged field (TAF) and secular variation models.

Russell, J.K., Edwards, B.R., Porritt, L., and Ryane, C., 2014. Tuyas: a descriptive genetic classification; Quaternary Science Reviews, v. 87, p. 70-81.

Abstract: We present a descriptive genetic classification scheme and accompanying nomenclature for glaciovolcanic edifices herein defined as tuyas: positive-relief volcanoes having a morphology resulting from ice confinement during eruption and comprising a set of lithofacies reflecting direct interaction between magma and ice/melt water. The combinations of lithofacies within tuyas record the interplay between volcanic eruption and the attending glaciohydraulic conditions. Although tuyas can range in composition from basaltic to rhyolitic, many of the characteristics diagnostic of glaciovolcanic environments are largely independent of lava composition (e.g., edifice morphology, columnar jointing patterns, glass distributions, pyroclast shapes). Our classification consolidates the diverse nomenclature resulting from early, isolated contributions of geoscientists working mainly in Iceland and Canada and the nomenclature that has developed subsequently over the past 30 years. Tuya subtypes are first recognized on the basis of

variations in edifice-scale morphologies (e.g., flat-topped tuya) then, on the proportions of the essential lithofacies (e.g., lava-dominated flat-topped tuya), and lastly on magma composition (e.g., basaltic, lava-dominated, flat-topped tuya). These descriptive modifiers potentially supply additional genetic information and we show how the combination of edifice morphologies and lithofacies can be directly linked to general glaciohydraulic conditions. We identify nine distinct glaciovolcanic model edifices that potentially result from the interplay between volcanism and glaciohydrology. Detailed studies of tuya types are critical for recovering paleo-environmental information through geological time, including: ice sheet locations, extents, thicknesses, and glaciohydraulics. Such paleo-environmental information represents a new, innovative, underutilized resource for constraining global paleoclimate models.

Souther, J.G., 1990. Volcano tectonics of Canada; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 110-115.

Summary: Canada occupies a gap in the Pacific Ring of Fire between the Cascades of the western United States and the Aleutian volcanoes of Alaska. This tectonic setting, which has produced five principal volcano-tectonic belts in British Columbia and the Yukon, is discussed in detail, with separate sections for the Pemberton Volcanic Belt, the Garibaldi Volcanic Belt, the Alert Bay Volcanic Belt, the Chilcotin Group, the Anahim Volcanic Belt, the Stikine Volcanic Belt, and the Wrangell Volcanic Belt. Volcanoes of of east central British Columbia (the Clearwater-Quesnel and McConnell Creek volcanic provinces), which probably formed due to regional extension, are discussed briefly in a separate section.

Souther, J.G., 1991. Volcanic regimes; *in* Chapter 14 of Geology of the Cordilleran Orogen in Canada, (ed.) H. Gabrielse and C.J. Yorath; Geological Survey of Canada, Geology of Canada, no. 4, p. 457-490.

Summary: This book chapter summarizes the volcanic regimes of Canada's Cordilleran Orogen, ranging in age from Paleozoic to Recent, and includes a discussion of the areas that are currently volcanically active. A more detailed description of these volcanic areas is given in Chapter 10 (Neogene Assemblages) of this book.

Souther, J.G. and Yorath, C.J., 1991. Neogene assemblages; *in* Chapter 10 of Geology of the Cordilleran Orogen in Canada, (ed.) H. Gabrielse and C.J. Yorath; Geological Survey of Canada, Geology of Canada, no. 4, p. 373-401.

Summary: This book chapter summarizes the Neogene assemblages of Canada's Cordilleran Orogen. This summary includes detailed discussions of the early development of the Pemberton, Garibaldi, Wrangell, Anahim, and Stikine volcanic belts, as well as a discussion of the volcanism of the Clearwater-Quesnel and McConnell Creek areas and the Chilcotin Group basalts, which spans Neogene to Quaternary time.

Stasiuk, M.V., Hickson, C.J., and Mulder, T., 2003. The vulnerability of Canada to volcanic hazards; Natural Hazards, v. 28, p. 563-589.

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.

Reports, Government Publications, and Theses

Clague, J.J. and Evans, S.G. 1994. Formation and failure of natural dams in the Canadian Cordillera; Geological Survey of Canada, Bulletin 464, 40 p.
Abstract: In western Canada, existing and former lakes dammed by landslides, moraines, and glaciers have drained suddenly to produce floods orders of magnitude larger than normal stream flows. Landslide dams consisting of failed bedrock generally are stable, whereas those comprising Quaternary sediments or volcanic debris fail soon after they form, typically by overtopping and incision. Moraine dams are susceptible to failure because they are steep-sided and consist of loose, poorly sorted sediment. Irreversible rapid incision to a moraine dam may result from a large overflow associated with a severe rainstorm, avalanche, or rockfall. Some glacier-dammed lakes drain suddenly though englacial and subglacial tunnels to produce large floods. Most outburst floods are characterized by an exponential increase in discharge, followed by an abrupt drop to background levels when the water supply is exhausted. Peak discharges are controlled by lake volume, dam characteristics, failure mechanisms, and downstream topography and sediment availability. An appraisal of the likelihood that a natural dam will fail can be made by studying the dam, the reservoir and the surrounding terrain. A moraine dam may be hazardous if it contains ice or has a low width-to-height ratio, or if the reservoir is bordered by steep, rockfall- or avalanche-prone slopes. All glacier-dammed lakes with a recent history of outburst floods should be considered hazardous, but even stable lakes may drain suddenly after a long period of glacier retreat. Many landslides' dams fail soon after they form, consequently hazard appraisal may be concerned more with the location and size of potential dams than with the stability of existing dams.

Erdman, L.R., 1985. Chemistry of Neogene basalts of British Columbia and the adjacent Pacific Ocean floor; a test of tectonic discrimination diagrams; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 294 p.
Modified abstract: Seventy-one samples of subalkaline and alkaline basalts from British Columbia and the adjacent Pacific seafloor were analyzed for 33 major, trace and rare earth elements using x-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA). These basalts are all less than 22 Ma in age and come from various magmatic belts, each with a distinct, well-known, tectonic setting; (1) Convergent margin (Garibaldi and Pemberton Belts), (2) Back-arc (Chilcotin Basalts), (3) Hotspot (Anahim Volcanic Belt), (4) Incipient rift (Stikine Volcanic Belt), (5) Arc-trench gap (Alert Bay Volcanic Belt) and (6) Ocean floor (Offshore basalts of the Juan de Fuca-Explorer Ridge Systems). Element abundances and ratios were plotted on eighteen diagrams that have been propsed to discriminate between tectonic settings on the basais of magma chemistry. Although eruption through continental crust has modified the abundances of Ba, Th, U, K and Sr, in most cases this did not affect the ability of the diagrams to distinguish tectonic setting.

Fiesinger, D.W., 1975. Petrology of the Quaternary volcanic centers in the Quesnel Highlands and Garibaldi Provincial Park areas, British Columbia; Ph.D. thesis, University of Calgary, Calgary, Alberta, 132 p.

Modified abstract: Quaternary eruptions in the Wells Gray Park – Quesnel lake area of east-central British Columbia formed numerous isolated cinder cones and related flows of relatively basic composition. The eruptive products include alkali olivine basalt, ankaramite, basanitoid and nephelinite. Many of these lavas contain spinel lherzolite nodules, gabbroic xenoliths and bedrock fragments. Xenocrysts of quartz and hypersthene with reaction rims of augite are also present. Temperatures and pressures at which these lavas could have been in equilibrium with the lherzolite nodules were calculated by combining analytical data on the rocks and minerals with thermodynamic expressions. The chemical variation between two rocks of one eruptive center can be explained by low pressure fractionation. No sequential fractionation process at either low or high pressures can account for the chemical variation among the remaining lavas. Quaternary eruptions in the Garibaldi Park – Squamish River area of southwestern British Columbia have formed cinder cones, volcanic piles and related flows of highly differentiated lavas. The eruptive products include olivine basalt, basaltic andesite, andesite, dacite and rhyodacite. Many of these lavas contain quartz xenocrysts, often with reaction rims of augite, and xenocrysts of sodic plagioclase (Ab_{73}). The chemical variation of these lavas can be explained in part by a process of low pressure fractionation.

Hickson, C. J., 1992. Volcanic hazards and volcanism in the Canadian Cordillera; *in* Geologic Hazards of British Columbia, (ed.) P. Bobrowsky; Geologic Hazards '91 Workshop, Victoria, British Columbia; British Columbia Geological Survey, Open File 1992-15, p. 35-55.

Modified abstract: British Columbia and the Yukon encompass a geologically dynamic region which includes subduction zones, areas of crustal rifting and high heat flow. As a consequence of this dynamic environment, some 100 volcanoes and volcanic fields have formed. These are arranged in five broad belts: the Garibaldi, Anahim, Alert Bay, Stikine, and Wrangell volcanic belts; plus other less-well-defined volcanic regions. Volcanoes range from monogenetic mafic cinder cones, to peralkaline shield volcanoes, and calc-alkaline strato-volcanoes. Determining the age of an eruption is sometimes difficult, but it is thought that the Tseax River Cone, in northeastern British Columbia, erupted about 200 years ago and is Canada's youngest volcano. The most recent large explosive eruption occurred 1300 years ago in the Yukon. The eruption, from a vent just inside the Alaska border, expelled an estimated 30 cubic kilometres of pyroclastic material covering 300,000 square kilometres of Yukon under a blanket of ash. In southwestern British Columbia, the most recent volcanic event is thought to be a plinian eruption from Mt. Meager stratovolcano about 2300 years ago which spread ash across southern British Columbia into Alberta. The tectonic forces that produced these volcanoes are still active and the potential for a volcanic eruption in the Canadian Cordillera continues to exist. Much remains to be done to correctly assess the risk of a volcanic eruption in the Cordillera due to numbers and remoteness of volcanoes, and limited funding and personnel.

Hickson, C.J. and Edwards, B.R., 2001. Volcanoes and volcanic hazards in Canada; *in* A Synthesis of Geological Hazards in Canada, (ed.) G.R. Brooks; Geological Survey of Canada, Bulletin 548, p. 1-248.

Abstract: In Canada, potentially active volcanoes are found only in British Columbia and the Yukon Territory, where they represent cinder cones, shield volcanoes, and stratovolcanoes. Magma composition controls how a volcano erupts. Low-viscosity magmas (basalt) erupt effusively and represent a low-level hazard. Magmas with higher viscosity (dacite) often erupt explosively, creating significant, far-reaching hazards. The explosion creates small rock fragments or ash that is often carried high above the volcano. These abrasive particles, caught in high-altitude winds, are carried for hundreds of kilometres and affect equipment with moving parts. Hot avalanches of semi-molten rock, or pyroclastic flows, can destroy large areas around the volcano. Additionally, when they descend snow-covered flanks, they can lead to catastrophic melting, sending mud and water cascading into surrounding drainage systems. Even long after an eruption, denuded slopes and unstable rock faces can make the area prone to floods and rock avalanches.

Holland, S.S., 1976. Landforms of British Columbia, a physiographic outline; British Columbia Department of Mines and Petroleum Resources Bulletin, v. 48, p. 1-138.

Abstract: The physiographic history of British Columbia is summarized and the system of subdivision described. Chapter 2, which includes over 70 pages, is devoted to detailed description of the physiographic subdivisions in the Eastern, Interior, and Western Systems of the Cordillera. Chapter 3 covers special aspects of the landscape--glaciation, rivers, coastline, volcanic landforms, and major lineaments. A large physiographic map accompanies the report and numerous photographs show the features described. Appendixes give the geologic time scale and a glossary.

Souther, J.G., 1966. Cordilleran volcanic study, 1965; Geological Survey of Canada, Paper 66-1, p. 87-89.

Summary: This is a brief summary of mapping on the British Columbia coast, at four young volcanic centres in the Milbanke Sound area, and a summary of mapping done at Mount Edziza.

Souther, J.G., 1968. Cordilleran volcanic study, 1967; Geological Survey of Canada, Paper 68-1, p. 42-43.

Summary: This is a short summary of ongoing mapping of volcanic rocks in the Canadian Cordillera, including descriptions of Mount Edziza and Mount Silverthrone, and the Rainbow, Ilgachuz, and the Itcha Ranges.

Souther, J.G., 1977. Volcanism and tectonic environments in the Canadian Cordillera – a second look; *in* Volcanic Regimes in Canada, (ed.) W.R.A. Baragar, L.C. Coleman, and J.M. Hall; Geological Association of Canada, Special Paper, v. 16, p. 3-24.

Abstract: Variation in the style of volcanicity and the setting of volcanic rocks provide criteria fundamental to interpretations of the tectonic evolution of the Canadian Cordillera. From its inception in the late Precambrian through early Paleozoic time the Cordilleran Orogen was the locus of continental margin sedimentation accompanied by infrequent eruptions of basic lava. In contrast the late Paleozoic record is dominated by submarine lavas and associated marine sediments suggestive of a deep oceanic environment whereas early Mesozoic andesitic volcanic and related rocks have many of the features of volcanic arcs. Uplift and block faulting during the late Mesozoic and early Tertiary time was accompanied by explosive eruption of felsic calc-alkaline lavas that contrast with the younger floods of alkaline basalt accompanying late Tertiary and Quaternary transcurrent movement parallel with the continental margin. Recent chemical, isotopic, and petrologic data, while in general agreement with this broad interpretation, suggest that no unique style of volcanism prevailed in all parts of the Cordillera during any given stage of its evolution. Volcanic rocks in the Proterozoic succession, though mainly diabasic, include thick local piles of pyroclastic rocks that appear to be products of explosive eruption. Locally the late Paleoxoic record includes volcanic rocks with arc affinities whereas many of the so-called 'calc-alkaline' rocks of the early Mesozoic succession are shown to be alkaline. Similarly the predominantly alkaline late Tertiary lavas of the south central Cordillera are coeval with calc-alkaline lavas farther north. The importance of these 'exceptions' should not be overlooked. They provide a rational basis for reappraising and refining existing generalized models of Cordilleran tectonic evolution.

Conference Proceedings, Abstracts, and Symposium Volumes

Grove, E.W., 1976. Deglaciation; a possible triggering mechanism for Recent volcanism; *in* Proceedings of the symposium on Andean and Antarctic volcanology problems, (ed.) O. Gonzalez Ferran; International Association on Volcanism and the Chemistry of the Earth's Interior, Santiago, Chile, unpaginated.

Modified abstract: The Cordillera of British Columbia presents scattered evidence of widespread, important Tertiary volcanism. Because of the nature of these generally poorly consolidated rocks the recognition of individual vents has been largely confined to Pleistocene and younger volcanoes. These are generally confined to linear clusters with north-south, northeast, and east-west trends. These rocks suggest a record of almost continuous volcanism from the Pliocene to the near present. Although good historical records are almost non-existent for most of northerly British Columbia, it has been suggested that at least one small volcano still erupted about 1904. Recent geological studies in the Iskut-Unuk River areas of north-western British Columbia have revealed evidence showing the intercalation of glacial debris and thin Neogene volcanic flows. The obvious localization of the lava, tills, and glaciers to prominent fracture systems at many sites has been taken to imply a simple cause and effect relationship. That is, periodic deglaciation involving the rapid removal of a considerable hydrostatic load from fissure zones has triggered basaltic volcanism during the Neogene along at least one major graben-like feature. In continental areas then, deglaciation should be considered as another mechanism, in addition to earth tides, etc., for the triggering of volcanism.

Hickson, C.J., 1992. Volcanism in the Canadian Cordillera: should we worry?; First Canadian Symposium on Geotechnique and Natural Hazards, Vancouver, British Columbia, 10 p.

Abstract: The Canadian Cordillera encompasses a geologically dynamic region which includes subduction zones, major transcurrent faults, areas of crustal rifting and high heat flow. As a consequence of this dynamic environment, some 100 volcanoes and volcanic fields have formed. These are arranged in five broad belts: the Garibaldi, Anahim, Alert Bay, Stikine, and Wrangell volcanic belts; plus other less-well-defined volcanic regions. The tectonic forces that produced these volcanic belts are still active and thus the potential for a volcanic eruption in the Canadian Cordillera continues to exist. Much remains to be done to assess the risk of a volcanic eruption in the Cordillera due to numbers and remoteness of volcanoes. Studies to date suggest that small localized basaltic eruptions producing tephra that covers limited areas, and more infrequent violent explosive events, severely impacting vast areas are both possible. Basaltic eruptions may occur with little or no warning, but will only pose a hazard if the eruption occurs close to a populated area or a transportation corridor. Explosive eruptions usually have associated earth tremors that will be picked up on the regional seismic network. Unfortunately, however, some significant events elsewhere in the world have occurred where precursor seismicity commenced only hours before the volcano erupted explosively. Apart from the hazard posed by the eruption of a volcano, a continuing hazard is posed by the extreme relief of many vent areas and the unstable nature of volcanic deposits. Landslides and debris flows from volcanoes pose a very real threat. Comparable debris flows generated in volcanic areas have much greater run out distances than those generated in nonvolcanic areas, in part, because of a greater percentage of fine material in "volcanic" debris flows. Where human development is pushed into volcanic areas, this hazardous aspect of Cordilleran volcanoes must be taken into consideration during planning. Should an eruption occur, the impact would be much wider reaching.

Hickson, C. J., 1994. Volcanism in the Canadian Cordillera; Canada's hazard response preparedness; *in* Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety, Seattle, Washington, (ed.) T.J. Casadevall; United States Geological Survey, Bulletin 2047, p. 47-55.

Abstract: British Columbia and the Yukon are geologically dynamic regions, enocompassing subduction zones, rifting, and thermal anomalies (hot spots). Approximately 100 volcanic vents are arranged in five broad belts and in more widely scattered regions. Holocene eruptions have occurred in four of the belts. The most recent documented event, a small basaltic eruption, occurred about 200 years ago in northwestern British Columbia. The most recent large explosive eruption occurred about 1.2 thousand years ago when a vent near the Alaska-Yukon border expelled about 30 km^3 of pyroclastic material, covering 300,000 km^2 of the Yukon under a blanket of ash. In southwestern British Columbia, a Plinian eruption from Mount Meager stratovolcano, occurred about 2.4 thousand years ago. This eruption spread ash across southern British Columbia into Alberta. In Canada, an integrated response plan to deal with volcanic hazards is now in place and involves all levels of government. Four key agencies operate jointly to ensure timely and appropriate response to a volcanic eruption, including the safe passage of air traffic. Response procedures are being coordinated between the United States and Canada to ensure safety and minimize disruption among residents and aviators.

Hickson, C.J. and Spurgeon, T., 1993. Volcano hazard warning procedures and mitigation in Canada; *in* International Association for Volcanology and Chemistry of the Earth's Interior (IAVCEI) General Assembly, Ancient Volcanism and Modern Analogues, Canberra, Australia, v. 1, no. 1, p. 48.

Abstract: Unlike other Circum-Pacific countries, Canada has no active volcanoes. This is not to say volcanism is absent in Canada, but long quiescent periods between eruptions are typical. Small cone or shield building eruptions have occurred sporadically over the last two million years. These eruptions in the Canadian Cordillera (largely restricted to 4 broad belts) occur between the active volcanoes of the western United States and those of the Aleutian Arc in Alaska. Canada's proximity to active volcanoes both south and north, large eruptions in the past, coupled with increased sensitivity worldwide to the hazards of airborne ash, brought about the implementation of a *Interagency Volcanic Event Notification Plan* (IVENP). This plan coordinates the alerting of appropriate responding agencies to a volcanic hazard and serves to disseminate information about that hazard. The IVENP is a redundant, multiple path communication network, and uses existing 24 hour a day operating facilities and services. Key to notification are the operational plans of the responsing agencies. Critical to the rapid flow of information are direct contacts to "sister" agencies in adjoining jurisdictions. The direct linkage of Canadian and US air traffic controllers is vital for the safe passage of aircraft. Additionally, rapid availability of plume trajectory information is critical. These features are incorporated into the Canadian response plans.

Souther, J.G., 1976. Geothermal potential of western Canada; *in* Proceedings of the 2nd United Nations symposium on development and use of geothermal resources, San Francisco, Washington D.C.; United States Government Printing Office, p. 259-267.

Abstract: An investigation of the geothermal resources potential of western Canada was initiated by the Federal Department of Energy, Mines and Resources in 1972. Initial work included; (1) Expansion of the regional heat flow program; (2) Compilation of data on the distribution, age, and petrochemistry of the Quaternary volcanoes; and (3) Systematic sampling and chemical analysis of the water from all known thermal springs. Integration of these new data with existing geological and geophysical information on the crustal structure of the Canadian Cordillera indicates a board thermal anomaly extending through west-central British Columbia and southern Yukon. It is bounded on the west by a well defined front of Quaternary volcanoes including more than 100 postglacial eruptive centers. Within this broad thermal zone, specific targets based on local heat flow anomalies and water geochemistry are closing associated with those volcanic centers that have produced rhyolite or dacite domes. One of these (Meager Mountain) was selected for more detailed study, including the drilling of two 50m holes in 1973. Subsequently, this target was chosen as the focus of a more detailed geothermal resource evaluation commissioned by the British Columbia Hydro and Power Authority.

Chilcotin Basalts

Scientific Books and Articles

Andrews, G.D.M., Plouffe, A., Ferbey, A., Russell, J.K., Brown, S.R., and Anderson, R.G., 2011. The thickness of Neogene and Quaternary cover across the central Interior Plateau, British Columbia: analysis of water-well drill records and implications for mineral exploration potential; Canadian Journal of Earth Sciences, v. 48, p. 973-986.

Abstract: Analysis of over 10 000 water-well records has been used to produce new depth-to-bedrock maps for areas around five cities on the central Interior Plateau of central British Columbia: 100 Mile House, Prince George, Quesnel, Vanderhoof, and Williams Lake. Hitherto, exploration for mineral and hydrocarbon resources has been hampered by a lack of basic knowledge of the thickness of Neogene and Quaternary lithologies. Interpretation of these new maps provides first-order constraints on the localization of thick drift in pre-Late Wisconsinan bedrock paleovalleys, some of which are now buried. Basalt lavas of the Chilcotin Group are restricted to erosional remnants of previously extensive sheets emplaced onto an older peneplain. Our results confirm that the Neogene and Quaternary cover is primarily controlled by paleotopography and is generally thin and patchy across much of the region. Increased understanding of the three-dimensional distribution of cover produces a corresponding increase in the utility of geological, geochemical, and geophysical exploration techniques, and a reduction in the risk for future mineral exploration activities, especially when combined with more sophisticated data sets.

Andrews, G.D.M., Russell, J.K., Brown, S.R., and Enkin, R.J., 2011. Pleistocene reversal of the Fraser River, British Columbia; Geology, v. 40, no. 2, p. 111-114.

Abstract: The Fraser River in British Columbia, Canada, is the longest non-dammed river on the west coast of North America and supplies 20 X 10^6 t/yr of sediment to the Pacific Ocean. Abundant geomorphological evidence indicates that the Fraser River reversed its course to southward flow in the recent geological past. Investigation of two volcanic dams at Dog Creek demonstrates northward flow of the Fraser until at least 1.06 Ma, before reversal and erosion of the 270-km-long Fraser Canyon. We propose that the submarine Nitinat Fan off the coast of British Columbia records the reversal and sudden input of coarse continental-derived sediment ca. 0.76 Ma. This study confirms reversal of the Fraser River and places a firm constraint on the maximum age of that reversal. Reversal likely followed stream capture in response to enhanced glaciofluvial erosion and uplift of the Coast Mountains.

Bevier, M. L., 1983a. Implications of chemical and isotopic composition for petrogenesis of Chilcotin Group basalts, British Columbia; Journal of Petrology, v. 24, no. 2, p. 207-226.

Abstract: Thin, flat-lying basalt flows of the Mio-Pliocene Chilcotin Group, erupted from central vents, coalesce to form a 50,000 km^2 lava plateau in south-central British Columbia. Olivine-bearing transitional basalt is the predominant rock type; alkali basalt and quartz tholeiite are also present. Sr and Pb isotopic ratios indicate a mantle source for the magmas. Based on *Mg* values of 45–65, and Ni contents of <250 ppm, Chilcotin basalts are differentiated magmas. The genesis of Chilcotin basalt magma can be modelled in two steps, (1) partial melting of spinel lherzolite to produce picritic basalt, and (2) fractionation of olivine from picritic magma to produce transitional basalt. Residual peridotite left over from the partial melting event is similar in mode and composition to ultramafic nodules found in many alkali basalt flows from western North America. Magma was not trapped in the crust long enough to react with it or to produce silicic differentiates. Individual flows of Chilcotin basalt from different vents are isotopically distinct and

cannot be related to each other by any reasonable crystal fractionation model, suggesting that the mantle source for Chilcotin basalt is heterogenous on the scale of the basalt plateau, and that many batches of slightly different primary magma were parental to the basalts that make up the volcanic field.

Bevier, M. L., 1983b. Regional stratigraphy and age of Chilcotin Group basalts, south-central British Columbia; Canadian Journal of Earth Sciences, v. 20, no. 4, p. 515-524.

Abstract: Mio-Pliocene Chilcotin Group basalt flows form a 50 000 km^2 plateau in south-central British Columbia. Two periods of eruptive activity at 2-3 and 6-10 Ma are indicated by a compilation of available age data, including 10 new K-Ar age determinations, and basalts from these two periods are chemically indistinguishable. The Chilcotin Group consists of thin, crudely columnar-jointed pahoehoe flows, some thick, tiered flows, pillow lava and pillow breccia, and rare silicic tephra layers. The presence of many vesicle sheets and cylinders and collapsed pahoehoe toes suggests that the basalts were volatile-rich. Known vents (gabbro and basalt plugs) for the basalt flows form a northwest trend along the axis of the lava plateau. The plateau appears to have formed from the overlap of many low-profile shield volcanoes and is similar in morphology to other plains basalts such as the Snake River Plain and parts of Iceland. Glaciation has stripped off an unknown volume of the flat-lying basalt flows.

Bevier, M.L., 1990. Chilcotin basalt; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, New York, p. 136-137.

Summary: The Miocene to Pliocene Chilcotin basalt flows of south-central British Columbia are summarized briefly.

Dostal, J., Hamilton, T.S., and Church, B.N., 1996. The Chilcotin basalts, British Columbia (Canada); geochemistry, petrogenesis and tectonic significance; Neues Jahrbuch für Mineralogie, v. 170, no. 2, p. 207-229.

Abstract: The Chilcotin basalts are a contiguous suite of lavas which occurs in the central and southern interior region of British Columbia. The ages of the lavas, which are spread thinly over an area of 25, 000 km^2, range from 24 Ma to Recent. The basalts, which show only a small variation in composition, are predominantly transitional in character (olivine tholeiites and mildly silica undersaturated alkali basalts). Most of the basalts, many of which contain spinel peridotite xenoliths, resemble oceanic island basalts and were derived from a garnet peridotite source, probably the asthenospheric mantle. The subordinate quartz-normative tholeiites are characterized by a distinct LILE enrichment relative to high-field-strength elements. The source of these rocks, which compositionally resemble flood basalts, was probably subcontinental lithospheric mantle which was enriched by earlier subduction processes. Upwelling of asthenospheric mantle, a source of the majority of the basalts, probably triggered melting in the subcontinental lithosphere.

Hayward, N. and Calvert, A.J., 2009. Eocene and Neogene volcanic rocks in the southeastern Nechako Basin, British Columbia; interpretation of the Canadian Hunter seismic reflection surveys using first-arrival tomography; Canadian Journal of Earth Sciences, v. 46, no. 10, p. 707-720.

Abstract: Geological investigation of the near-surface in the southeastern Nechako Basin is difficult. Shallow seismic reflection imaging is poor due in part to an extensive cover of Eocene and Neogene volcanic rocks. Outcrops of these volcanic rocks, and the primarily Cretaceous bedrock, are commonly obscured by Quaternary deposits and vegetation. Estimates of near-surface P-wave velocity are derived from the tomographic inversion of seismic first-arrivals, an effective tool when seismic imaging is poor. Tomographic model velocities are in agreement with sonic logs and laboratory samples, except for those from the Neogene Chilcotin Group. Cretaceous sedimentary rocks have velocities of approximately 2800-4200 ms^{-1}. The Eocene Endako and

Ootsa Lake groups, which have velocities of approximately 3000-4200 ms^{-1}, are not distinguishable based on velocity. The velocity, the character (density, focus, and penetration depth) of rays, and ties with well and surface geology constrain the subsurface extent of the Endako Group adjacent to well b-82-C. The Chilcotin Group typically exhibits velocities (approximately 2400-3000 ms^{-1}) lower than corresponding velocities from sonic logs (4500-5200 ms^{-1}) and laboratory measurements (5000-5200 ms^{-1}). These low model velocities may be due to the presence of high porosity, brecciated rocks near to the surface, in comparison with the other measurements that have focussed on lower porosity massive lavas. The lowest mean velocities, located to the southeast, are related to anomalously thick, high porosity, breccia-rich deposits of Chilcotin Group. This conclusion is consistent with the interpretation that the Chilcotin Group is thicker in paleo river valleys.

Hayward, N. and Calvert, A.J., 2011. Interpretation of structures in the southeastern Nechako Basin, British Columbia, from seismic reflection, well log, and potential field data; Canadian Journal of Earth Sciences, v. 48, no. 6, p. 1000-1020.

Abstract: The structure and stratigraphy of the southeast Nechako Basin, which are poorly understood primarily because of substantial volcanic cover, are investigated in an analysis of seismic reflection, well, and potential field data. Formation and development of the SE Nechako Basin resulted in sub-basins containing Cretaceous and Eocene rocks. Interpretation reveals that dextral transtension in the Early to Middle Eocene created NNW-trending, en echelon, strike-slip faults linked by pull-apart basins, which locally contain a thickness of Eocene volcaniclastic rocks of >3 km. This structural pattern is consistent with regional observations that suggest the transfer of slip from the Yalakom fault to the north via a series of en echelon strike-slip faults. In the Middle to Late Eocene, faults associated with a change in the direction of stress, echoed by the north-trending right-lateral Fraser fault, reactivated and cut earlier structures. A simple model agrees with local observations, that northeast-directed compression was subparallel to the relic Cretaceous grain. Cretaceous rocks are discontinuous throughout the basin and may be remnants of a broader basin, or a number of contemporaneous basins, formed in a regional transpressional tectonic setting that caused northeast-directed thrusting along the eastern side of the Coast Plutonic Complex. Results suggest that thrusting affected most of the SE Nechako Basin, as observed across the Intermontane Belt to the northwest and southeast. The pattern of deposition of Neogene volcanic rocks of the Chilcotin Group was in part controlled by the Eocene structural grain, but we find no evidence of Neogene deformation.

Mathews, W. H., 1989. Neogene Chilcotin basalts in south-central British Columbia; geology, ages, and geomorphic history; Canadian Journal of Earth Sciences, v. 26, no. 5, p. 969-982.

Abstract: An extensive but generally thin mantle of basalt flows, the Chilcotin Group, covers much of the Interior Plateau of south-central British Columbia. It provides material for dating and for reconstructing the original form of the paleosurface on which it was deposited. K–Ar whole-rock dates demonstrate that several ages of basalt are represented, from Early Miocene (or even Late Oligocene?) to Early Pleistocene, with particularly abundant eruptions about 14–16, 9–6, and 1–3 Ma ago. Basalts of Middle Miocene and later ages, if not the Early Miocene relics as well, clearly rest on land surfaces of low local relief. In places the low-relief surfaces had been incised to depths of 100–200 m and the valleys backfilled with mid-or late Cenozoic sediments prior to burial by the basalts. The low-relief surfaces throughout the area are believed to have been developed close to a common base level, and regional differences in their present elevation are thus largely a product of post-basalt deformation. This is recorded by Miocene or later uplift of the southern Coast Mountains and gentle flexing in parts of the Interior Plateau. Major stream incision to depths of up to 1000 m following uplift provides a convenient, but not infallible, means of distinguishing Chilcotin basalts from mid-Pleistocene and younger "valley basalts." The Chilcotin Group is, for the most part, a small-scale counterpart of the roughly contemporaneous Columbia River basalt group of Washington and Oregon.

Mathews, W.H. and Rouse, G.E., 1986. An Early Pleistocene pro-glacial succession in south-central BC; Canadian Journal of Earth Sciences, v. 23, p. 1796-1803.
Abstract: A succession of conglomerates, sandstones, siltstones, and tills, herein named the Dog Creek Formation, is sandwiched between flat-lying basalts along Dog Creek (lat. 51°36′N, long. 122°02′–122°12′W) for about 15 km east of Fraser River. The sedimentary succession rests disconformably on underlying basaltic lavas (herein referred to as the Harpers Creek Formation), which have yielded K–Ar dates of 1.3–2.9 Ma, and in one place, on a glaciated surface carved in metavolcanic rocks of Permian(?) age. The sedimentary succession is capped by basalt flows yielding K–Ar whole-rock ages of 1.1 Ma. The occurrence of proglacial beds and a glaciated surface in south-central British Columbia, 70 km away from any high mountains capable of supporting glaciers today, testifies to a major glacial stage in Early Pleistocene time. The record of sedimentation and volcanism sheds light on early incision of the nearby valley of Fraser River.

Reports, Government Publications, and Theses

Andrews, G.D.M. and Russell, J.K., 2007. Mineral exploration potential beneath the Chilcotin Group (NTS 092O, P; 093A, B, C, F, G, J, K), south-central British Columbia: preliminary insights from volcanic facies analysis; Geological Fieldwork 2006, British Columbia Ministry of Energy, Mines, and Petroleum Resources, Paper 2007-1, p. 229-238.
Summary: This paper reports on the results of volcanological field mapping of the lithofacies, thickness variations and basement windows within the Chilcotin basalts.

Andrews, G.D.M. and Russell, J.K., 2008. Cover Thickness across the Southern Interior Plateau, British Columbia (NTS 092O, P; 093A, B, C, F): Constraints from Water-Well Records; Geoscience BC Summary of Activities 2007; Geoscience BC, Report 2008-1, p. 11-20.
Summary: Basalts of the Chilcotin Group, situated in the southern Interior Plateau physiographic region of central British Columbia, cover an area of 30,000 km^2. They are typically underlain by Paleozoic and Mesozoic basement rocks with high potential for Cu-Au-Mo deposits (e.g. Quesnel Trough), Eocene volcanic successions that host epithermal Au deposits (e.g. Blackdome), and Jurassic and Cretaceous sedimentary rocks of the Nechako Basin with hydrocarbon and possible mineral potential. The distribution of known mineral resources and prospects on the periphery of the Chilcotin Group makes the potential for unexploited mineral resources beneath the Chilcotin Group compelling. However, there is currently little coherent data on its spatial distribution (e.g. thickness), the lithostratigraphy (facies variations), and physical properties (density, porosity, magnetic susceptibility, and conductivity). This paper analyzes the geological information on the Chilcotin Group that is available from the WELLS database (which comprises depth and lithology information recorded as water wells were drilled); thickness estimates from exposed sections and hydrocarbon exploration wells are also included. The work is part of Geoscience BC project 2006-003, which aims to produce 3-D facies and thickness models for the Chilcotin Group that can be used to (1) extrapolate regional geology, metallogeny, and structure beneath the Chilcotin Group cover, (2) find windows to the basement and identify the basement geology, (3) delineate areas where the Chilcotin Group is thin or absent, and (4) provide a 3-D representation of physical property variations to allow the signature of the Chilcotin Group to be accurately stripped from total-field geophysical datasets.

Bevier, M.L., 1982. Geology and petrogenesis of Mio-Pliocene Chilcotin Group basalts, British Columbia; Ph.D. thesis, University of California at Santa Barbara, Santa Barbara, California, 110 p.

Modified abstract: Mio-Pliocene basalt flows, informally known as Chilcotin Group basalts, cover 50,000 km^2 in south-central British Columbia and have a volume of some 3300 km^3. The Chilcotin Group consists of thin, crudely columnar-jointed pahoehoe flows, some thick tiered flows, pillow lava and pillow breccia, and rare silicic tephra layers. Known vents (gabbro and basalt plugs) for the basalt flows form a northwest trend along the axis of the lava plateau. The plateau appears to have formed from the overlap of many low-profile shield volcanoes and is morphologically similar to the Snake River Plain and parts of Iceland. Chilcotin Group flows erupted due to asthenospheric upwelling in a back-arc tectonic setting, 150 km inland from coeval arc volcanic activity. Olivine-bearing transitional basalt is the predominant rock type; Mg values of 45-65 and Ni contents of <250 ppm suggest that Chilcotin basalts are differentiated magmas. The genesis of Chilcotin basalt magma can be modeled in two steps, (1) partial melting of spinel lherzolite to produce picritic basalt, and (2) fractionation of olivine from picritic basalt to produce transitional basalt. Sr and Pb isotopic data suggest that Chilcotin magmas have not assimilated more radiogenic crustal material and that the upper mantle beneath south-central British Columbia is heterogeneous on the scale of the volcanic field.

Caven, S., 2009. A geochemical and petrological study of the Chilcotin Group with implications of a complex tectonic and magmatic history; M.Sc. thesis, University of Leicester, Leicester, United Kingdom, 60 p.

Abstract: The Chilcotin Group basalts are situated in the back arc of the Garibaldi Arc within the southern Canadian Cordillera of British Columbia, Canada. The Cordillera is geologically complex, having sustained dynamic and varied plate tectonic processes throughout the Cenozoic. The Chilcotin covers an area of ~55,000km^2 and is composed of a series of basaltic lavas accompanied by volcaniclastic deposits and intrusive plugs. Although generally regarded as a product of Neogene subduction, complexities in the tectonic and magmatic origin of the Chilcotin Group are poorly understood. Recent tectonic modelling details an intricate sequence of tectonic events including passage of a slab window, a projected slab tear and reconfiguration in plate dynamics. These processes were sustained throughout Chilcotin Group magmatism and therefore may be of relevance. This report presents a spatially and temporally constrained petrological and geochemical analysis of the Chilcotin Group including a comparison to the adjacent Eocene Endako Group, the Anahim Volcanic Belt and the Wells Gray Volcanic Field. The Chilcotin Group basalts are geochemically complex and it is apparent that the uniform processes involved in subduction-related back arc volcanism cannot be applied throughout Chilcotin Group history. Instead, evidence of a dynamic range of magmatic processes is presented variously involving slab tear, slab anatexis, fluid or thermal metasomatism of the sub-lithosphereic mantle and the plate tectonic reconfiguration. These processes are reflected by the spatial, temporal and geochemical complexities of the Chilcotin Group.

Croft, S.A.S., 1983. Stability Assessment of the Capricorn Creek Valley, British Columbia; B.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 87 p.

Abstract: Geologic instability in the Capricorn Creek basin is indicated by the large volume of landslide rubble which clogs its lower reaches. Situated on the flanks of volcanic Meager Mountain, southwest British Columbia, the creek drains a steep glacial valley cut into thick andesitic flows and altered quartz diorite basement rocks. The source of most of the debris is a major landslide located 4 km upstream from the confluence of Meager and Capricorn Creeks. A dendrochronological study indicates the slide (an estimated 10 million cubic meters) to have occurred during the 1920s. A high velocity/low viscosity debris flow swept downstream for 3 km, banking up the outside of turns in the winding canyon. The bulk of the material was deposited in a series of terraces formed at broader, flatter sections of the valley. Blocked by the landslide, Capricorn Creek eventually overtopped the debris, cutting deeply into the unstable rubble, and flooding the lower sections of the creek. Redeposition downstream was sufficiently rapid to have dammed Meager Creek. Continued instability in the Capricorn area is evidenced by rockfalls,

sloughing, minor debris flows, and large scale slope creep. The hazard from major landslides is moderate and the risks of development in the area must be evaluated accordingly.

Dohaney, J. A. M., 2009. Distribution of the Chilcotin Group basalts, British Columbia; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 125 p.

Abstract: The Chilcotin Group basalts (CGB) are Oligocene to Late Pleistocene, stratified olivine-phyric basaltic lavas that overlie a large proportion of the Interior Plateau of British Columbia. The distribution of the CGB is poorly understood regionally; the current distribution is based on compilations of previously published geological maps that employ a diverse set of lithostratigraphic definitions of the Group. Exposure of the basalts is typically poor, but the thickest and most extensive sections are exposed in the valley-margins of major rivers (e.g., the Fraser River). This study collates and interprets spatial data sets and reassesses the distribution of the CGB with the intent of producing a new, more robust distribution of the CGB within the Taseko Lakes (0920) and Bonaparte Lake (092P) map areas, with the goal of better characterizing their geological history and physical volcanology. The new distribution map demonstrates several important observations: (1) the distribution of the CGB is less extensive than previous compilations by up to 48%; this implies that, regionally, the CGB is probably significantly over-estimated; (2) there are abundant, yet not previously identified “windows” through the basalt that expose underlying rock units which may be geologically and economically important; (3) CGB volcanism spanned the Oligocene to the Pleistocene (—30 Ma) and was centered in the central Fraser River area (south of Williams Lake, B.C.) throughout the Pliocene Pleistocene; (4) the CGB was likely erupted from a multitude of small-volume monogenetic vents, rather than a series of long-lived volcanic centres or fissures; and (5) the CGB is thickest where lavas ponded in paleo-valleys, providing a key to mapping the distribution of Neogene channels in the Fraser Basin drainage.

Dohaney, J., Andrews, G.D.M., Russell, J.K., and Anderson, R.G., 2010. Distribution of the Chilcotin Group, Taseko Lakes and Bonaparte Lake map areas, British Columbia; Geological Survey of Canada, Open File 6344; Geoscience BC, Map 2010-02-1, scale 1: 250 000.

Summary: The Oligocene to Late Pleistocene Chilcotin Group comprises stratified olivine–phyric basaltic flows that underlie much of the Interior Plateau of British Columbia. The distribution of the Chilcotin Group portrayed on published maps is imprecise because of poor outcrop exposure on the plateau, multiple generations of mappers, and lack of consensus concerning definition of the Group. The thickest and most extensive sections are exposed in the valley–margins of major rivers (e.g. the Fraser River). This new distribution map leads to several important conclusions: the Chilcotin Group is less extensive than shown in previous compilations for Taseko Lakes and Bonaparte Lake map areas by as much as 48%; by analogy, this implies that elsewhere the areal extent of the Chilcotin Group is also significantly over-estimated; the numerous areas indicated as not overlain by Chilcotin Group in the compilation constitute previously unidentified basement "windows" that are geologically and economically important; Chilcotin Group volcanism spanned the Oligocene to the Pleistocene (approximately 30 m.y. duration) and was centered in the central Fraser River area (south of Williams Lake) throughout the Pliocene—Pleistocene; episodic eruption of Chilcotin Group lavas was likely via a multitude of small–volume, short–lived, monogenetic vents, rather than a series of long–lived volcanic centres or fissures; and the Chilcotin Group is thickest where lavas ponded in paleo–valleys, a key indicator for mapping the distribution of Neogene channels in the Fraser Basin drainage.

Dohaney, J., Joseph, J.M.R., and Andrews, G.D.M., 2010. Interactive bibliography and database for the Chilcotin Group basalts (NTS 82E, L, M; 83D; 92H, I, J, O, P; 93A, B, C, F, G, J, K, L), south-central British Columbia; Geological Survey of Canada, Open File 6286, compact disc.

Summary: This is an electronic bibliography and database for the Chilcotin basalts. It includes geochemical, lithological, stratigraphic, geochronological, and other data, plus references.

Duffell, S., 1959. Whitesail Lake map-area, British Columbia; Geological Survey of Canada, Memoir 299, 119 p.

Summary: This paper describes the Whitesail Lake map-area of west-central British Columbia, which mostly comprises Mesozoic to Oligocene sedimentary and igneous rocks, but it also includes short descriptions of post-Oligocene basalt flows that probably belong to the Chilcotin Group.

Farrell, R.-E., 2010. Volcanic facies architecture of the Chilcotin Group basalts at Chasm Provincial Park, British Columbia, M. Sc. thesis, University of British Columbia, Vancouver, British Columbia, 164 p.

Abstract: The Chilcotin Group basalt (CGB) of south-central British Columbia, Canada defines a medium-sized igneous province (ca. 17, 000 km^2), characterized by basaltic lavas, volcaniclastic deposits, and paleosols with minor ash deposits. The CGB has previously been mapped only at reconnasissance scale (1:250 000), and most studies concentrated on geochemical and petrological studies; no stratigraphic relationships or volcanological models were attempted. Chasm canyon exposes one of the thickest successions of the CGB. Here, I explicate the volcanic facies architecture at Chasm to reconstruct the emplacement history and volcanism in the Neogene using geological mapping, cross-sections, and graphic logs. Specifically, seven discrete facies are recognized. The coherent facies are: i) vesicular/amygdaloidal pahoehoe lobes; ii) columnar-jointed, sheet-like lava; and iii) intact basaltic pillow lava. The clastic facies are: iv) paleosols; v) pillow-fragment breccia; vi) hyaloclastite; and vii) lacustrine sandstone. Facies are grouped into broad facies associations including the subaerial facies and interstratified subaqueous and subaerial facies. The subaqueous facies are a minor component in the canyon stratigraphy. The geometry of the lavas is indicative of the eruptive style of volcanism at Chasm, which defines the volcanic facies architecture. Four architectural elements have been observed: i) tabular-classic (TC), which represents a steady continuous supply of subaerial effusive basaltic lavas; ii) compound-braided (CB), which is typical of a shield volcano where anastomosing, branching flow fields result; iii) transitional-mixed, a combination of TC- and CB-type suggestive of bimodal emplacement, perhaps sourced from coalesced shield volcanoes and flank fissures; and iv) foreset-bedded indicative of subaqueous lavas. The exposed rocks record the evolution of CGB volcanism through ten distinct eruptive episodes and intermittent lakes, with periods of quiescence characterized by the paleosol development. Whole-rock Ar-Ar dates were obtained; the duration of volcanism is calculated as 1.28 ± 0.61 m.y. Emplacement is suggestive of shield volcanoes and small fissure eruptions with a northerly flow direction. Laterally extensive paleosols, classified as Brunisolic soils, were examined closely and display a range of morphological features suggestive of the paleo-environment. Lateral variability amongst paleosols have been mapped over a distance of more than 8 km, including a subqueous to subaerial transition.

Farrell, R.-E., Anderson, R.G., Simpson, K.A., Andrews, G.D.M., and Russell, J.K., 2009. Geology, Chasm Provincial Park and vicinity, British Columbia. Geological Survey of Canada, Open File 6230; Geoscience BC Map 2009-16-1, scale 1: 20 000.

Summary: Chasm Provincial Park is located northeast of Clinton, British Columbia, occupies 3067 hectares. Within the park, which includes the Chasm Canyon, extending approximately 8 km to the south and ranging from 500 - 3000 m wide and 300 m deep, the Chilcotin Group basalt dominates the landscape and bedrock geology. The Chilcotin Group basalt overlies rocks of the Permian Cache Creek Group, Eocene Kamloops Group and Miocene Deadman River Formation. This Geoscience BC Report/GSC Open File provides the distribution of these units as well as graphic logs, georeferenced magnetic susceptibility data, geochronology sample locations, and location and mineral deposits. All of these data are referenced on the map. It also provides a

summary of interim reports on the area. A main focus of this publication is the volcanic facies distribution of the Chilcotin Group basalt, which is well exposed in the Chasm Canyon.

Farrell, R.-E., Andrews, G.D.M., Russell, J.K., and Anderson, R.G., 2007. Chasm and Dog Creek lithofacies, Chilcotin Group basalt, Bonaparte Lake map area, British Columbia; Geological Survey of Canada, Current Research 2007-A5, 11 p.

Abstract: A diverse range of lithofacies occur within the Neogene Chilcotin Group in south-central British Columbia. Stratigraphic sections at Chasm Park and Dog Creek are dominated by subaerial, flat-lying basaltic lavas on top of, or interstratified with, minor pillow basalt and hyaloclastite units. The stratigraphic successions show depositional environments consistent with lava emplacement into mature paleochannels containing rivers and lakes. The nature of deposits observed in the Chasm and Dog Creek sequences show pronounced differences in the style of subaerial lava emplacement related to the differences in effusion rates, proximity to the vent, and paleotopography. A fundamental conclusion is that the complex stratigraphy of the subaerial lavas of the Chilcotin Group define a variety of lithofacies; the Chasm and Dog Creek lithofacies are defined in this paper.

Farrell, R.-E., Russell, J.K., and Simpson, K.A., 2010. Bedrock cross-sections in Chasm Provincial park; Geological Survey of Canada, Open File 6657; Geoscience BC Map 2010-15-1.

Summary: This report contains four photomosaic and associated line drawing cross-sections related to Geoscience BC Map 2009-16-1 (GSC Open File 6320) "Geology, Chasm Provincial Park and vicinity, British Columbia."

Farrell, R.-E., Simpson, K.A., Andrews, G.D.M., Russell, J.K., and Anderson, R.G. 2008. Preliminary interpretations of detailed mapping in the Chilcotin Group, Chasm Provincial Park, British Columbia; Geological Survey of Canada, Current Research 2008-13, 13 p.

Abstract: Within Chasm Provincial Park, the Chilcotin Group basalt overlies rocks of the Permian Cache Creek Group, the Eocene Kamloops Group, and the Miocene Deadman River Formation. Detailed mapping of the Chilcotin Group has identified a variety of subaqueous and subaerial volcanic and sedimentary facies. Within the coherent rocks, three distinct facies have been described, 1) plagioclase-phyric basalt (Pp), 2) aphyric columnar-jointed basalt (Ac), and 3) aphyric massive basalt (Am). All coherent facies are interpreted as subaerial, fl at-lying basalt lavas. Clastic facies include pillow-fragment breccia (Pf) and sandstone-to-breccia (Sb). The presence of intact pillows, pillow fragments, and hyaloclastite within the pillow-fragment breccia facies provides evidence for a local subaqueous environment. The sandstone-to-breccia units occur between the coherent lava units and are interpreted as paleosols that represent volcanic hiatuses during emplacement of the Chilcotin Group lavas.

Gordee, S.M., Andrews, G.D.M., Simpson, K., and Russell, J.K., 2007. Sub-aqueous, channel-confined volcanism within the Chilcotin Group, Bull Canyon Provincial Park (NTS 093B/03), south-central British Columbia; Geological Fieldwork 2006, British Columbia Ministry of Energy, Mines, and Petroleum Resources, Report 2007-1, p. 285-290.

Summary: This is a summary of Chilcotin basalts at Bull Canyon Provincial Park, and includes descriptions of the volcanic stratigraphy and lithofacies, introduction of a proposed type section for the Chilcotin Group, and a discussion of eruption style and distribution and thickness of the Chilcotin Group.

Hayward, N. and Calvert, A.J., 2009. Preliminary first-arrival modelling constraints on the character, thickness and distribution of Neogene and Eocene volcanic rocks in the southeastern Nechako Basin, south-central British Columbia (NTS 092N, O, 093B, C); Geoscience BC Report, v. 2009-1, p. 151-156.

Abstract: A report on a seismic reflection survey of the Nechako Basin which is primarily a Mesozoic sedimentary basin located between the Rocky and Coast mountains of southern British Columbia. The basin formed over, and in part from, the accreted terranes of the western Canadian Cordillera. Transpressional tectonic processes were dominant until the Eocene (Best, 2004), when there was a shift to a dextral transtensional regime (Price, 1994). This episode of transtension was responsible for the formation of the Yalakom and Fraser faults, and was associated with widespread volcanism.

Hickson, C. J., 1992. An update on the Chilcotin-Nechako project and mapping in the Taseko Lakes area, west-central British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 92-1A, p. 129-135.

Abstract: Detailed mapping (1:50 000) and geochronology in Taseko Lakes (NTS 92O) area demonstrated that the mid-Jurassic Mount Alex plutonic complex and overlying volcanic rocks (previously correlated with the Hazelton Group) are mid-Cretaceous (Albian). Correlation of these rocks with the Spences Bridge Group is now more likely. Slightly younger, Late Albian to Cenomanian, volcanic rocks conformably overlie Silverquick conglomerates and may be correlative with Powell Creek volcanics found farther to the southwest. Northwesterly trending, northeasterly verging, reverse (thrust?) faults have displaced and fragmented stratigraphic packages as late as Albian-Cenomanian time. Miocene to Pleistocene age (Chilcotin Group) lavas overlie much of the region. Discovery of hyaloclastite breccia, along the Fraser River associated with the youngest known lava flows (Dog Creek Formation), confirms regional glaciation about 1 million years ago and incision of the Fraser River valley to a depth of at least 350 m (1800 ft).

Hickson, C. J. and Higman, S., 1993. Geology of the northwest quadrant, Taseko Lakes map area, west-central British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 93-1A, p. 63-67.

Abstract: The 1992 mapping of Taseko Lakes (92O) focused on the northwest quadrant, namely 92O/11, 12, 13 and the southwest corner of 92O/14. The region is largely drift covered and thick sequences of glacial fluvial deposits occupy river valleys. Flows of Chilcotin basalt are laterally extensive beneath Quaternary cover. Two porphyritic plutons were discovered of probable Late Cretaceous or early Tertiary age. One, in close association with granodiorite, resembles plutonic rocks found farther to the east. A second granodiorite body, in close association with felsic volcanic rocks, is extensively altered. West of Big Creek and roughly parallel to it, Eocene volcanic rocks are exposed that range in composition from picritic basalt to quartz-phyric rhyolite. Farther west along the ridge system of which Vedan Mountain is part, volcanic rocks of probable Early Cretaceous age are exposed. Separation of Cretaceous rocks from Eocene rocks may be a continuation along Little Basin Fault.

Hickson, C.J., Read, P., Mathews, W.H., Hunt, J.A., Johansson, G., and Rouse, G.E., 1991. Revised geological mapping of northeastern Taseko Lakes map area, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 91-1A, p. 207-217.

Abstract: Regional mapping in Taseko Lakes (NTS 92O/NE) straddles the dextral strike-slip Fraser Fault. Although the western Belt of cache Creek Complex underlies both sides of the fault, only to the west is it intruded by the Later Permian Farwell Pluton. Southwest of the pluton, leucoquartz monzonite intrudes Lower Jurassic(?) volcanics, but does not contact fossiliferous Lower Jurassic sediments. Farther southwest, the mid-Jurassic(?) Mount Alex plutonic complex nonconformably

underlies Upper(?) Jurassic volcanics. In the south, Paleozoic and lower Mesozoic rocks disappear under a cover of Cretaceous, Eocene, and Miocene-Pleistocene volcanics and sediments. In Churn Creek, uppermost Albian to Cenomanian sediments of the Silverquick formation unconformably underlie Eocene volcanics. Near the Fraser River, Pliocene and Pleistocene basalts and underlying Miocene-Pliocene sediments and rhyolite ash comprise the Chilcotin Group. Four eruptive centres, 10-35 km west of the river, were the source of the flows that covered the sediments deposited in a northerly flowing river.

Metcalfe, P. and Hickson, C.J., 1994. Preliminary study of Tertiary volcanic stratigraphy in the Clisbako River area, central British Columbia; *in* Current Research1994-A, Geological Survey of Canada, p. 105-108.

Abstract: Three volcanic assemblages are exposed in the Clisbako River area of central British Columbia. The oldest undeformed units in the area are felsic to intermediate volcanic flows and pyroclastic rocks, which host hydrothermal alteration and mineralization. These are overlain by an assemblage of intermediate to mafic lava flows. The area of outcrop of the felsic volcanic rocks and the overlying mafic assemblage is a circular highland area, approximately 40 km in diameter. It is possible that this area is an eroded caldera, partially filled with younger basaltic lavas of the Chilcotin Group.

Mihalynuk, M.G., 2007. Neogene and Quaternary Chilcotin Group cover rocks in the Interior Plateau, south-central British Columbia: a preliminary 3-D thickness model; Geological Fieldwork 2006, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 2007-1, p. 143-147.

Summary: This is an account of the methods and results of a first-generation three-dimensional thickness model for Chilcotin Group cover over a portion of the Interior Plateau of British Columbia.

Resnick, J., 1999. Neogene magmatism from the northern Nechako and Summit Lake map areas, British Columbia: implications for the petrology of the lithosphere; B.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 105 p.

Abstract: Eleven remnant basaltic and diabase volcanic centres, lava flow(s?), and a dyke related to Neogene magmatism occur on the northern periphery of the Chilcotin group basalt field, in central British Columbia. The centres are preserved as moderate topographic highs and range in areas between 200 m^2 and 1 km^2. Well developed, vertical to subvertical columnar jointing is typical. Some centres erupted along pre-existing brittle fault systems. Petrologically the rocks are dominantly alkali olivine basalts and basanites, with subordinate amounts of transitional basalt and diabase (gabbro). Volcanic rocks are rarely vesicular and contain xenocrysts and megacrysts of olivine, clinopyroxene, magnetite, and plagioclase. Volcanic rocks are typically olivine phenocrystic and microphenocrystic. Infrequently clinopyroxene, plagioclase, and magnetite are observed are rare phenocrysts. Groundmass is composed of plagioclase, clinopyroxene, magnetite, feldspathoid (nepheline and/or leucite), olivine and ilmenite. Chemically all rocks are of the alkaline basalt clan. They are typically weakly to substantially silica undersaturated. These rocks are different from coeval Chilcotin Group basalts to the south in that they are substantially more alkaline, contain common ultramafic xenoliths, and contain feldspathoid mineral in the groundmass. Commonly entrained in the basaltic rocks are ultramafic, plutonic, and metamorphic xenoliths. Regional trends in the occurrence of these xenoliths at different locations, surface geology, liquid temperatures of the lavas, and reported two-pyroxene equilibration temperature of the ultramafic xenoliths, are used to construct a lithostratigraphic cross-section across 250 km of central British Columbia. Two-pyroxene equilibration temperatures of ultramafic xenoliths, and abundance and diversity of crustal xenoliths increase progressively eastward. These are interpreted to represent a thickening of the lithosphere to the east. Regional variation in major and trace elements of the basaltic rocks, the common occurrence of different ultramafic xenolith

lithologies, and differences in the percent melting of pyrolite required to produce different rock types is indicative that the mantle source region of these lavas in heterogeneous.

Schiarizza, P. and Bligh, J.S., 2008. Geology and mineral occurrences of the Timothy Lake area, south-central British Columbia (NTS 092P/14); Geological Fieldwork 2007, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 2008-1, p. 191-211.

Abstract: This is a summary of bedrock mapping for the Timothy Lake area, including a description of two outlying flows of Chilcotin basalt.

Symons, D.T.A., 1969. Paleomagnetism of the late Miocene plateau basalts in the Cariboo region of British Columbia; Geological Survey of Canada, Paper 69-43, p. 1-11.

Summary: This paper describes a detailed study of the paleomagnetism of Late Miocene Chilcotin basalt flows in the Cariboo region. Although the focus is on pre-Pleistocene flows, there is also a brief mention of younger basalts, and the lengthy discussion of Miocene units provides a good introduction to the Chilcotin Group.

Conference Proceedings, Abstracts, and Symposium Volumes

Andrews, G.D.M., Russell, J.K., and Anderson, R.G., 2007. New insights into Neogene landscape and topography within the Intermontane Belt of the Canadian Cordillera; mapping the base of the Chilcotin Group basalts; Geological Society of America, Abstracts with Programs, v. 39, no. 4, p. 70.

Abstract: The Cordilleran Intermontane Belt of British Columbia is characterized by extensive plateaux underlain by apparently undeformed basalt lavas of the Neogene (24 - 1.5 Ma) Chilcotin Group (CG) and overlying glacial till. CG represents a medium-sized igneous province (ca. 36,500 km^2 in area) whose distribution constrains estimates of Coast Mountain Belt uplift (Mathews, 1989), and the history of evolution of the Fraser Basin (Tribe, 2003), and Early Pleistocene glaciations (Mathews and Rouse, 1986). The CG was emplaced across highly-variable relief of Eocene volcanic and Mesozoic basement rocks. Poor exposure of the CG hinders mapping of its distribution, thickness, stratigraphy, and possible sources. Mapping of lava emplacement directions is an important proxy for local and regional landscape architecture and provides critical evidence for reconstructing the Neogene tectonic history of the Intermontane Belt. Our re-examination of the CG, with emphasis on understanding the volcanic facies architecture, is revealing several new and important aspects of the pre-CG topography: 1) the CG is typically very thin (< 25 m) across much of mapped distribution; 2) the CG is only thick where is has infilled paleo-drainages, producing volcanic lithofacies characteristic of lava-water interaction; 3) mapped paleo-drainages coincide with present-day rivers and valleys, suggesting that the regional drainage pattern was unchanged for several m.y.. Further research will investigate and better constrain the interplay between regional tectonic tilting, the ancestral Fraser River basin, and sustained (and, episodic) volcanism.

Andrews, G.D.M., Russell, J.K., and Anderson, R.G., 2009. Neogene and Quaternary evolution of the Fraser River basin, British Columbia; evidence from the Chilcotin Group basalts; Geological Society of America, Abstracts with Programs, v. 41, no. 7, p. 641.

Modified abstract: The Fraser River basin has experienced dramatic hydrologic and geomorphic changes in the past 3 Myrs; not least its reversal to flow southward, and eventually into the Pacific Ocean. There is abundant geomorphic evidence in the form of young canyons truncating broad, mature valleys that are now abandoned. The Miocene to Pleistocene Chilcotin Group basalts were erupted into the Fraser Basin. Our mapping and dating of these lavas, in conjunction with published works, is revealing the temporal evolution of the basin's paleo-geomorphology. Specifically, our data establish stream-flow directions and base-levels, and the presence of and early Pleistocene ice sheets. Here we present new field observations and Ar/Ar ages from Pliocene and Pleistocene lavas that indicate reversal of the Fraser River after 1.17 Ma. This interpretation is based on identification and dating of a large (approximately 3 km^3), lava and pillow-breccia-delta dam indicating northward flow at 3.1 Ma. The 3.1 Ma volcanic sequence was buried by a pro-glacial and glacial succession (preserved in Dog Creek), and a 1.17 Ma lava. The presence of this thin but extensive lava on either side of the present-day Fraser River Canyon provides a maximum age for it. A conservative minimum of age is established by it being part-filled by Fraserian sediments, a base-level drop of 700 m. We propose that canyon formation and base-level drop were intrinsically linked to the reversal of the Fraser River, most likely resulting from enhanced erosion in its southern Coast Mountain headwaters due to tectonic uplift and repeated development of Pleistocene ice caps, leading to the capture of rivers that flowed south into the Present-day Lower Fraser Valley. This history explains the abandonment of mature tributaries on the adjacent plateaus and the formation of similar canyons along the Thompson and Clearwater Rivers, fundamentally changing the drainage network and producing much of the dramatic relief observed today.

Andrews, G.D.M., Russell, J.K., and Caven, S., 2010. The Chilcotin Group; enigmatic Neogene basaltic volcanism in intermontane British Columbia; Geological Society of America, Abstracts with Programs, v. 42, no. 5, p. 343.

Abstract: The Chilcotin Group (CG) is the largest of several contemporaneous and adjacent Neogene basaltic provinces across the plateaus of central British Columbia. It forms an extensive (approximately 17,500 km^2) veneer of basalt lavas and associated valley-filling hyaloclastite-pillow successions, interspersed with remnants of small shields and dolerite plugs. The CG is comprised of multiple localised basaltic fields erupted on to a peneplain spasmodically between about 25 Ma and 100,000 years. Due to its longevity it should serve as a excellent gauge of tectonic and geomorphic changes in the Canadian Cordillera through the Neogene; for example, derangement of the Fraser River and uplift of the Coast and Cariboo Mountains. The CG occurs in the retro-arc region (sensu latto) to the Garibaldi and preceding Pemberton volcanic arcs of the northern Cascades, however it does not convincingly appear to be a "typical" back-arc regime. Furthermore, it appears to have been formed as British Columbia passed over at least one slab window. There is no tectono-magmatic synthesis for the CG, largely due to a paucity of accurate dates and good geochemical analyses with temporal-spatial context. It is enigmatic in several ways: (1) Why has basaltic volcanism been so long-lasting? (2) Why is the magmatic volume flux so low? (3) Is there a temporal-spatial or temporal-spatial-geochemical control? (4) Why is there no evidence of extension or translation (i.e. faults) in the CG? This presentation will introduce some of our recent work in the CG in an attempt to: (1) address some of these questions; (2) highlight it for further and more extensive study; and (3) to look for analogs in similar tectonic environments.

Garibaldi Volcanic Belt

<u>Scientific Books and Articles</u>

Adams, M. C. and Moore, J.N., 1987. Hydrothermal alteration and fluid geochemistry of the Meager Mountain geothermal system, British Columbia; American Journal of Science, v. 287, no. 7, p. 720-755.

Modified abstract: Drilling for geothermal fluids at Meager Mountain, in southwestern Canada, has provided an opportunity to study hydrothermal processes and fluid flow beneath an active stratovolcano. Drill holes have encountered temperatures as high as 264°C in altered crystalline basement rocks which act as the geothermal reservoir. Petrographic, mineralogic, and trace element studies have been used to establish the paragenetic relationships among the several thermal events that have affected these rocks. These relationships indicate that fault and fracture zones, steeply dipping dikes, and hydrothermal breccias related to recent volcanic activity have focused the upward movement of the geothermal fluids.

Andrews, G.D.M., Russell, J.K., and Stewart, M., 2014. The history and dynamics of a welded pyroclastic dam and its failure; Bulletin of Volcanology, v. 76, 16 p.

Abstract: The 2,360 BP eruption of Mount Meager, British Columbia, began as an explosive, dacitic sub-Plinian eruption that waned rapidly to a sustained period of Vulcanian, eruption-triggered dome collapse events producing voluminous block and ash flow (BAF) deposits. The earliest BAF deposits accumulated rapidly enough immediately downslope of the vent to retain heat and weld; using the deposit as a paleoviscometer determines an effective viscosity of 10^9 - 10^{10} Pa s during welding. This prolific production of hot lava and block and ash flows, in a steep mountainous terrain, created a ~110 m high, largely impermeable dam capped by permeable, non-welded BAF deposits and unconsolidated avalanche deposits that blocked the flow of the Lillooet River and created a temporary lake. The welded pyroclastic dam was compromised and overtopped at least once before the peak dam height was reached. Renewed eruption caused build-up of the dam to a maximum of 780 m asl and grew the temporary lake to an elevation of 740 m asl and a minimum volume of 0.55 km^3. Rise of lake-level led to catastrophic failure of the top of the dam, generating an outburst flood that carved a canyon through most of the dam and resulted in a voluminous lahar that is traced at least 65 km downstream. Based on current flow rates of the Lillooet River, the lake would have overtopped the final dam a minimum of 39 to 65 days after its formation. The peak deluge lasted approximately 8 hours and eroded a 2.5 km long canyon into the still hot dam core before returning to background flow rates.

Beaudoin, A. B. and King, R.H., 1986. Using discriminant function analysis to identify Holocene tephras based on magnetite composition; a case study from the Sunwapta Pass area, Jasper National Park; Canadian Journal of Earth Sciences, v. 23, no. 6, p. 804-812.

Abstract: The magnetite composition from three sets of samples of Mazama, St. Helens set Y, and Bridge River tephras from Jasper and Banff national parks are used to test whether discriminant function analysis can unambiguously distinguish these tephras. The multivariate method is found to be very sensitive to the change in reference samples. St. Helens set Y tephra is clearly distinguished. However, discrimination between Mazama and Bridge River tephras is less distinct. A set of unknown tephras from the Sunwapta Pass area was used to test the classification schemes. Unknown tephras are assigned to different tephra types depending on which reference tephra set is used in the discriminant function analysis.

Bovis, M. J. and Jakob, M., 2000. The July 29, 1998, debris flow and landslide dam at Capricorn Creek, Mount Meager volcanic complex, southern Coast Mountains, British Columbia; Canadian Journal of Earth Sciences, v. 37, no. 10, p. 1321-1334.

Abstract: A very large debris flow was triggered during a period of record-breaking high temperatures in upper Capricorn Creek, within the Mount Meager Volcanic Complex, a part of the Garibaldi Volcanic Belt of the southern Coast Mountains. The debris flow deposit impounded Meager Creek, creating an 800 m long landslide-dammed lake. The total event volume was $1.2X10^6$ m^3. The debris flow was followed by three days of almost continuous hyperconcentrated flow surges, which caused significant fluvial aggradation in the Meager Creek flood plain below the Capricorn Creek confluence. Within a few days of the formation of the landslide dam, a spillway notch had

been cut through the deposit, thereby preventing the occurrence of a catastrophic dam break. The landslide, which triggered the debris flow, originated in deep volcanic colluvium having a previous history of progressive slope deformation, a consequence of glacial downwasting since the Neoglacial maximum. This paper highlights an important landslide response to recent glacial retreat and suggests that similar events could reoccur within Capricorn Creek, as well as at other sites where steep colluvial and weak bedrock slopes have been glacially debuttressed.

Brewster, G. R. and Barnett, R.L., 1979. Magnetites from a new unidentified tephra source, Banff National Park, Alberta; Canadian Journal of Earth Sciences, v. 16, no. 6, p. 1294-1297.

Abstract: Electron microprobe examination of glass-encased magnetites present within surficial volcanic ash deposits located in Banff and Jasper National Parks revealed five distinct magnetite populations. Three of the magnetite populations represented the Mazama, St. Helens Y, and Bridge River volcanic units previously identified in this area of the Canadian Rocky Mountains. The remaining two magnetite groups are characterized by glass-encased magnetites which have titanium oxide concentrations of 11.59 and 10.33%, values considerably higher than those characteristic of either Mazama, St. Helens Y, or Bridge River volcanic units. The high-titanium magnetites are of unknown provenance, and although the section provided no means for dating these volcanic groups, their distribution within the section suggests that they are older than Bridge River, and one group may predate Mazama.

Brooks, G. R. and Friele, P.A., 1992. Bracketing ages for the formation of the Ring Creek lava flow, Mount Garibaldi volcanic field, southwestern British Columbia; Canadian Journal of Earth Sciences, v. 29, no. 11, p. 2425-2428.

Abstract: The Ring Creek lava flow, extending from Opal Cone, generally is considered to be the youngest volcanic feature in the southern section of the Mount Garibaldi volcanic field, southwestern British Columbia. An *in situ* stump dated 10 650 ± 70 BP (Beta 43865) obtained from a raised delta partially overridden by the lava flow indicates that the lava was extruded after ca. 10.7 ka. At the Skookum Creek and Mamquam River confluence, sediments eroded from the Ring Creek lava flow form an alluvial fan that contains charcoal dated 9360 ± 160 BP (Beta 38914), which indicates that the extrusion probably occurred before ca. 9.3 ka. Thus these radiocarbon ages bracket the age of the Ring Creek lava flow and indicate that volcanic activity in the southern section of the Mount Garibaldi volcanic field has been dormant since at least ca. 9.3 ka.

Brooks, G. R. and Hickin, E.J., 1991. Debris avalanche impoundments of Squamish River, Mount Cayley area, southwestern British Columbia; Canadian Journal of Earth Sciences, v. 28, no. 9, p. 1375-1385.

Abstract: Squamish River has been impounded temporarily by debris avalanches from Mount Cayley on numerous occasions. Evidence of these impoundments comes from backwater deposits and also from a cluster of *in situ* stumps protruding from a bar along Squamish River. Backwater deposits consist of both lacustrine and fluvial deposits that have formed within the low-energy depositional environment created by a river impoundment. Three main backwater deposits occur in the study area. The fan toe deposit is ~14 m thick and represents a single impoundment of Squamish River that likely formed behind a large ~4800 BP debris avalanche. *In situ* ~3200 BP stumps along Squamish River probably were killed by a river impoundment due to a debris avalanche. The upper terrace backwater deposit is ~6 m thick and forms an aggradational terrace along Squamish River which probably accumulated behind an ~1100 BP debris avalanche. The lower terrace deposit also forms an aggradational terrace along Squamish River but represents four or possibly five separate impoundments. These occurred between ~1100 BP and 1955 AD, and it seems likely that one of the deposits relates to an ~500 BP debris avalanche. Seven or eight Holocene impoundments of Squamish River have been identified in the study area.

Brooks, G. R. and Hickin, E.J., 1995. The origin of a tephra-like bed near Mount Cayley Volcano, southwestern British Columbia, Canada; Canadian Journal of Earth Sciences, v. 32, no. 12, p. 2040-2045.

Modified abstract: A distinct white bed 1–2 cm thick is present within backwater deposits at the upstream end of the Turbid Creek debris fan, southwestern British Columbia, Canada. This white bed and the enclosing backwater deposits accumulated within an impoundment of Squamish River caused by a large ca. 4800 BP debris avalanche originating from Mount Cayley, a Pliocene–Pleistocene volcano.

Campbell, M.E., Russell, J.K., and Porritt, L.A., 2013. Thermomechanical milling of accessory lithics in volcanic conduits; Earth and Planetary Science Letters, v. 377-378, p. 276-286.

Abstract: Accessory lithic clasts recovered from pyroclastic deposits commonly result from the failure of conduit wall rocks, and represent an underutilized resource for constraining conduit processes during explosive volcanic eruptions. The morphological features of lithic clasts provide distinctive 'textural fingerprints' of processes that have reshaped them during transport in the conduit. Here, we present the first study focused on accessory lithic clast morphology and show how the shapes and surfaces of these accessory pyroclasts can inform on conduit processes. We use two main types of accessory lithic clasts from pyroclastic fallout deposits of the 2360 B.P. subplinian eruption of Mount Meager, British Columbia, as a case study: (i) rough and subangular dacite clasts, and (ii) variably rounded and smoothed monzogranite clasts. The quantitative morphological data collected on these lithics include: mass, volume, density, 2-D image analysis of convexity (C), and 3-D laser scans for sphericity (Psi) and smoothness (S). Shaping and comminution (i.e. milling) of clasts within the conduit are ascribed to three processes: (1) disruptive fragmentation due to high-energy impacts between clasts or between clasts and conduit walls, (2) ash-blasting of clasts suspended within the volcanic flux, and (3) thermal effects. We use a simplified conduit eruption model to predict ash-blasting velocities and lithic residence times as a function of clast size and source depth, thereby constraining the lithic milling processes. The extent of shape and surface modification (i.e. rounding and honing) is directly proportional to clast residence times within the conduit prior to evacuation. We postulate that the shallow-seated dacite clasts remain subangular and rough due to short (<2 min) residence times, whereas monzogranite clasts are much more rounded and smoothed due to deeper source depths and consequently longer residence times (up to approximately 1 h). Larger monzogranite clasts are smoother than smaller clasts due to longer residence times and to greater differential velocities within the ash-laden jet. Lastly, our model residence times and mass loss estimates for rounded clasts are used to estimate minimum attrition rates due to volcanic ash-blasting within the conduit (e.g., 12 $cm^3\ s^{-1}$ for 25 cm clasts, sourced at 2500 m depth).

Clague, J. J., Friele, P.A., and Hutchinson, I., 2003. Chronology and hazards of large debris flows in the Cheekye River basin, British Columbia, Canada; Environmental and Engineering Geoscience, v. 9, no. 2, p. 99-115.

Abstract: Stump Lake is strategically located to provide a sediment record of very large debris flows that travel down Cheekye River to lower Cheekye fan from the west flank of Mount Garibaldi, a Quaternary volcano in the southern Coast Mountains of British Columbia. Cores collected from Stump Lake span the last 11,500 years and consist largely of gyttja. However, a diamicton layer and an associated detrital organic layer, which is capped by a clay lamina, record a large debris flow derived from the headwaters of Cheekye basin. Radiocarbon ages indicate that this event occurred about 6,900 years ago. We estimated the peak discharge of the flow by measuring cross-sections of the Cheekye River channel adjacent to Stump Lake and by calculating flow velocity using a Newtonian flow model. Reasonable values of peak discharge, calculated in this way, were input into an empirical equation linking discharge and debris-flow volume, developed for non-granitic debris flows. The estimated minimum volume of the debris flow is 3 to $5X10^6\ m^3$. Another large debris flow (ca. $3X10^6\ m^3$), which occurred about 800 years ago, is not recorded in Stump Lake sediments and thus was too small to reach the lake. The Stump Lake sediment sequence indicates that no debris flows larger than several million cubic meters have reached lower Cheekye fan in post-glacial time.

Clague, J. J. and Souther, J.G., 1982. The Dusty Creek landslide on Mount Cayley, British Columbia; Canadian Journal of Earth Sciences, v. 19, no. 3, p. 524-539.

Abstract: A large (ca. 5×10^6 m^3) landslide occurred on the west flank of Mount Cayley in the southern Coast Mountains of British Columbia in 1963. Failure commenced when a large block of poorly consolidated tuff breccia and columnar-jointed dacite was detached from the subvolcanic basement and slid into the valley of Dusty Creek, a small tributary of Turbid Creek. As the detached block accelerated, it quickly fragmented into an aggregate consisting of angular clasts up to several metres across, partially supported by a matrix of fine comminuted rock material. The landslide debris moved about 1 km down Dusty Creek as a wedge-shaped mass up to 70 m thick, banking up on turns and attaining a maximum velocity of 15–20 m/s. The debris mass thinned as it spread across the broader, flatter valley of Turbid Creek, and was deposited as an irregular blanket with a maximum thickness of 65 m along a 1 km length of this valley. As a result of the landslide, Turbid and Dusty Creeks were blocked, and lakes formed behind the debris. These debris dams were soon overtopped and rapidly breached, causing floods and probably debris flows to sweep down Turbid Creek valley far beyond the terminus of the landslide.

Clague, J.J., Turner, R.J., and Reyes, A.V., 2003. Record of recent river channel instability, Cheakamus Valley, British Columbia; Geomorphology, v. 53, no. 3-4, p. 317-332.

Abstract: Rivers flowing from glacier-clad Quaternary volcanoes in southwestern British Columbia have high sediment loads and anabranching and braided planforms. Their floodplains aggrade in response to recurrent large landslides on the volcanoes and to advance of glaciers during periods of climate cooling. In this paper, we document channel instability and aggradation during the last 200 years in lower Cheakamus River valley. Cheakamus River derives much of its flow and nearly all of its sediment from the Mount Garibaldi massif, which includes a number of volcanic centres dominated by Mount Garibaldi volcano. Stratigraphic analysis and radiocarbon and dendrochronological dating of recent floodplain sediments at North Vancouver Outdoor School in Cheakamus Valley show that Cheakamus River aggraded its floodplain about 1-2 m and buried a valley-floor forest in the early or mid 1800s. The aggradation was probably caused by a large (ca. 15-25x10^6 m^3) landslide from the flank of Mount Garibaldi, 15 km north of our study site, in 1855 or 1856. Examination of historical aerial photographs dating back to 1947 indicates that channel instability triggered by this event persisted until the river was dyked in the late 1950s. Our observations are consistent with data from many other mountain areas that suggest rivers with large, but highly variable sediment loads may rapidly aggrade their floodplains following a large spike in sediment supply. Channel instability may persist for decades to centuries after the triggering event.

Clark, I.D., Fritz, P., Michel, F.A., and Souther, J.G., 1982. Isotope hydrogeology and geothermometry of the Mount Meager geothermal area; Canadian Journal of Earth Sciences, v. 19, no. 7, p. 1454-1473.

Abstract: A survey of stable and radioactive environmental isotopes has been carried out in order to investigate the recharge, thermal history, age, and geothermometry of the thermal waters at Mount Meager, British Columbia, a Quaternary volcano that is currently the site of active exploration for geothermal resources. Isotope determinations include ^{18}O, ^{2}H, and ^{3}H in precipitation, thermal and cold groundwaters, and glacier ice; ^{13}C and ^{14}C in dissolved inorganic carbon; ^{18}O and ^{34}S in dissolved sulphate from thermal and cold groundwaters; and ^{13}C and ^{18}O in hydrothermal calcite crystals. Major ion analyses were performed on thermal and cold spring waters. Precipitation data are used to define the local meteoric water line and to document the altitude effect on waters recharging the geothermal system, demonstrating that there are two hydrogeologically separate reservoirs recharged at different altitudes. Both pools of geothermal waters have experienced shifts of between +0.5 and +2.5‰ in $\delta^{18}O$ values, indicating a limited

degree of ^{18}O exchange with hot silicate minerals. Tritium contents indicate that these waters recharged prior to 1955. ^{13}C contents of dissolved inorganic carbon and hydrothermal calcites from drill core document contamination of the thermal waters with "dead" volcanogenic CO_2 plus carbon exchange with fracture calcite, which precludes the possibility of "dating" the thermal waters using ^{14}C. Several chemical and isotopic geothermometers are used to estimate the maximum temperatures experienced by the thermal waters. The fractionation of ^{18}O between SO_4^{2-} and H_2O in these waters gives calculated maximum temperatures of less than 140 °C. The Mg-corrected Na–K–Ca geothermometer shows excellent correlation with the SO_4–H_2O estimates with maximum temperatures of less than 140 °C. Fractionation of ^{13}C and ^{18}O in the systems $CaCO_3$–CO_2 and $CaCO_3$–H_2O using hydrothermal calcites and borehole fluids also offers no indications of subsurface temperatures in excess of 140 °C. Silica geothermometer results are not reliable because of equlibrium with amorphous silica phases in the subsurface. It is concluded that these thermal waters are not deeply circulating and have not experienced temperatures in excess of 140 °C.

Crider, J., Frank, D., Malone, S.D., Poland, M.P., Werner, C., and Caplan-Auerbach, J., 2011. Magma at depth: a retrospective analysis of the 1975 unrest at Mount Baker, Washington, USA; Bulletin of Volcanology, v. 73, no. 2, p. 175-189.

Abstract: Mount Baker volcano displayed a short interval of seismically-quiescent thermal unrest in 1975, with high emissions of magmatic gas that slowly waned during the following three decades. The area of snow-free ground in the active crater has not returned to pre-unrest levels, and fumarole gas geochemistry shows a decreasing magmatic signature over that same interval. A relative microgravity survey revealed a substantial gravity increase in the ~30 years since the unrest, while deformation measurements suggest slight deflation of the edifice between 1981–83 and 2006–07. The volcano remains seismically quiet with regard to impulsive volcano-tectonic events, but experiences shallow (<3 km) low-frequency events likely related to glacier activity, as well as deep (>10 km) long-period earthquakes. Reviewing the observations from the 1975 unrest in combination with geophysical and geochemical data collected in the decades that followed, we infer that elevated gas and thermal emissions at Mount Baker in 1975 resulted from magmatic activity beneath the volcano: either the emplacement of magma at mid-crustal levels, or opening of a conduit to a deep existing source of magmatic volatiles. Decadal-timescale, multi-parameter observations were essential to this assessment of magmatic activity.

Cruden, D. M. and Lu, Z.Y., 1992. The rockslide and debris flow from Mount Cayley, British Columbia, in June 1984; Canadian Geotechnical Journal, v. 29, no. 4, p. 614-626.

Abstract: A major rockslide and debris flow occurred on Mount Cayley, British Columbia, in June 1984. Approximately 3.2 million cubic metres of volcanics travelled 2.0 km down Avalanche Creek at velocities up to 35 m/s to dam the confluence of Avalanche and Turbid Creeks. The breaking of the landslide dam caused an extremely fast debris flow. The velocity of the debris flow and associated wind gusts, up to 34 m/s, caused superelevations, hurled rocks and wood through the air, uprooted trees, and spattered mud 16 m up trees. The debris flow removed the logging road bridge and road approaches at the mouth of Turbid Creek, blocked the Squamish River during surges, and introduced huge quantities of sediment to the Squamish River. The uniaxial compressive strength of wet tuff collected from the head scarp of the rock slide is 1.0–1.5 MPa, about two thirds of the strength of dry specimens, the friction angle on wet tuff bedding surfaces is 30°, and the slake durability index is 26%. Weak tuffs form the rupture surface of the 1984 rockslide on Mount Cayley, and their slaking contributed fines to the debris flow. The tuff, steep, narrow creeks intersecting at high angles, high precipitation, and snow and ice accumulation in creeks combine to make the western slopes of Mount Cayley extremely hazardous.

Evans, S.G., 1992. Landslides and river damming events associated with the Plinth Peak volcanic eruption, southwestern British Columbia; *in* Geotechnical and Natural Hazards, Bi Tech Publishers, Vancouver, British Columbia, p. 405-412.

Abstract: The flank eruption of Plinth Peak within the Mount Meager volcanic complex, at about 2350 BP, deposited the Bridge River ash up to 550 km east-northeast of the vent and is the most recent major volcanic eruption in the Garibaldi Volcanic Belt of southwestern British Columbia. A radiocarbon-controlled chronology of deposits in the Lillooet River valley in the vicinity of Plinth Peak is being constructed and has revealed a complex series of events associated with the eruption. A major pre-eruption landslide deposit (est. vol. > 50 x 10^6 m^3) has been mapped in Salal Creek, a northerly tributary of the Lillooet River. It extends 5 km from the Lillooet River up to el. 1158 m and has also been mapped at scattered locations in the Lillooet Valley. The lithology of the deposit suggests a source on Plinth Peak but the deposit is overlain by Bridge River Tephra. Eruptive products of the Plinth Peak event include tephra, pyroclastic flow and debris flow deposits overlain by a welded breccia. The initial eruption was closely followed by a second major landslide, a debris avalanche from Plinth Peak (est. vol. 2-4 x $10^8$$m^3$). Its debris filled the Lillooet valley and dammed the river. Debris flow deposits possibly related to a breach of the debris dam are found up to 6 km downstream. The landslide events were followed by an eruption of a small lava flow into the bowl created by the landslides and initial eruption. Sediments deposited during subsequent damming events, up to at least 900 y BP, are found in the Lillooet River valley upstream of Plinth Peak.

Evans, S. G. and Brooks, G.R., 1991. Prehistoric debris avalanches from Mount Cayley Volcano, British Columbia; Canadian Journal of Earth Sciences, v. 28, no. 9, p. 1365-1374.

Abstract: An investigation of diamicton units exposed in an extensive accumulation of volcanic debris in the Squamish valley, west of Mount Cayley volcano, has yielded evidence for at least three major debris avalanches, initiated by the collapse of the western flank of Mount Cayley in the mid-Holocene. Radiocarbon ages obtained from tree fragments contained in the deposits indicate that the events took place at 4800, 1100, and 500 BP. All three debris avalanches dammed the Squamish River and formed temporary lakes upstream of the debris. Failure of the cone took place after considerable dissection of the original edifice had exposed weak pyroclastic materials at the base of the steep upper slope of the volcano. No evidence of older debris avalanches from Mount Cayley has been discovered. Smaller scale debris avalanches probably have been common, and at least two have occurred in historic time (1963 and 1984). Debris avalanches from Mount Cayley and the effects of a possible damming of the Squamish River are major geomorphic hazards to public safety and economic development in the Squamish valley.

Evans, S. G., Hungr, O., and Clague, J.J., 2001. Dynamics of the 1984 rock avalanche and associated distal debris flow on Mount Cayley, British Columbia, Canada; implications for landslide hazard assessment on dissected volcanoes; Engineering Geology, v. 61, no. 1, p. 29-51.

Abstract: In 1984 a mass of Quaternary pyroclastic rock (est. vol. 0.74x10^6 m^3) slid from the western flank of Mount Cayley volcano in southwest British Columbia. The disintegrating rock mass entrained a further 0.20X10^6 m^3 and formed a rock avalanche that travelled a horizontal distance of 3.46 km from its source over a vertical elevation difference of 1.18 km, equivalent to a fahrboschung of 19 degrees . From the superelevation of the debris trimline in the mid-path, it is estimated that velocities reached at least 42 m/s; in the upper part of its path velocities may have approached 70 m/s. The rock avalanche was partially transformed into a distal debris flow that travelled a further 2.6 km down Turbid Creek in a narrow channelised path to the Squamish River, temporarily blocking it. The motion of the rock avalanche, including the production of a distal debris flow, was successfully simulated using a dynamic analytical model. Both the results of this analysis and field evidence indicate that the rock avalanche did not come to a halt in the upper part of its path as suggested by Cruden and Lu (1992), but travelled to its distal limit in one uninterrupted movement. This finding has important implications for landslide hazard assessment at Mount Cayley and similar sites. The landslide is typical of those which occur on the steep slopes of dissected volcanoes and is one of seven high-velocity rock avalanches that have occurred in the Garibaldi Volcanic Belt of southwest British Columbia since 1855.

Friele, P. A. and Clague, J.J., 2004. Large Holocene landslides from Pylon Peak, southwestern British Columbia; Canadian Journal of Earth Sciences, v. 41, no. 2, p. 165-182.

Abstract: Mount Meager massif, the northernmost volcano of the Cascade volcanic belt, has been the site of very large (>107 m^3) landslides in the Holocene Epoch. We document two complex landslides at Pylon Peak, one of the peaks of the Mount Meager massif, about 7900 ^{14}C and 3900 ^{14}C years ago (about 8700 and 4400 calendar years ago). Together, the two landslides displaced approximately $6X10^8$ m^3 of volcanic rock from the south flank of Pylon Peak into nearby Meager Creek valley. Each landslide consisted of at least two phases, an early debris flow resulting from failure of hydrothermally altered pyroclastic rock at mid levels on the mountain and a later rock avalanche from a higher source. Both debris flows likely traveled down Meager Creek, and preliminary evidence from drilling indicates the 4400-year-old event traveled down Lillooet River into areas that are now settled and where population density is increasing rapidly. The mobility of the debris flows was due to the high content of fine, weathered volcanic sediment and the availability of sufficient water. The causes of the landslides are a wet climate and the presence of weak, hydrothermally altered volcanic rock containing abundant phreatic water on glacially oversteepened slopes. The landslides may have been triggered by earthquakes or by upwelling of magma to shallow depths within the volcano. However, they may also have occurred without specific triggers following extended periods of progressive weakening of the volcanic rocks.

Friele, P.A. and Clague, J.J., 2005. Multifaceted Hazard Assessment of Cheekye Fan, a Large Debris-Flow Fan in South-Western British Columbia; *in* Debris-Flow Hazards and Related Phenomena, (ed.) M. Jakob and O. Hungr; Springer, Berlin, Federal Republic of Germany, p. 659-683.

Summary: The Cheekye fan, situation in the southern Coast Mountains 50km north of Vancouver, is one of the largest and most thoroughly studied alluvial fans in British Columbia. This chapter summarizes the substantial body of previous research on the Cheekye fan and illustrates the wide range of approaches that have been applied over the last 50 years to assess debris-flow hazards and risk. The possibility of a disaster of the Cheekye fan is increasing as development spreads across the lower part of the fan. Conditions that predispose this area to a disaster include: the steepness of the Cheekye River basin, with 2,470m of relief; the presence in the upper part of the basin of the unstable, precipitous, western slope of Mount Garibaldi; and heavy runoff during the intense fall rains, rain-on-snow, and spring snowmelt events. This potent mix of landslide-generating phenomena demands a thorough understanding of the hazard before further development of the fan is approved. This compilation, representing a comprehensive analysis of fan geomorphology and debris-flow hazard, provides the scientific basis for risk management.

Friele, P.A. and Clague, J.J., 2009. Paraglacial geomorphology of Quaternary volcanic landscapes in the southern Coast Mountains, British Columbia; *in* Periglacial and paraglacial processes and environments, (ed.) J. Knight and S. Harrison; Geological Society Special Publications, v. 320, p. 219-233.

Abstract: An important paradigm in geomorphology is paraglacial sedimentation, a phrase first used almost 40 years ago to describe reworking of glacial sediment by mass wasting and streams during and after continental-scale deglaciation. The concept has been extended to include non-glacial landforms and landscapes conditioned by glaciation. In this paper we apply the paraglacial concept to volcanoes in southern British Columbia, Canada, that formed, in part, in contact with glacier ice. The Cheekye River basin, a small watershed on the flank of a volcano that erupted

against the decaying Cordilleran ice sheet, has a Holocene history marked by an exponential decay in debris-flow activity and sediment yield. Its history is consistent with the primary exhaustion model of the paraglacial cycle. At larger spatial scales, this primary sediment is reworked by rivers and transported downstream and augmented by stochastic geomorphic events. Repeated large landslides from Mount Meager volcano in southern British Columbia have delivered a disproportionate volume of sediment to the fluvial system: although occupying only 2% of the watershed area, 25-75% of the 10 km^3 of sediment deposited in Lillooet River valley during the Holocene originated from the volcano. In these cases a significant overall reduction in sediment yield must await the removal, by erosion, of volcanic edifices, a process that could take up to millions of years. These examples of paraglacial activity on Quaternary volcanoes are end members in the spectrum of landscape response to Pleistocene deglaciation.

Friele, P.A., Clague, J.J., Simpson, K., and Stasiuk, M., 2005. Impact of a Quaternary volcano on Holocene sedimentation in Lillooet River valley, British Columbia; Sedimentary Geology, v. 176, no. 3-4, p. 305-322.

Abstract: Lillooet River drains 3850 km^2 of the rugged Coast Mountains in southwestern British Columbia, including the slopes of a dormant Quaternary volcano at Mount Meager. A drilling program was conducted 32-65 km downstream from the volcano to search for evidence of anomalous sedimentation caused by volcanism or large landslides at Mount Meager. Drilling revealed an alluvial sequence consisting of river channel, bar, and overbank sediments interlayered with volcaniclastic units deposited by debris flows and hyperconcentrated flows. The sediments constitute the upper part of a prograded delta that filled a late Pleistocene lake. Calibrated radiocarbon ages obtained from drill core at 13 sites show that the average long-term floodplain aggradation rate is 4.4 mm a^{-1} and the average delta progradation rate is 6.0 m a^{-1}. Aggradation and progradation rates, however, varied markedly over time. Large volumes of sediment were deposited in the valley following edifice collapse events and the eruption of Mount Meager volcano about 2360 years ago, causing pulses in delta progradation, with estimated rates to 150 m a^{-1} over 50-yr intervals. Two of the volcaniclastic units identified in drill core correlate with previously documented strong acoustic reflectors in Lillooet Lake at the downstream end of the basin. The Mount Meager massif constitutes only 2% of the Lillooet River drainage, but lithology counts of Lillooet River channel gravels indicate that a disproportionate percentage of the sediment is derived from the volcano. The data indicate that deposits of large debris flows are important elements of the sedimentary sequence and that Mount Meager dominates the sediment supply to Lillooet River.

Friele, P. A., Ekes, C., and Hickin, E.J., 1999. Evolution of Cheekye Fan, Squamish, British Columbia; Holocene sedimentation and implications for hazard assessment; Canadian Journal of Earth Sciences, v. 36, no. 12, p. 2023-2031.

Abstract: Cheekye fan, a large (~25 km^2) fan located at the head of Howe Sound, southwestern British Columbia, has its origins in the collapse of the western flank of Mount Garibaldi onto a waning Late Pleistocene glacier, followed by post-glacial redistribution of colluvial-glacial sediments. Reconstruction of internal fan architecture allowed characterization of the rapid decline in sediment delivery to the lower fan through the paraglacial period, a result holding important implications for hazard assessment. A ground penetrating radar profile on lower Cheekye fan has reflectors with a steep (25°), westerly dip lying between 48 and 26 m above sea level, which are interpreted as foreset beds. Radiocarbon ages from marine deltaic deposits at the head of Howe Sound indicate that the sea stood at about 45 m above sea level at 10 200 BP. Together, the data indicate that the head of Howe Sound was deglaciated by 10 200 BP, that the fan had prograded 2.5 km into the fjord by this time, and continued to prograde as relative sea level fell. Reflectors at -10 m above sea level with a steep southerly dip along the southern edge of the lower fan, and radiocarbon ages in this vicinity, indicate it had reached close to its modern extent by 8000-9000 BP. Calculation of the volume of sediment stored in the lower fan indicates that at least 90% of the material was deposited before 6000 BP. This indicates that the Cheekye fan is largely a relict feature, putting its large size into context for future hazard assessments.

Friele, P., Jakob, M., and Clague, J., 2008. Hazard and risk from large landslides at Mount Meager volcano, British Columbia, Canada; Georisk, v. 2, no. 1, p. 48-64.

Abstract: During the past 8000 years, large volcanic debris flows from Mount Meager, a Quaternary volcano in southwest British Columbia, have reached several tens of kilometres downstream in Lillooet River valley, with flow velocities of many metres per second and flow depths of several metres. These debris flows inundated areas that have become settled in the past 100 years and are now experiencing rapid urban growth. Notably, Pemberton, 65 km from Mount Meager, has doubled in size in the past five years. Approval of subdivision and building permits in Pemberton and adjacent areas requires assessment and mitigation of flood hazards, but large, rare debris flows from Mount Meager are not considered in the permitting process. Unlike floods, some volcanic debris flows can occur without warning. We quantify the risk to residents in Lillooet River valley from non-eruption triggered volcanic debris flows based on Holocene landslide activity at Mount Meager. The calculated risk exceeds, by orders of magnitude, risk tolerance thresholds developed in Hong Kong, Australia, England, and in one jurisdiction in Canada. This finding poses a challenge for local governments responsible for public safety.

Green, N.L., 1981. Geology and petrology of Quaternary volcanic rocks, Garibaldi Lake area, southwestern British Columbia; Geological Society of America Bulletin, v. 92, Pt. I, p. 697-702; Pt. II, p. 1359-1470.

Summary: Subduction of the Juan de Fuca plate beneath the North American plate has been accompanied by Pleistocene-Holocene eruptions of basalt, andesite, and dacite along the Garibaldi volcanic belt in southwestern British Columbia (Souther, 1997; Keen and Hyndman, 1979). The 25-km-wide belt, comprising of at least eighteen volcanic complexes, lies approximately 250 km inland from the convergent margin. It extends from Mount Garibaldi, at the head of Howe Sound, northwesterly for 140 km to Bridge River. Volcanism in the Garibaldi Lake area, about 6 km north of Mount Garibaldi, produced a succession of flat-lying olivine basalts at the Cinder Cone and Sphinx Moraine centers, and a line of the three andesitic complexes: the Table, Mount Price and the Black Tusk. The Garibaldi Lake volcanic suites record at least two periods of eruptive activity.

Green, N.L., 1982. Fluorine geochemistry of Quaternary volcanic rocks from southwestern British Columbia; some petrogenetic implications; Contributions to Mineralogy and Petrology, v. 79, no. 4, p. 405-410.

Modified abstract: Fluorine contents in the 38 Quaternary volcanic rocks, representing calc-alkaline andesite eruptive groups from the Garibaldi Lake area, were determined by a selective ion-electrode method. A close relationship is evident between F abundance and the type of ferromagnesian phenocrysts present in the andesitic rocks. Different eruptive suites can be grouped on the basis of F differentiation patterns into (1) a hornblende-free lava series in which F content of basaltic andesite is less that that of andesite, and (2) a hornblende-bearing lava series in which F contents remain constant or decrease slightly from basaltic andesite through dacite. Fluorine variation in the former series was controlled largely by fractionation of anhydrous minerals, whereas that in the latter was influenced by crystallization of amphibole, biotite and apatite. The distinctive F variation patterns of the two lava series appear to represent real differences in the volatile contents of Garibaldi Lake magmas. These different volatile concentrations may reflect varying degrees of magma-wall-rock interaction, differences in the initial volatile contents of the primary magmas, or some combination of these factors.

Green, N.L., 1990. Garibaldi Lake; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 143-144.

Summary: The stratovolcanoes, lavas, and cinder cone of Garibaldi Lake, in southwestern British Columbia's Garibaldi Volcanic Belt, are summarized briefly.

Green, N. L., 1994. Mechanism for middle to upper crustal contamination; evidence from continental-margin magmas; Geology, v. 22, no. 3, p. 231-234.
Abstract: Lavas and feeder dikes of two Quaternary volcanic complexes in southwest British Columbia provide evidence of an upper crustal syntectic origin for many dacite magmas. Contamination initially involves solid-liquid and liquid-liquid interdiffusion between the magma and ≤1-cm-wide, partially melted (≤60%) margins of wall-rock xenoliths. Subsequent abrasion of mechanically unstable margins contributes both silicic melt and xenocrysts to the magma. Hybridization continues by elemental exchange between the magma and crustal liquid, where mechanical mixing produces a "meshlike" distribution of <1 mm rhyolite strands in the lava matrix. The magma may assimilate large quantities of crustal material through disaggregation of xenoliths within high-level subvolcanic dikes.

Green, N.L., 2006. Influence of slab thermal structure on basalt source regions and melting conditions; REE and HFSE constraints from the Garibaldi volcanic belt, northern Cascadia subduction system; Lithos, v. 87, no. 1-2, p. 23-49.
Modified abstract: Garibaldi volcanic belt (GVB) basalts were erupted above the relatively young (≤24 Ma) Juan de Fuca plate, which comprises the subducted oceanic lithosphere that becomes progressively younger (22-13 Ma), and presumably hotter, northward along the northern Cascadia convergent margin. Primitive and near-primitive mafic lavas of the 15-km-wide volcanic belt change from high-alumina olivine tholeiites and magnesian andesites near Glacier Peak, northwestern Washington, through transitional basalts to alkali-olivine basalts and basanites in the Bridge River-Salal Glacier areas, southwestern British Columbia. The distribution of different basalt types is consistent with varied source conditions imposed by differences in the thermal structure of the underlying subducted plate. Significant arc-parallel variations characterize REE and HFSE contents in GVB basalts and suggest that source enrichment processes and melting conditions vary within the mantle wedge as the age and thermal state of the underlying subducted plate changes. These HFSE-REE variations in primitive GVB basalts cannot be explained by variable degrees of depletion produced during prior episodes of melt generation in the mantle wedge. Instead, these differences in basalt chemistry probably reflect different extents of melting of a regionally homogeneous, locally heterogeneous, mantle wedge under conditions influenced by the thermal structure of the underlying subduction zone. Phase relationships and REE systematics of the primitive to near-primitive basalts argue that conditions of magma generation beneath the Bridge River, Salal Glacier, Meager Mountain and Cheakamus Valley lava fields involved lower degrees of melting, higher pressures, and mantle sources richer in garnet than those beneath Mount Baker and Glacier Peak.

Green, N. L., Armstrong, R.L., Harakal, J.E., Souther, J.G., and Read, P.B., 1988. Eruptive history and K-Ar geochronology of the late Cenozoic Garibaldi volcanic belt, southwestern British Columbia; Geological Society of America Bulletin, v. 100, no. 4, p. 563-579.
Abstract: The Cenozoic Garibaldi belt comprises 6 volcanic fields spaced at irregular intervals along an axis extending 240 km north-northwest from the head of Howe Sound to the Bridge River area; 2 additional fields, the Franklin Glacier and Silverthrone lie 140 and 190 km west of the north end of the main volcanic belt. The volcanoes erupted lavas ranging in composition from augite-olivine basalt, through hypersthene andesite, hornblende andesite, and hornblende-biotite andesite, to biotite rhyodacite. Many of the volcanic complexes are characterized by geomorphic features which indicate complex interactions between volcanism and the Pleistocene ice sheets, but preglacial and postglacial phases are also present. Whole-rock samples from 18 volcanic complexes have been dated by the K-Ar method. Most of the results are internally consistent with stratigraphic relationships and with limited ^{14}C and paleomagnetic data.They suggest that volcanic activity was episodic; most of the analyzed andesitic and dacitic lavas were erupted in the intervals 2.3 to 1.7 Ma and 1.1 Ma to present in the northern part and in the intervals 1.4 to

1.0 Ma and 0.7 Ma to present in the southern part of the belt. Basaltic volcanism occurred only during the past 0.15 m.y., except in the Salal Glacier area where hawaiite and alkali-olivine basalt, which are perhaps an "edge effect" related to subduction of the Juan de Fuca plate, were erupted as early as 0.97 Ma. The timing of Garibaldi belt volcanism provides information bearing on the distribution of pre-Wisconsin glaciers in southwestern British Columbia and constrains interpretations of late Cenozoic changes in Explorer-Juan de Fuca-North American plate configuration along the continental margin.

Green, N.L. and Harry, D.L., 1999. On the relationship between subducted slab age and arc basalt petrogenesis, Cascadia subduction system, North America; Earth and Planetary Science Letters, v. 171, p. 367-381.

Abstract: Olivine-normalized ≤2.0 Ma magnesian basalts erupted close to the volcanic axis of the Cascadia subduction system exhibit arc-parallel compositional variations compatible with a northward decrease in slab-derived components in the underlying mantle wedge. Inferred decreases in slab input correlate strongly with a systematic decrease in age of the oceanic crust along the convergent margin. Geochemical trends are most pronounced in southwestern British Columbia and northern Washington basalts, where the Garibaldi belt strikes obliquely to the trend of isochrons on the subducted plate. From southern Washington to northern California, High Cascades arc segments trend nearly parallel to subducted plate isochrons, and basalts show more subdued arc-parallel variations. These observations support a model in which temperature and depth of melting in the mantle wedge beneath the arc are influenced by the age of the subducted plate. Where the arc is underlain by relatively young and hot oceanic crust, only a minor amount of heating during subduction is required before dehydration reactions begin in the subducted plate. The slab loses much of its volatiles trenchward of the arc, and the volatile budget in the mantle wedge beneath the arc is relatively low. In the Garibaldi belt, which overlies very young oceanic crust, this produces progressively more alkalic basalts to the north. The High Cascades overlies older oceanic lithosphere which was cooler at the time of subduction. As a result, dehydration reactions are delayed and a greater amount of volatiles are released beneath the arc. This results in lower melt temperatures and higher degrees of melting, producing predominantly low-K tholeiite and LILE-enriched HFSE-depleted calc-alkaline basalt magmas.

Green, N. L. and Henderson, P., 1984. Rare earth element concentrations in Quaternary volcanic rocks of southwestern British Columbia; Canadian Journal of Earth Sciences, v. 21, no. 6, p. 731-736.

Modified abstract: A suite of hawaiites, mugearite, and calc-alkaline andesitic rocks from the Garibaldi Lake area exhibits fractionated, slightly concave-upward REE patterns (Ce_N /Yb_N = 4.5-15), heavy REE contents about 5-10 times the chondritic abundances, and no Eu anomalies. The REE contents of the Garibaldi Lake lavas are not incompatible with previous interpretations that (1) the hawaiites have undergone considerable fractionation of olivine, plagioclase, and clinopyroxene; and (2) the individual andesitic suites were derived from separate batches of chemically distinct magma that evolved along different high-level crystallization trends. In general, however, the andesites are characterized by lower light REE contents than the basaltic andesites.

Green, N.L. and Sinha, A.K., 2005. Consequences of varied slab age and thermal structure on enrichment processes in the sub-arc mantle of the northern Cascadia subduction system; Journal of Volcanology and Geothermal Research, v. 140, no. 1-3, p. 107-132.

Abstract: The 15-km-wide Late Cenozoic Garibaldi volcanic belt (GVB) of the northern Cascadia Subduction System is intimately associated with aseismic subduction of extremely young (≤22 Ma) and presumably "hot" oceanic lithosphere beneath northwestern Washington and southwestern British Columbia. Age of the subducted plate beneath the volcanic front decreases northward by about 7 m.y. relative, suggesting that the thermal structure of the subducted oceanic crust changes along the convergent margin. GVB basalts exhibit significant arc-parallel variations in major-element, trace-element, and Sr isotopic compositions that correlate with inferred age of the underlying subducted oceanic crust. Phase relations and trace-element characteristics of the basalts imply that magma generation within the northern Cascadia sub-arc mantle involves progressively lower degrees of melting under increasingly higher temperatures and pressures, as the underlying slab becomes younger, hotter, and probably drier northward. Similar high-field-strength-element (HFSE) and rare-earth-element (REE) characteristics of mantle sources beneath the Garibaldi Belt argue strongly that no systematic distribution of mantle source heterogeneities exists along the volcanic front. Along-strike variations in concentrations of fluid-mobile and immobile elements are therefore interpreted to reflect arc-parallel variations in both (1) the nature and magnitude of slab-derived fluxes and (2) varied degrees of partial melting within metasomatized source regions in the mantle wedge. Elevated B, Ba, K, Pb and $(Sr/P)_N$ in GVB lavas, together with large-ion-lithophile element (LILE)/HFSE and Nb/Ta variations, suggest that the subduction component was dominantly a residual fluid derived from strongly dehydrated and altered basalt crust and sediment in a downgoing Juan de Fuca Plate.

Guthrie, R.H., Friele, P., Allstadt, K., Roberts, N., Evans, S.G., Delaney, K.B., Roche, D., Clague, J.J., and Jakob, M., 2012. The 6 August 2010 Mount Meager rock slide-debris flow, Coast Mountains, British Columbia: characteristics, dynamics, and implications for hazard and risk assessment; Natural Hazards and Earth System Sciences, v. 12, no. 5, p. 1277-1294.

Abstract: A large rock avalanche occurred at 03:27:30 PDT, 6 August 2010, in the Mount Meager Volcanic Complex southwest British Columbia. The landslide initiated as a rock slide in Pleistocene rhyodacitic volcanic rock with the collapse of the secondary peak of Mount Meager. The detached rock mass impacted the volcano's weathered and saturated flanks, creating a visible seismic signature on nearby seismographs. Undrained loading of the sloping flank caused the immediate and extremely rapid evacuation of the entire flank with a strong horizontal force, as the rock slide transformed into a debris flow. The disintegrating mass travelled down Capricorn Creek at an average velocity of 64 m s^{-1}, exhibiting dramatic super-elevation in bends to the intersection of Meager Creek, 7.8 km from the source. At Meager Creek the debris impacted the south side of Meager valley, causing a runup of 270 m above the valley floor and the deflection of the landslide debris both upstream (for 3.7 km) and downstream into the Lillooet River valley (for 4.9 km), where it blocked the Lillooet River river for a couple of hours, approximately 10 km from the landslide source. Deposition at the Capricorn-Meager confluence also dammed Meager Creek for about 19 h creating a lake 1.5 km long. The overtopping of the dam and the predicted outburst flood was the basis for a night time evacuation of 1500 residents in the town of Pemberton, 65 km downstream. High-resolution GeoEye satellite imagery obtained on 16 October 2010 was used to create a post-event digital elevation model. Comparing pre- and post-event topography we estimate the volume of the initial displaced mass from the flank of Mount Meager to be 48.5 X 10^6 m^3, the height of the path (H) to be 2183 m and the total length of the path (L) to be 12.7 km. This yields H/L = 0.172 and a fahrboeschung (travel angle) of 9.75°. The movement was recorded on seismographs in British Columbia and Washington State with the initial impact, the debris flow travelling through bends in Capricorn Creek, and the impact with Meager Creek are all evident on a number of seismograms. The landslide had a seismic trace equivalent to a M = 2.6 earthquake. Velocities and dynamics of the movement were simulated using DAN-W. The 2010 event is the third major landslide in the Capricorn Creek watershed since 1998 and the fifth large-scale mass flow in the Meager Creek watershed since 1930. No lives were lost in the event, but despite its relatively remote location direct costs of the 2010 landslide are estimated to be in the order of $10 M CAD.

Hammer, P. T. C. and Clowes, R.M., 1996. Seismic reflection investigations of the Mount Cayley bright spot; a midcrustal reflector beneath the Coast Mountains, British Columbia; Journal of Geophysical Research, v. 101 B9, p. 20119-20131.

Abstract: An unusually high-amplitude, midcrustal reflector was discovered by a Lithoprobe seismic reflection survey crossing a predominantly plutonic region in southwestern British Columbia,

Canada. The “bright spot” was observed adjacent to Mount Cayley, a large Quaternary volcanic center associated with the Cascadia subduction zone magmatic arc. Characterization of the bright spot may advance our understanding of either the midcrustal structure of magmatic supply systems or the presence and storage of saline fluids in the midcrust. The location and three-dimensional geometry of the reflector were determined using travel time inversion. The resulting suite of models consistently describe a northwest dipping reflector that lies 12.5 to 13 km beneath the Mount Cayley volcanic complex. The areal extent of the reflective surface is 3 km by 1 km and the structure is less than 1.6 km thick. The transition between the body and the country rock must be rapid (< 200 m) and exhibit a large impedance contrast in order to generate reflections of such high frequencies (30 Hz) and relative amplitudes (8.0 dB). Our preferred interpretation for the reflector is a fossil sill complex associated with the volcanic development of Mount Cayley. However, the data do not rule out the possibility that the reflective structure represents melt lenses or saline fluid produced by the dewatering of the subducted slab. The Mount Cayley bright spot lies just below the brittle upper crust, as do the midcrustal reflectors detected beneath Japanese subduction arc volcanoes. This correlation suggests that thermal and rheological properties just below the brittle/ductile crustal transition may be favorable for reflector formation.

Hickson, C. J., Russell, J.K., and Stasiuk, M.V., 1999. Volcanology of the 2350 B.P. eruption of Mount Meager volcanic complex, British Columbia, Canada; implications for hazards from eruptions in topographically complex terrain; Bulletin of Volcanology, v. 60, no. 7, p. 489-507.

Abstract: The Pebble Creek Formation (previously known as the Bridge River Assemblage) comprises the eruptive products of a 2350 calendar year B.P. eruption of the Mount Meager volcanic complex and two rock avalanche deposits. Volcanic rocks of the Pebble Creek Formation are the youngest known volcanic rocks of this complex. They are dacitic in composition and contain phenocrysts of plagioclase, orthopyroxene, amphibole, biotite and minor oxides in a glassy groundmass. The eruption was episodic, and the formation comprises fallout pumice (Bridge River tephra), pyroclastic flows, lahars and a lava flow. It also includes a unique form of welded block and ash breccia derived from collapsing fronts of the lava flow. This Merapi-type breccia dammed the Lillooet River. Collapse of the dam triggered a flood that flowed down the Lillooet Valley. The flood had an estimated total volume of 109 m^3 and inundated the Lillooet Valley to a depth of at least 30 m above the paleo-valley floor 5.5 km downstream of the blockage. Rock avalanches comprising mainly blocks of Plinth Assemblage volcanic rocks (an older formation making up part of the Mount Meager volcanic complex) underlie and overlie the primary volcanic units of the Formation. Both rock avalanches are unrelated to the 2350 B.P. eruption, although the post-eruption avalanche may have its origins in the over-steepened slopes created by the explosive phase of the eruption. Much of the stratigraphic complexity evident in the Pebble Creek Formation results from deposition in a narrow, steep-sided mountain valley containing a major river.

Kelman, M. C., Russell, J.K., and Hickson, C.J., 2002. Effusive intermediate glaciovolcanism in the Garibaldi volcanic belt, southwestern British Columbia, Canada; *in* Volcano-Ice Interaction on Earth and Mars, (ed.) J.L. Smellie and M.G. Chapman; Geological Society Special Publications, v. 202, p. 195-211.

Abstract: The Garibaldi Volcanic Belt (GVB) in southwestern British Columbia is dominated by intermediate composition volcanoes in a setting that has been intermittently subjected to widespread glaciation. The glaciovolcanic features produced are distinctive, and include flow-dominated tuyas, subglacial domes, and ice-marginal flows. Flow-dominated tuyas, which are intermediate in composition, are unlike conventional basaltic tuyas; they consist of stacks of flat-lying lava flows, and lack pillows and hyaloclastite. They are inferred to represent subglacial eruptions that ultimately breached the ice surface. Subglacial domes occur as steep-sided masses of heavily-jointed, glassy lava, and represent eruptions that were entirely subglacial. Ice-marginal flows derive from subaerial flows that were impounded against ice. Two unique aspects of GVB glaciovolcanic products are the presence of flow-dominated tuyas and the apparent

scarcity of primary fragmental deposits. These unique features result from lava composition, the minimization of direct lava-water contact during eruptions, and topography. Composition influences morphology because eruption temperature decreases, and viscosity and glass transition temperature both increase with silica content. The result of this is that silicic subglacial volcanoes melt less water and are less likely to trap it near the vent, leading to the formation of structures whose shapes are strongly influenced by the surrounding ice. Topography also enhances meltwater drainage, favours lava flow impoundment in ice-filled valleys, and may, through erosion, influence the observed distribution of fragmental glaciovolcanic deposits.

Kovanen, D.J., Easterbrook, D.J., and Thomas, P.A., 2001. Holocene eruptive history of Mount Baker, Washington. Canadian Journal of Earth Sciences, v. 38, no. 9, p. 1355-1366.

Abstract: New radiocarbon dates associated with volcanic ashes and lahars improve our understanding of the volcanic activity of Mount Baker, a 3284 m-high, andesitic stratovolcano in the North Cascades, Washington. The geologic record shows that during the Holocene, four ashes and at least seven lahars were deposited on the flanks of Mount Baker and in the nearby North Cascades. Here, we document the ages of three previously undated ashes, the Schriebers Meadow scoria, the Rocky Creek ash, and the Cathedral Crag ash. Because Mount Baker lies at the head of the Nooksack drainage, eruptive activity may influence areas downstream. Understanding the timing and characteristics of volcanic eruptions from Mount Baker is useful from volcanic hazard and paleoclimatological perspectives.

Lawrence, R. B., Armstrong, R.L., and Berman, R.G., 1984. Garibaldi Group volcanic rocks of the Salal Creek area, southwestern British Columbia; alkaline lavas on the fringe of the predominantly calc-alkaline Garibaldi (Cascade) volcanic arc; Journal of Volcanology and Geothermal Research, v. 21, no. 3-4, p. 255-276.

Abstract: The Salal Creek area, at the north end of the main group of vents for the Quaternary Garibaldi (Cascade) Volcanic Belt, southwestern British Columbia, was the site of several small eruptions of mafic lava during the past 1 Ma. In contrast to the calc-alkaline character of all other parts of the Garibaldi Belt and the geographically nearly coincident Miocene and older Pemberton Volcanic Belt, the Salal Creek area Quaternary lavas are predominantly alkaline basalt and hawaiite with typical alkaline volcanic petrography, chemistry, and fractionation trends. Trace elements Ti-Zr-Y show within-plate character for the suite. As for other Garibaldi Belt volcanic rocks, Rb is low, Rb/Sr very low, and $^{87}Sr/^{86}Sr$ ratio is low, averaging 0.7032. The oxygen isotopic composition average, $^{18}O = 5.9$, is normal for mantle-derived volcanic rocks. This distinct change in magma type at the end of a volcanic are may be the consequence of a smaller degree of melting, melting at a slightly greater depth than calc-alkaline magma production, or a descending-plate edge effect. Ponded flows and pillow-palagonite accumulations indicate that several Salal Creek area eruptions occurred in proximity to ice which filled major valleys during pre-Wisconsin glacial periods.

Leonard, E. M., 1995. A varve-based calibration of the Bridge River tephra fall; Canadian Journal of Earth Sciences, v. 32, no. 12, p. 2098-2102.

Abstract: A 1 cm thick layer of Bridge River tephra is preserved in a core of varved lake sediments recovered from Hector Lake, Alberta. The varve sequence extends from the core top to well below the tephra layer and has bseen calibrated to calendar years. A varve count yields a calendar age of 2332 BP for the ash layer, with a potential error of about ±50 years. This age is about 30 years younger than the current best radiocarbon-based estimate of the time of the eruption. However, in light of the potential errors in both the varve count and the radiocarbon age, the two ages are not inconsistent. The tephra contains no biotite. In the past, biotite-free Bridge River tephra has been associated with a possible late (ca. 2000 BP) tephra fall, but the tephra from Hector Lake is clearly associated with the main (2300–2400 BP) eruptive event.

Lewis, T.J., Jessop, A.M., and Judge, A.S., 1985. Heat flux measurements in southwestern British Columbia: the thermal consequences of plate tectonics; Canadian Journal of Earth Sciences, v. 22, no. 9, p. 1262-1273.

Abstract: Measured heat fluxes from previously published data and 34 additional boreholes outline the terrestrial heat flow field in southern British Columbia. Combined with heat generation representative of the crust at 10 sites in the Intermontane and Omineca belts, the data define a heat flow province with a reduced heat flow of 63 mW m^2 and a depth scale of 10 km. Such a linear relationship is not found or depth scale of 10 expected in the Insular Belt and the western half of the Coast Plutonic Complex where low heat fluxes are interpreted to be the result of recent subduction. The apparent boundary between low and high heat flux is a transition over a distance of 20 km, located in Jervis Inlet 20–40 km seaward of the Pleistocene Garibaldi Volcanic Belt. The warm, thin crust of the Intermontane and Omenica Crystalline belts is similar to that of areas of the Basin and Range Province where the youngest volcanics are more than 17 Ma in age. Processes 50 Ma ago that completely heated the crust and upper mantle could theoretically produce such high heat fluxes by conductive cooling of the lithosphere. But it is more likely that the asthenosphere flows towards the subduction zone, bringing heat to the base of the lithosphere. Since the reduced heat flow is high but constant, large differences in upper crustal temperatures within this heat flow province at present are caused by large variations in both crustal heat generation and near-surface thermal conductivity. The sharp transition in heat flux near the coast is the result of the combined effects of convective heating of the eastern Coast Plutonic Complex, pronounced differential uplift and erosion across a boundary within the Coast Plutonic Complex, and the subducting oceanic plate.

Lu, Z. Y., and Cruden, D.M., 1996. Two debris flow modes on Mount Cayley, British Columbia; Canadian Geotechnical Journal, v. 33, no. 1, p. 123-139.

Abstract: The 1963 landslide on Mount Cayley, British Columbia, began at the head of Dusty Creek, a small tributary of Turbid Creek, a major creek draining Mount Cayley, and terminated at the present confluence of Dusty and Turbid creeks. About 5×10^6 m^3 of partially saturated, columnar-jointed dacite and weak pyroclastic rocks moved 2.4 km downstream. The depletion zone contained three separate blocks. The landslide deposits have distinct layers that can be traced back to similar bedrock units in the undisturbed material, which are three times thicker. The accumulation zone is divided by two gullys into three blocks, which preserve, much thinned, different but overlapping portions of the volcanic stratigraphy. The 1984 rock slide on Avalanche Creek, 0.8 km away, involved tuff breccia, tuff lapilli, and tuff, all easily broken. Its main track ran over thick snow and ice on the bottom of the creek. Differences in water content and displaced material led to different flow modes: the 1963 fragments formed laminar flows, which supported comparatively undeformed central plugs; the turbulent 1984 flow's deposits have no distinct layers. The two modes, laminar flow and turbulent flow, also formed different types of landslide dams.

Lu, Z. Y., Evans, S. G., and Brooks, G.R., 1992. Prehistoric debris avalanches from Mount Cayley Volcano, British Columbia; discussion and reply; Canadian Journal of Earth Sciences, v. 29, no. 6, p. 1342-1347.

Summary: This is a detailed discussion, by Lu, of the Evans and Brooks hypothesis that debris avalanche deposits in the Turbid Creek fan downslope of Mount Cayley in the Squamish River Valley result from a large debris avalanche around 4800 BP. Lu disagrees with the hypothesis and postulates that multiple smaller events could have formed the debris fan. However, Evans and Brooks refute this argument in their reply, and emphasize the possibility of future similar landslides which could dam the Squamish river and create a major hazard.

Mathewes, R. W., and Westgate, J.A., 1980. Bridge River tephra; revised distribution and significance for detecting old carbon errors in radiocarbon dates of limnic sediments in southern British Columbia; Canadian Journal of Earth Sciences, v. 17, no. 11, p. 1454-1461.

Abstract: Ash-grade Bridge River tephra, identified as such on the basis of shard habit, modal mineralogy, and composition of ilmenite, occurs in sedimentary cores from three lakes located to the south of the previously documented plume and necessitates a significant enlargement of the fallout area of that tephra in southwestern British Columbia. These new, more southerly occurrences are probably equivalent to the ~2350 year old Bridge River tephra, although it can be argued from the evidence at hand that the ^{14}C dates and biotite-rich nature support relationship to a slightly earlier Bridge River event. Large differences exist in the ^{14}C age of sediments immediately adjacent to the Bridge River tephra at these three lake sites; maximum ages of 3950 ± 170 years BP (GX-5549) and 3750 ± 210 years BP (I-10041) were obtained at Phair and Fishblue lakes, respectively, whereas the corresponding age at Horseshoe Lake is only 2685 ± 180 years BP (GX-5757). The two older dates are considered to be significantly affected by old carbon contamination for the bedrock locally consists of calcareous sedimentary rocks and the lacustrine sediments are very calcareous. The ^{14}C date from Horseshoe Lake, which occurs in an area of igneous rocks, appears to be only slightly too old relative to the ~2350 year old Bridge River tephra. Well-dated tephra beds, therefore, can be very useful in assessing the magnitude of old carbon errors associated with radiocarbon dates based on limnic sediments. Calcareous gyttja deposits beneath Bridge River tephra within the study area exhibit old carbon errors of the order of 1350–1550 years.

Mathews, W. H., 1951. The Table, a flat-topped volcano in southern British Columbia; American Journal of Science, v. 249, no. 11, p. 830-841.

Abstract: The Table, a steep-walled mass of lava, is made up of a core of thick, flat-lying layers partly surrounded by thin, nearly vertical sheets adhering to the core like icing on the sides of a layer cake. Field evidence suggests that eruptions took place while land in the vicinity of the vent was covered by Pleistocene ice. An intraglacial origin for the volcano is assumed, as follows: (1) volcanic heat led to the thawing above the vent of a vertical pipe in the ice sheet; (2) lava repeatedly flooded the floor of the pipe, spreading laterally until it reached the ice walls, chilled first along the contact to forma solid ring, then the still-molten material, ponded within the ring, acquired a tabular form and a level upper surface; and (3) molten lava locally overflowed down into narrow spaces between the solidified core and the ice, giving rise to the vertical sheets surrounding the horizontal layers.

Mathews, W.H., 1952. Ice-dammed lavas from Clinker Mountain, southwestern British Columbia; American Journal of Science, v. 250, p. 553-565.

Abstract: Lava flows from Clinker Mountain exhibit normal gradients and surface character wherever they came to rest at altitudes of more than about 4,000 feet, but distinctly anomalous features where they came to rest at appreciably lower levels. These anomalies include (1) precipitous, locally concave, terminal faces up to 1,500 feet high, subject to major landsliding, (2) unusual thickness of lava, as much as 800 feet in a single flow, and (3) accretion of lava as dribbles on at least one precipitous lava front. These anomalies are attributed to ponding of lava against the Cordilleran ice sheet at a time when it still filled valleys up to approximately the 4,000 foot level.

Mathews, W. H., 1952. Mount Garibaldi, a supraglacial Pleistocene volcano in southwestern British Columbia; American Journal of Science, v. 250, no. 2, p. 81-103.

Abstract: Mount Garibaldi is an extinct volcano built for the most part of glowing avalanches during an almost uninterrupted series of Peléan eruptions. A dacite core and lava flows from a vent on the northern slope make up the remainder of the mountain. A large volume of debris from the western slope of the cone now lies in nearby Squamish Valley as fanglomerate and late Pleistocene to Recent alluvium. Despite the loss of enormous quantities of material from this side of the cone, part of the original upper surface persists in an adjoining sector. Tuff-breccias laid down by the glowing avalanches do not extend as far from the apex of the cone down two pre-existing valleys as they do on an intervening ridge. The cone was built during occupation of the valleys by Cordilleran ice of Wisconsin age and part of it was evidently deposited on the ice. Ice filling the old valleys may have prevented extrusion of the glowing avalanches beyond the limit reached on the intervening ridge which then protruded only a little above the ice surface. Melting of the ice in late Wisconsin time permitted extensive landsliding and transfer of debris from the cone to Squamish Valley.

Mathews, W. H., 1957. Petrology of Quaternary volcanics of the Mount Garibaldi map-area, southwestern British Columbia; American Journal of Science, v. 255, no. 6, p. 400-415.

Abstract: The petrology of a suite of volcanic rocks having limited age range and areal distribution but wide compositional differences is described. The mineralogy shows remarkably little relationship to bulk composition of the rocks. Cooling histories, particularly as influencing mineral zoning and degree of crystallization, and pressure histories are important in determining what minerals are present and what is the composition of these minerals. Rock classification based on chemical composition is hence more suited for correlation of these rocks than is one based on mineralogic composition. Petrologic characteristics and the volumetric distribution of rock types suggests the differentiation of a basaltic magma contaminated by granitic material, followed by gravitative selection during extrusion.

Mathews, W. H., 1958. Geology of the Mount Garibaldi map-area, southwestern British Columbia, Canada; Part 1, Igneous and metamorphic rocks; Part 2, Geomorphology and Quaternary volcanic rocks; Geological Society of America Bulletin, v. 69, no. 2, p. 161-198.

Abstract: The Mount Garibaldi map-area is in the southern Coast Mountains of British Columbia. The bold topography of the area is a product of two cycles of stream erosion modified by continental and alpine glaciation and by Quaternary vulcanism. The volcanic rocks of the map-area are lavas and pyroclastic rocks which postdate the second cycle of stream erosion; most if not all are Pleistocene, and many appear to have been erupted during periods of glaciation. Many of the anomalous structures can be attributed to deposition of lava or pyroclastic debris against, beneath, or onto glacial ice. Extrusive rocks range in composition from basalt to dacite; the latter are most voluminous.

Mathews, W. H., 1964. Potassium-argon age determinations of Cenozoic volcanic rocks from British Columbia; Geological Society of America Bulletin, v. 75, no. 5, p. 465-468.

Abstract: Potassium-argon age determinations of 13 Cenozoic volcanic rocks from southern and central British Columbia indicate one to be 62 million years old (Paleocene), nine to be 45-53 million years old (Eocene), and three to be 10-13 million years old (early Pliocene or late Miocene). The concentration of Eocene dates suggests a distinct volcanic episode roughly contemporaneous with tectonic activity in the Rocky Mountains to the east. The lack of dates from 45 to 13 million years and the development of a mature erosion surface by the more recent date suggest a prolonged stage of tectonic quiescence in southern and central British Columbia in mid-Cenozoic time.

Mathews, W.H., 1990. Garibaldi; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 144-145.

Summary: The composite cone and domes of Mount Garibaldi, in southwestern British Columbia's Garibaldi Volcanic Belt, are summarized briefly.

Michol, K. A., Russell, J.K., and Andrews, G.D.M., 2008. Welded block and ash flow deposits from Mount Meager, British Columbia, Canada; Journal of Volcanology and Geothermal Research, v. 169, no. 3-4, p. 121-144.

Modified abstract: The 2360 years B.P. eruption of Mount Meager, British Columbia, produced a succession of rarely observed, welded block and ash flow deposits and non-welded equivalents. We report on these rhyodacitic block and ash flow deposits by describing the deposits, documenting the nature of the welding process, and establishing the origins of these pyroclastic deposits. Variations in welding intensity are tracked by image analysis of field texture maps, petrographic study of shard morphology, and measurements of sample density and porosity. Pyroclast oblateness from image analysis of texture maps provides a qualitative record of welding intensity, but underestimates the amount of compactional (e.g., volume) strain when compared to estimates from physical property measurements (e.g., density, porosity). The pyroclastic flow deposits result from accumulation in a narrow, confined river valley; the accumulation was sufficiently rapid to keep the deposits above their glass transition temperature thereby allowing the succession to weld as a single cooling unit. The nature and distribution of isolated porosity in the juvenile clasts of rhyodacite suggest an explosive (rather than effusive) origin for these block and ash flow deposits that may be analogous to some Vulcanian-eruption-triggered dome-collapse processes observed at Soufriere Hills Volcano, Montserrat (rather than gravitational collapse).

Moore, D.P. and Mathews, W.H., 1978. The Rubble Creek landslide, southwestern British Columbia; Canadian Journal of Earth Sciences, v. 15, p. 1039-1052.

Abstract: A 19th century slide, involving an estimated 25 x 10^6 m^3 of rock, devastated Rubble Creek Valley, 80 km north of Vancouver, B.C. Breaking away from a headwall composed of late glacial dacitic lava, the slide travelled as much as 4.6 km with a maximum drop of 1060 m, thus moving on an average slope of 8.5°. Velocities, estimated from the superelevation of the slide as it moved around curves in the valley, exceed 20 m/s (72 km/h) and sliding was probably completed within 10 min. Tree-ring data indicate that the slide occurred in the fall or winter of 1855–1856. The trigger mechanism has not been identified, but the presence of an exceedingly steep original slope of the lava front, attributed to ponding against latest Pleistocene ice occupying the valley below, was clearly a contributing factor. Both the precipitous headwall and a second ice-dammed lava front are considered to be potential sources for new slides. Some evidence suggests that previous slides have occurred here since the last glaciation, about 11 000 years ago. A court ruling barring residential development in the area devastated in 1855–1856 on the grounds of future hazard to life seems justified.

Mullen, E.K. and Weis, D., 2013. Sr-Nd-Hf-Pb isotope and trace element evidence for the origin of alkalic basalts in the Garibaldi Belt, northern Cascade arc; Geochemistry, Geophysics, Geosystems, v. 14, no. 8, p. 3126-3155.

Abstract: In the Garibaldi Belt, the northern segment of the Cascade arc, basalts at Bridge River Cones, Salal Glacier, and Mt. Meager (BSM volcanic centers) are alkalic, atypical for an arc setting. Subduction signatures are negligible or absent from primitive alkalic basalts from Salal Glacier and Bridge River, while altered oceanic crust may have contributed a minimal amount of fluid at Mt. Meager. More evolved BSM basalts display trace element signatures considered typical of arc lavas, but this is a consequence of deep crustal assimilation rather than primary input from the subducted slab. Primary BSM basalts represent 3-8% melts that segregated from enriched garnet lherzolite at significantly higher temperatures and pressures (70-105 km) than calc-alkaline Cascade arc basalts. The BSM mantle source is significantly more incompatible element-enriched than the depleted mantle tapped by calc-alkaline Cascade arc basalts. The BSM basalts are also isotopically distinct from calc-alkaline Cascade arc basalts, more similar to MORB and intraplate basalts of the NE Pacific and NW North America. The relatively deep, hot, and geochemically distinct mantle source for BSM basalts is consistent with upwelling asthenosphere. The BSM volcanic centers are close to the projected trace of the Nootka fault, which forms the boundary between the subducting Juan de Fuca plate and the near-stagnant

Explorer plate. A gap or attenuated zone between the plates may promote upwelling of enriched asthenosphere that undergoes low-degree decompression melting to generate alkalic basalts that are essentially free of slab input yet occur in an arc setting.

Nasmith, H., Mathews, W.H., and Rouse, G.E., 1967. Bridge River ash and some other Recent ash beds in British Columbia; Canadian Journal of Earth Sciences, v. 4, no. 1, p. 163-170.

Abstract: The character, distribution, and age of the Bridge River ash from postglacial sites in British Columbia and Alberta are discussed. The ash consists of dust-sized shards with ellipsoidal fragments of pumice. With a source in the region of the upper Lillooet River, the ash both, thins and fans out east-northeasterly as far as westernmost Alberta in the vicinity of the North Saskatchewan River. Peat immediately below the ash in a bog near Jesmond, British Columbia, was dated by radiocarbon at 2 440 ± 140 years before present (B.P.). The track of the Bridge River ash overlaps that of the Mazama ash of about 6 600 years, but lies north of the presently known distribution of St. Helens Y ash of approximately 3 200 years B.P. It is suggested that with a distinctive character and limited distribution, the Bridge River ash is potentially valuable as a postglacial marker horizon in southcentral British Columbia.

Rogers, G.C., 1985. Variation in Cascade volcanism with margin orientation; Geology, v. 13, no. 7, p. 495-498.

Abstract: The orientation of the convergent margin of the Juan de Fuca subduction zone changes from north-south off Oregon to northwest-southeast off British Columbia. Because of this change, the effective ratio of overriding plate velocity to roll-back velocity of the subducting plate increases by at least 20% from Oregon to British Columbia. This appears to alter the tectonic regime from slightly extensional in Oregon to slightly compressional in Washington and British Columbia and thus may account for the lesser amount of volcanism at the northern end of the Cascade volcanic chain. The variation in margin geometry may also explain other tectonic features such as initiation of the Nootka fault zone and the Quaternary change of the volcanic pattern in British Columbia.

Russell, J.K. and Stasiuk, M.V., 1997. Characterization of volcanic deposits with ground-penetrating radar; Bulletin of Volcanology, v. 58, p. 515-527.

Abstract: Field-based studies of surficial volcanic deposits are commonly complicated by a combination of poor exposure and rapid lateral variations controlled by unknown paleotopography. The potential of ground-penetrating radar (GPR) as an aid to volcanological studies is shown using data collected from traverses over four well-exposed, Recent volcanic deposits in western Canada. The deposits comprise a pumice airfall deposit (3-4 m thick), a basalt lava flow (3-6 m thick), a pyroclastic flow deposit (15 m thick), and an internally stratified pumice talus deposit (60 m thick). Results show that GPR is effective in delineating major stratigraphic contacts and hence can be used to map unexposed deposits. Different volcanic deposits also exhibit different radar stratigraphic character, suggesting that deposit type may be determined from radar images. In addition, large blocks within the pyroclastic deposits are detected as distinct point diffractor patterns in the profiles, showing that the technique has potential for providing important grain-size information in coarse poorly sorted deposits. Laboratory measurements of dielectric constant (K’) are reported for samples of the main rock types and are compared with values of K’ for the bulk deposits as inferred from the field data. The laboratory values differ significantly from the “field” values of K’; these results suggest that the effectiveness of GPR at any site can be substantially improved by initial calibration of well-exposed locations.

Sherrod, D. R., Smith, J. G. 1990. Quaternary extrusion rates of the Cascade Range, northwestern United States and southern British Columbia; Journal of Geophysical Research: Solid Earth, v. 95, no. B12, p. 19465-19474.

Abstract: Quaternary (2–0 Ma) extrusion rates change significantly along the Cascade Range volcanic arc. The extrusion rate north of Mount Rainier is about 0.21 $km^3\ km^{-1}\ m.y.^{-1}$; the rate in southern Washington and northern Oregon south to Mount Hood is about 1.6 $km^3\ km^{-1}\ m.y.^{-1}$; in central Oregon the rate is 3–6 $km^3\ km^{-1}\ m.y.^{-1}$; and in northern California, the rate is 3.2 $km^3\ km^{-1}\ m.y.^{-1}$. Eruption style also changes along the arc but at latitudes different from rate changes. At the ends of the arc, volcanism is focused at isolated intermediate to silicic composite volcanoes. The composite volcanoes represent ~30% of the total volume of the arc. Mafic volcanic fields partly ring some composite volcanoes, especially in the south. In contrast, volcanism is diffused in the middle of the arc, where numerous overlapping mafic shields and a few composite volcanoes have built a broad ridge. Contrasting eruption style may signify diffuse versus focused heat sources or may reflect changes in permeability to ascending magma along the arc.

Simpson, K. A., Stasiuk, M., Shimamura, K., Clague, J.J., and Friele, P., 2006. Evidence for catastrophic volcanic debris flows in Pemberton Valley, British Columbia; Canadian Journal of Earth Sciences, v. 43, no. 6, p. 679-689.
Abstract: The Mount Meager volcanic complex in southern British Columbia is snow and ice covered and has steep glaciated and unstable slopes of hydrothermally altered volcanic deposits. Three large-volume (>10^8 m^3) volcanic debris flow deposits derived from the Mount Meager volcanic complex have been identified. The volcanic debris flows travelled at least 30 km downstream from the volcanic complex and inundated now populated areas of Pemberton Valley. Clay content and mineralogy of the deposits indicate that the volcanic debris flows were clay-rich (5%-7% clay in the matrix) and derived from hydrothermally altered volcanic material. The youngest volcanic debris flow deposit is interpreted to be associated with the last known volcanic eruption, approximately 2360 calendar (cal) years BP. The other two debris flows may not have been directly associated with eruptions. Volcanic debris flow hazard inundation maps have been produced using the Geographic Information System (GIS)-based modeling program, LAHARZ. The maps provide estimates of the areas that would be inundated by future moderate to large-magnitude events. Given the available data, the probability of a volcanic debris flow reaching populated areas in Pemberton Valley is approximately 1 in 2400 years. Additional mapping in the source regions is necessary to determine if sufficient material remains on the volcanic edifice to generate future large-magnitude, clay-rich volcanic debris flows.

Souther, J.G., 1990. Bridge River cones; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 139-141.
Summary: The monogenetic cones, small stratovolcanoes, and tuyas of the Bridge River area, in southwestern British Columbia's Garibaldi Volcanic Belt, are summarized briefly.

Souther, J.G., 1990. Cayley; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 142-143.
Summary: The Mount Cayley stratovolcano and surrounding lava domes, in southwestern British Columbia's Garibaldi Volcanic Belt, are summarized briefly.

Souther, J.G., 1990. Silverthrone; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 138-139.
Summary: The Silverthrone caldera complex, near the north end of southwestern British Columbia's Garibaldi Volcanic Belt, is summarized briefly.

Souther, J.G. and Dellechaie, F., 1984. Geothermal exploration at Mount Cayley – a Quaternary volcano in southwestern British Columbia; Geothermal Resources Council Transactions, v. 8, p. 463-468.

Abstract: Mt. Cayley is a deeply dissected multiple plug dome in the Central Garibaldi belt, 125 km north of Vancouver, B.C. Potassium argon dates from the central edifice range from 5.7 to 0.6 Ma whereas peripheral domes gives dates as young as 0.11 Ma. The base of the complex and underlying crystalline basement rocks have undergone intense hydrothermal alternation in a zone that contains warm seeps of high Cl – SO_4 water. Resistivity and magnetotelluric surveys have defined a conductive anomaly (<100 m) beneath the altered zone and diamond drilling has confirmed thermal gradients as high as 105°C/km. Following work by the Geological Survey of Canada beginning in 1979 the area was designated by the Provincial Government as a KGRA and in 1983 O'Brien Resources acquired and began exploration of parcel G3 which includes the principal anomaly.

Stasiuk, M., 1990. Meager Mountain; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 141-142.
Summary: The Meager Mountain volcanic complex, in southwestern British Columbia's Garibaldi Volcanic Belt, is summarized briefly.

Stewart, M. L., Russell, J.K., and Hickson, C.J., 2003. Discrimination of hot versus cold avalanche deposits; implications for hazard assessment at Mount Meager, British Columbia; Natural Hazards and Earth System Sciences, v. 3, no. 6, p. 713-724.
Abstract: The surficial deposits surrounding the Mount Meager volcanic complex include numerous avalanche deposits. These deposits share many attributes: (a) they are nearly monolithologic and comprise mainly intermediate volcanic rock clasts, (b) they lack internal structure, and (c) they are very poorly sorted. Despite these similarities, the avalanche deposits represent two distinct processes. Mass wasting of the Mount Meager volcanic edifice has produced cold rock avalanche deposits, whereas gravitational collapse of active lava domes and flows has produced hot block and ash avalanche deposits. The ability to discriminate between these "hot" and "cold" avalanche deposits is a critical component in the assessment of hazards in volcanic terranes. Hot block and ash avalanche deposits can be distinguished by the presence of radially-oriented joints, breadcrust textures, and incipient welding, which are features indicative of high emplacement temperatures. Conversely, rock avalanche deposits resulting from mass wasting events may be distinguished by the presence of clasts that preserve pre-depositional weathering and jointing surfaces. Volcanic avalanches are mechanically similar to rock avalanches but pose a greater hazard due to high temperatures, increased fluidization from degassing and the potential to decouple highly mobile elutriated ash clouds. The increasing use of hazardous regions such as the Lillooet River valley requires more reliable risk assessment in order to minimize losses from future hazardous events.

Werner, C., Evans, W.C., Poland, M., Tucker, D.S., and Doukas, M.P., 2009. Long-term changes in quiescent degassing at Mount Baker Volcano, Washington, USA; Evidence for a stalled intrusion in 1975 and connection to a deep magma source; Journal of Volcanology and Geothermal Research, v. 186, no. 3-4, p. 379-386.
Abstract: Long-term changes have occurred in the chemistry, isotopic ratios, and emission rates of gas at Mount Baker volcano following a major thermal perturbation in 1975. In mid-1975 a large pulse in sulfur and carbon dioxide output was observed both in emission rates and in fumarole samples. Emission rates of CO_2 and H_2S were ~ 950 and 112 t/d, respectively, in 1975; these decreased to ~ 150 and < 1 t/d by 2007. During the peak of the activity the C/S ratio was the lowest ever observed in the Cascade Range and similar to magmatic signatures observed at other basaltic–andesite volcanoes worldwide. Increases in the C/S ratio and decreases in the CO_2/CH_4 ratio since 1975 suggest a long steady trend back toward a more hydrothermal gas signature. The helium isotope ratio is very high (> 7 R_c/R_A), but has declined slightly since the

mid-1970s, and δ13C–CO_2 has decreased by ≥ 1‰ over time. Both trends are expected from a gradually crystallizing magma. While other scenarios are investigated, we conclude that magma intruded the mid- to shallow-crust beneath Mount Baker during the thermal awakening of 1975. Since that time, evidence for fresh magma has waned, but the continued emission of CO_2 and the presence of a long-term hydrothermal system leads us to suspect some continuing connection between the surface and deep convecting magma.

Westgate, J. A., 1977. Identification and significance of late Holocene tephra from Otter Creek, southern British Columbia, and localities in West-central Alberta; Canadian Journal of Earth Sciences, v. 14, no. 11, p. 2593-2600.

Abstract: Three thin, light-coloured, ash-grade tephra beds occur within the uppermost metre of peat at Otter Creek bog in southern British Columbia. The youngest tephra is related to the ~2600 year old Bridge River tephra but is probably the product of a younger and weaker eruption that directed tephra to the southeast of the vent, believed to be located in the Meager Mountain district of southwestern British Columbia. The middle unit is ~2100 years old and is tentatively correlated with one of the upper beds of set P tephra of Mount St. Helens in Washington. The lowermost tephra is equivalent to the Yn bed of set Y, derived from an eruption of Mount St. Helens about 3400 years ago.The Yn tephra has been located as far north as Entwistle in west-central Alberta but mineralogically and chemically similar tephra elsewhere in this region is ~4300 years old and thus represents an older part of the Y set. Significant compositional differences between these two extensive members of the Y set have not yet been recognized.

Westgate, J. A. and Dreimanis, A., 1967. Volcanic ash layers of Recent age at Banff National Park, Alberta, Canada; Canadian Journal of Earth Sciences, v. 4, no. 1, p. 155-161.

Abstract: Three distinctive volcanic ash layers are present in the postglacial sediments at Banff National Park, Alberta. The chemical and mineralogical composition of the ash deposits, together with the radiocarbon age of associated charcoal, indicate the presence of Bridge River ash, whose source area is approximately located in the heart of the southern Coast Mountains, British Columbia, and Mazama ash, derived from Mount Mazama at Crater Lake, Oregon. A maximal age for Bridge River ash is 2670±140 years B.P. (GSC-531); a minimal age is 2120±150 years B.P, (G5C-577). Mazama ash is established as being about 6600 years old, although a slightly younger date of 6020±90 years B.P. (S-191) was obtained on organic matter associated with this ash at Banff National Park. The source and age of the third ash deposit is not definitely known, but the presence of cummingtonite suggests that it might be St. Helens Y ash, derived from Mount St. Helens, Washington.

Reports, Government Publications, and Theses

Anderson, R.G., 1975. Geology of the volcanics in the Meager Creek map-area, southwestern British Columbia; B.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 130 p.

Abstract: The distribution and gensis of the Garibaldi Group volcanic nearMeager Creek, B. C. is investigated through field, petrographical, geochronological and petrochemical studies. Pylon Peak, Mt. Meager and Plinth peak have been centers for most of the volcanism in the map-area. Whole rock potassium-argon dates on the volcanics and a published radiocarbon date for the Bridge River ash shows that the area has been active from at least 4.1 my ago up to 2440 years BP. Volcanism is chiefly andesitic although significant volumes of pyroclastic rocks and dacite flows are present. Pylon Peak was the center for whitish ash flow tuffs and dark andesite flows on its western summit and coarse pyroclastics and altered red and black andesites to the east. Development of a rhyolitic dome on Mt. meagre occurred after the last extensive Fraser glaciation 10,000 years ago. Bridge River ash ejected from the northwest flank of Plinth Peak overlies the

pink to grey andesite to dacite flows and light to dark welded ash flows also extruded from this center. Mineralogy and petrographic features are similar to those of other calc-alkaline suites. The presence of the late-forming cristobalite is significant as is the absence of classic pyroclastic textures in some of the ash flows. Bulk chemistry of the volcanics by XRF, atomic absorption and wet chemical analyses, reveals that the Meager Creek assemblage is calc-alkaline and may be derived from the fractional crystallization of a high alumina basalt parent. Stronmtium isotope ratios between 0.7032 and 0.7038 and the low Rb/Sr ratios imply a genetic similarity to the Cascade volcanic suite and may indicate derivation of the magmas from partial melting of the upper mantle at depths below that for the stability of plagioclase.

Bruno, S.J. 2011. Derivation of the eruption history of the prehistoric Ring Creek lava flow, southern British Columbia; M.Sc. thesis, Western Washington University, Bellingham, Washington, 115 p.

Abstract: The Ring Creek lava flow is a 10,000 year old, post-glacial dacitic lava flow that originated from Opal Cone, a small cinder cone on the south east flank of Mt. Garibaldi, British Columbia. Disequilibrium texture of amphibole combined with clotting in plagioclase suggests that the Ring Creek magma stalled beneath Opal Cone for at least 440 days before the eruption of the Ring Creek lava flow. Use of an igneous plagioclase-liquid thermo barometer and hygrometer indicate shallow storage conditions of 818-868º C, 2.4-3.6 kbar, and 0.2-2.0 wt% H_2O. Surge in plagioclase growth, evidenced by complex zonation and clotting, in conjunction with amphibole reaction, indicates substantial degassing prior to the emplacement of the Ring Creek lava flow. A possible reason for stalling of the Ring Creek magma, as well as eruption mechanism for Opal Cone, is glacial ice. Glacial studies suggest the Mamquam River valley, which the Ring Creek lava flow currently occupies, was completely deglaciated just prior to the emplacement of the Ring Creek lava flow in approximately 900 years or less. Deglaciation of the Mamquam River valley corresponds to a deduction of at least 4.5 MPa of overburdening pressure, which could have initiated a positive feedback loop of degassing and upwelling of the Ring Creek magma. This scenario is supported by progressive amphibole reaction observed in samples associated with three morphologically distinct (yet chemically identical) flow units which include a torta (or potentially a tuya), a lava flow underlying the Ring Creek lava flow, and the Ring Creek lava flow. Because of the prehistoric nature of the Ring Creek lava flow and the lack of ideal phases such as magnetite and stable amphibole, multiple assumptions were made.

Bye, A., Edwards, B.A., and Hickson, C.J., 2000. Preliminary field, petrographic, and geochemical analysis of possible subglacial, dacitic volcanism at the Watts Point volcanic centre, southwestern British Columbia; Geological Survey of Canada, Current Research 2000-A20, 9 p.

Abstract: The Watts Point volcanic centre, located 40 km north of Vancouver, British Columbia, along the north shore of Howe Sound, is the southernmost volcanic centre in the Garibaldi segment of the Cascades volcanic arc. The Watts Point volcanic centre comprises approximately 0.02 km^3 of sparsely porphyritic, highly jointed hornblende and pyroxene dacite lava and lava breccia. Lavas from the centre overlie the mid-Cretaceous Coast plutonic complex and are overlain locally by sediments and glacial till. The rocks are characterized by columnar joints, ranging in diameter from 5 cm to 40 cm and exhibiting locally radiating patterns. The distinctive, radial columnar joint patterns, the glassy to fine-grained groundmass, the stratigraphic relationships to overlying glacial till, as well as previously published geochronometric constraints support the formation of the Watts Point volcanic centre in a subglacial to englacial environment.

Cameron, V.J., 1989. The late Quaternary geomorphic history of the Sumas Valley; M.A. thesis, Simon Fraser University, Burnaby, British Columbia, 154 p.

Abstract: The Sumas Valley is located in the eastern portion of the Fraser Lowland of British Columbia. A long, flat-floored valley sandwiched between two elongate mountains and bordered at each end by rivers, the Sumas Valley's evolution has commanded much interest but only limited directed study. The objectives of this study were: 1) to reconstruct the geomorphic evolution of the Sumas Valley in the Late Quaternary time by examination of the subsurface sedimentary architecture of the regions, and 2) to address the question of whether the Fraser River (or a distributary) could have flowed through the valley and discharged into Bellingham Bay. To achieve these objectives, subsurface sample collection was necessary. Core obtained in the field was examined for texture, sedimentary structure, lithology, and organic matter content. Personally collected data was supplemented with water well drill logs and B.C. Department of Highways test hole data. Correlation of the data permitted the identification of nine lithostratigraphic units, which were then used to construct the subsurface sedimentary architecture of the Sumas Valley. The subsurface sedimentary architecture of Sumas Valley suggests that the most significant aspect of the Sumas Valley's evolution in the post glacial time was the progradation of two fans into a basin left by downwasting of glacial ice. The fans are identified, in both the north end and the south end of the Sumas Valley, by lobes of gravel which display the lateral and vertical grading pattern characteristic of a prograding fan or delta. The presence of Mazama tephra in some of the cores, as well as the age of radiocarbon dated wood, places the deposition of these fan sediments clearly within the Holocene. Lithological identification of sediments suggests that the source of the northern fan is the Chilliwak River, whereas the southern fan is believed to have originated from the progradation of the Nooksack River, or a greatly enlarged Sumas River, into the valley. The hypothesis of the Fraser River flowing through the Sumas Valley during the Holocene is rejected due to the obstacle presented by the Nooksack gravel lobe in the southern portion o the valley and because of the absence of the Fraser River sediments in the valley.

Campbell, M., 2012. Thermomechanical milling of lithics in volcanic conduits; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 201 p.

Abstract: Pyroclastic deposits resulting from explosive volcanic eruptions commonly contain clasts originating from the conduit wall rocks, which were entrained into the rapidly ascending stream of erupting material. These particles are termed accessory lithic clasts. Previous studies of the relative abundances and compositions of accessory lithic clasts have been used to identify the subsurface wall rocks of the volcanic conduit, to document variations in eruptive intensity, or to track changes in conduit or vent geometry over the course of the eruption. However, the morphological properties of accessory lithic clasts are largely ignored and offer an unused means of studying the processes operating in the conduit during explosive eruptions. During a volcanic eruption, wall rocks are violently fragmented to produce clasts that are incorporated into a hot, high velocity, particle-laden gas jet. There the clasts are subjected to elevated temperatures, blasting by volcanic ash, and occasional collisions with other large particles or with the conduit walls. The resultant morphologies of the accessory lithic clasts will be influenced by 1) the intrinsic physical properties of the clasts in question; 2) the specific physical and thermal processes to which the clasts were subjected within the conduit; and 3) the residence times of the clasts within the conduit. The 2360 B.P. Pebble Creek Formation of the Mount Meager Volcanic Complex in SW British Columbia is the product of the most recent explosive eruption in Canada. This formation includes a widespread pumice fallout deposit containing anomalously rounded and smoothed monzogranite accessory lithic clasts. In this study, I seek to explain the unusual shapes and surface textures of these clasts through detailed field work, analysis of sample morphology, and the computation of likely conditions within the conduit. My aim is to produce a comprehensive, mechanistic model of how these lithic clasts were reshaped within the volcanic conduit.

Cordey, P., 1999. Sedimentological evidence for the damming of the Lillooet River by the 2350 B.P. eruption of Mount Meager, southern Coast Mountains, B.C; B.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 29 p.

Abstract: The eruption of Mount Meager ejected large volumes of pumic that blanketed the nearby valleys and creeks and produced a welded lava breccia that blocked the adjacent Lillooet valley. The tephra plume has been enlarged by the discovery of an airfall deposit 1600 m west of the

earlier western margin. A deposit of well rounded and sorted, cross-stratified, clinoform sands and gravels is interpreted to be delta and a well rounded and sorted, planar bedded deposit of interbedded pumiceous silt and gravel is interpreted to be a beach. The existence of these deposits clearly indicates that a lake existed. Their relative stratigraphic position links the formation of the lake to the breccia dam that blocked the Lillooet River. Using the mean discharge of the Lillooet River and the rate of cooling of the lava dam which failed when it was still hot, it has been determined that the lake must have existed for at least 11 days and no more than 3 months. Finally, the sedimentology of this area is used to infer a specific sequence of events surrounding the eruption of Mount Meager.

Delahaye, E., 2002. Single station detections for low-level seismicity in the Garibaldi Volcanic Belt, southwestern British Columbia. B.Sc. thesis, University of Victoria, Victoria, British Columbia, 49 p.

Abstract: The Cascade magmatic arc, extending from northern California to southwestern British Columbia, formed as a result of the subduction of the Juan de Fuca plate beneath the North America plate. The Garibaldi Volcanic Belt, the northernmost section of the arc, Consists of Mount Garibaldi, Mount Cayley and Mount Meager. The most recent volcanic activity was the explosive eruption of Mount Meager 2350BP. Volcanoes are monitored by many methods, including seismic observations. In modern times, almost all recorded volcanic eruptions were accompanied by changes in seismic activity. Seismicity in western Canada is monitored by the Canadian National Seismograph Network (CNSN) operated by the Pacific Geoscience Centre. The magnitude threshold for earthquake locations is between ML = 1.0 -1.5 for the south Coast Mountains. For the Mount Meager region the threshold is ML ~ 1.4. All earthquakes above ML = 1.4 are located but it is possible that earthquakes smaller than ML =1.4 are overlooked. Events that are too small to be located may be detected by single station detections. Single station detections from Pemberton (PMB), the station nearest Mount Meager, were examined for the period 1996 to 1998. Single station detections do not provide enough information to locate an earthquake but do produce station-to-source distances. Seven earthquakes likely in the area of Mount Meager were found between 1996 to 1998. The number of unlocated but detected events plus the number of the located events for the same period agrees with past seismicity rates near Mount Meager.

Evans, S. G., 1987. A rock avalanche from the peak of Mount Meager, British Columbia; Geological Survey of Canada, Paper 87-1A, p. 929-933.

Abstract: In March or April 1986 a rock avalanche occurred on the north peak of Mount Meager within the Mount Meager volcanic complex in the coast mountains of British Columbia. The detached rock mass of Pleistocene rhyodacite had an estimated volume of 0.5 x 10^6 m^3. The rock avalanche travelled over a glacier surface in the upper part of its track. Some of the debris reached Lillooet River, nearly 2000 m below the upper part of the detachment zone, and temporarily blocked it. The landslide is one of seventeen rock avalanches known to have occurred in the Cordillera since 1855.

Evans, S. G. and Savigny, K., 1994. Landslides in the Vancouver-Fraser Valley-Whistler region; *in* Geology and geological hazards of the Vancouver region, southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, 251-286.

Modified abstract: A great diversity of landslide types occur in the Vancouver region in response to high relief, steep slopes, heavy rainfall, seismicity, and a variety of landslide-prone materials. Rockfalls and small rock avalanches (less than a million cubic metres) are a significant hazard to land use development but their biggest impact has been on the transportation network and the Fraser River fishery. The deposits of larger rock avalanches (greater than a million cubic metres) are common throughout the region and have occurred along major transportation routes in the Fraser Valley and the Squamish-Pemberton corridor in the last 10,000 years. Volcanic rocks of

the Garibaldi Volcanic Belt are particularly prone to massive rapid landslides, some of which have blocked major rivers and formed temporary lakes upstream. Since the late Pleistocene, major collapses have taken place on the western flanks of Mount Garibaldi and Mount Cayley volcanoes. Large landslides continue to occur in the historical period and are a major consideration in land development in the Belt. Channellized debris flows within steep mountain watersheds triggered by heavy rains occur throughout the region. Debris flow defensive structures have been constructed by provincial authorities at numerous locations to protect transportation routes and/or communities. The expansion of development in the Vancouver region is increasing the vulnerability of communities, transportation routes, and the resource base to landslides.

Gardner, C.A., Scott, K.M., Miller, C.D., Myers, B., Hildreth, W., and Pringle, P.T., 1995. Potential volcanic hazards from future activity of Mount Baker, Washington; United States Geological Survey, Open-File Report 95-498, 16 p.

Summary: This report, aimed at emergency planners and personnel, federal and state agencies, and the public, describes potential hazards from future eruptions of Mount Baker, Washington. It is accompanied by a hazard zonation map. Although hazards that may affect Canada are not specifically discussed, Mount Baker's proximity to the Canadian border makes it clear that a Mount Baker eruption could have significant effects within Canada, either through ash fall hazards or lahar hazards. On the hazard zonation map, ash hazard zones and lahar hazard zones are truncated at the Canadian border because the map does not include Canada, however, it is clear from the map that these hazard zones should continue into Canada.

Green, N.L., 1978. Multistage andesite genesis in the Garibaldi Lake area, southwestern British Columbia, Canada; Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 246 p.

Modified abstract: The products of Pleistocene-Recent volcanism in the area just north of Mount Garibaldi are hornblende-andesite, hornblende-biotite andesite, and less voluminous two-pyroxene andesite, olivine-basalt, basaltic-andesite and hornblende-dacite. The basic lavas are predominantly alkali-basalt, hy-normative hawaiites and mugearites. Andesites and associated intermediate rocks have a calc-alkaline affinity, and show strong enrichment in Sr and Ba, further emphasizing the major compositional gap between these lavas and contemporaneous basalts. All lavas display depletion in Rb, low Sr^{87}/Sr^{86} ratios and high K/Rb ratios relative to typical orogenic volcanic series. Calculated phenocryst equilibration pressures range from 4.5 to 11 kb and average 7.5 kb (~25 km), indicating lower crustal crystallization. Estimated fH_2O for hornblende-bearing lavas suggest phenocryst equilibration under $PH_2O < P_{Total}$, with XH_2O^{Liq} ~ 0.09-0.15 (3-5 wt. %). The phenocryst mineralogies of The Table, Mount Price, and Black Tusk demonstrate that chemically distinct magma batches crystallized under different pressure-temperature conditions. The results of equilibrium calculations suggest that the parental magmas of the andesites could have equilibrated with peridotitic residuum at 1150-1235°C and 15-20 kb. The evolution of Garibaldi Lake andesite magmas can only be explained by a multistage model. It involves: (1) varying degrees of partial melting of wet peridotite above the Benioff zone to produce water-undersaturated tholeiite magmas; (2) high-pressure (>5 kb) fractionation of olivine ± clinopyroxene ± amphibole ± biotite + pyroxene + magnetite from more intermediate compositions; and (3) low-pressure (2-5 kb) segregation of plagioclase ± amphibole ± biotite ± pyroxene + magnetite from more intermediate compositions.

Hickson, C. J., 1994. Character of volcanism, volcanic hazards, and risk, northern end of the Cascade magmatic arc, British Columbia and Washington state; *in* Geology and geological hazards of the Vancouver region, southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 231-250.

Abstract: A band of Oligocene (30 Ma) to Recent volcanoes and associated intrusive rocks extend from latitude 44°N in northern California to latitude 52°N in southwestern British Columbia. These centres make up the Cascade magmatic arc. The arc formed in response to subduction of the Farallon Plate (the present day Juan de Fuca Plate). Volcanism from 5 Ma to the present is restricted to a linear belt of volcanoes broken into six segments. The northernmost segment extends from Glacier Peak in Washington State to the Bridge River cones in British Columbia. The most recent significant volcanic event in this segment of the arc is a Plinian to Pelean eruption from Mount Meager (2400 BP). This event blocked the Lillooet River and spread ash across southern British Columbia into Alberta. Activity at Mount Baker occurred as recently as 1975. The geological record of lava flows and volcanic deposits suggests that both basaltic and andesitic eruptions, and infrequent violent dacitic explosive eruptions, may occur. Of the numerous hazards associated with volcanic eruptions, the most likely to affect large numbers of people are airfall tephras and debris flows. A continuing hazard is posed by the extreme relief of many vent areas and the unstable nature of volcanic deposits. At least 44 large postglacial debris flows are known at Mount Baker and landslides from Mount Cayley and the "Barrier" (near Mount Garibaldi) have blocked the Squamish and Cheakamus Rivers. The loose unconsolidated nature of some volcanic deposits leads to increased sediment loads in surrounding drainages and leaching of soluble elements into the groundwater.

Kelman, M.C., 2005. Glaciovolcanism at the Mount Cayley volcanic field, Garibaldi volcanic belt, southwestern British Columbia. Canada; Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 258 p.

Abstract: This thesis investigates glaciovolcanism in the Mount Cayley volcanic field (MCVF) of southwestern British Columbia's Garibaldi Volcanic Belt (GVB). The MCVF is dominated by intermediate magma compositions, has been intermittently glaciated, and has extreme topography. No study to date has focused on intermediate composition glaciovolcanic products in a similar setting. The core of this thesis is a 1:20,000 volcanological map, which was used in conjunction with field observations, geochemical data, and petrographic examinations to investigate the volcanological history of the MCVF, to investigate the eruptive processes that produce specific glaciovolcanic landforms, and to make predictions about paleo-ice thicknesses and distributions. The MCVF (and the entire GVB) has three dominant intermediate composition glaciovolcanic landform types: subglacial domes, flow-dominated tuyas, and impoundment features. Subglacial domes are irregularly-shaped piles of lava flows representing subglacial eruptions that commenced beneath 100-650 m of ice and did not breach the surface; in many cases, the subglacial domes grew to within 150 m of the ice surface. Flow-dominated tuyas are steep-sided, flat-topped stacks of lava flows representing subglacial eruptions that ultimately breached the ice surface. Subglacial domes and flow-dominated tuyas represent the same eruptive process, the primary difference being whether or not the ice was breached. Impoundment features are subaerial lava flows with steep flanks or termini representing channeling or ponding of lava by ice. All three landforms have intense fine-scale jointing that indicates cooling surfaces inconsistent with apparent paleotopography. Additionally, all lack features recording eruption into water (pillows and hyaloclastite), indicating efficient and continuous meltwater drainage during eruptions. This is different from glaciovolcanic deposits in most other settings. It also makes these deposits distinct from basaltic glaciovolcanic deposits in the GVB. A combination of ice geometry, topography, and magma composition is responsible; thin ice promotes the formation of drainage pathways around subglacial vents, while thin ice coupled with steep bedrock topography creates hydraulic gradients away from vents. Magma composition probably also plays a role, due to its effect on quantities of ice melted and the pressure in subglacial vent cavities and drainage conduits.

Kelman, M.C., 2015. Preliminary Volcanic Ash Fall Susceptibility Map of Canada; Geological Survey of Canada, Open File 7679, 68 p., map scale 1:12 000 000.

Summary: This map shows the locations, types, and ages of 320 Canadian volcanoes with the potential for future eruptions, and four zones of estimated annual volcanic ash fall probability. The

ash hazard zones are based on ash layer data compiled for the six largest ash fall events in Canada during the Holocene, and extrapolations from data from the 1980 Mount St. Helens eruption. The map is accompanied by 61 pages of notes which explain how the map was made.

Kelman, M. C., Hickson, C.J., and Russell, J.K., 2008. Geology, Mount Cayley volcanic field, British Columbia; Geological Survey of Canada, Open File 5532, scale 1:20 000.

Summary: This is a 1:20,000 scale geologic map of the volcanics rocks of the Mount Cayley volcanic field. Geology of the underlying basement is not depicted. Mount Cayley geology is from mapping by Jack Souther in 1979-1980, while the geology shown for the outlying volcanic rocks is new and is based on field work by Kelman in 2001-2003.

Kelman, M. C., Russell, J.K., and Hickson, C.J., 2001. Preliminary petrography and chemistry of the Mount Cayley volcanic field, British Columbia; Geological Survey of Canada, Current Research 2001-A11, 9 p.

Abstract: Sixty-two samples from five volcanic centres (Ember Ridge, Mount Fee, Slag Hill, Ring Mountain, and Little Ring Mountain) were collected as part of a preliminary petrological investigation of the Mount Cayley volcanic field. The sampled deposits are flows and domes, and many show features indicative of ice contact during eruption (e.g. abundant glass, fine-scale joining). Mineralogically, the samples range from andesite to rhyodacite, and chemically, the rocks span a range from andesite to dacite. Glassy samples are abundant, with glass contents as high as 70%.

Kelman, M. C., Russell, J.K., and Hickson, C.J., 2002. Glaciovolcanism at Ember Ridge, Mount Cayley volcanic field, southwestern British Columbia; Geological Survey of Canada, Current Research 2002-A15, 13 p.

Abstract: Quaternary volcanic rocks at Ember Ridge were mapped at 1:20 000 scale as part of a larger investigation of glaciovolcanism within the Mount Cayley volcanic field in southwestern British Columbia. These deposits consist of at least six isolated, steep-sided andesite mounds, whose morphology and complex fine-scale jointing indicate lava quenching beneath ice. The scarcity of volcaniclastic material at the Ember Ridge deposits suggests the suppression of explosive fragmentation during eruption. If these deposits are coeval, then the elevation range covered by the glaciovolcanic rocks indicates a minimum ice thickness of at least 670 m.

Klohn Leonoff, 1991. Flooding of West Sumas Prairie November 9-12, 1990; British Columbia Environment Water Management, PB 5174 02.

Summary: This report summarizes data collected during the flooding of West Sumas Prairie from November 9 to 12, 1990. Analysis of the flood event is presented and the implications for floodplain management are discussed. The flooding was caused by overflow from the Nooksack River in Washington state. The estimated return period of the flow in the Nooksack River is between 7 and 11 years. Peak overflow during the 1990 flood was much greater than predicted by previous studies. It is recommended that immediate consideration be given to dyking and channel improvement in the Nooksack River at Everson; if no changes are made, a major overflow could cause an avulsion of the Nooksack River. A new channel would be formed flowing northwards and the consequences would be catastrophic. (This reference is included in the bibliography because the record of weather-related flooding due to Nooksack River overflow events is relevant to understaning the hazard from potential Nooksack River overflow events caused by lahars from the north side of Mount Baker.)

Klohn Leonoff, 1993. Nooksack River avulsion study; British Columbia Environment, Water Management, PB 5174 03.

Summary: The Nooksack River has overflowed into the Sumas River basin (thus causing flooding in Canada) eight times between 1909 and 1966. This report investigates the possibility of an avulsion of the Nooksack River channel at Everson, Washington, resulting in redirection of river flow northward into Canada. Although the report does not discuss the possibility of overspill floods or an avulsion as a result of a Mount Baker lahar in the Nooksack River, it is possible that a lahar could cause such an overspill flood or avulsion. This would pose a major hazard to the Sumas Prairie region of Canada.

Lawrence, R.B., 1979. Garibaldi Group volcanic rocks of the Salal Creek map area (northern half), southwestern British Columbia; B.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 83 p.

Abstract: Several patches of Pleistocene Garibaldi Group volcanic rocks unconformably overlie the late Miocene calc-alkaline Salal Creek Pluton. These volcanic of the Salal Creek area, unlike the typical calc-alkaline, intermediate silica Garibaldi Group volcanic rocks, are primarily alkali olivine basalts and hawaiites. Flows, pillow-palagonite accumulations and pyroclastic rocks of basalt-hawaiite composition are present. One erosional remnant of subalkaline basalt occurs just outside the Salal Creek Pluton boundary. Locally, the Salal Creek alkaline volcanic units were dammed by, ponded against or extruded beneath Pleistocene ice sheets. The largest volcanic complex studied yields whole rock K-Ar isotopic dates of 0.97 ± 0.05 Ma for a hawaiite flow and 0.59 ± 0.05 Ma for an alkali olivine basalt flow. Major element chemistry and mineralogy suggests that the alkaline rocks underwent differentiation at pressures below 15 kilobars. Fractional crystallization of olivine, and to a lesser extent, clinopyroxene accounts for the observed chemical variation.

Lee, L.J., 1988. Origin of columnar jointing in Recent basaltic flows, Garibaldi area, Southwest British Columbia; M.Sc. thesis, University of Calgary, Calgary, Alberta, 177 p.

Summary: Columnar joints are structures which occur most frequently in basic lava flows and shallow intrusions. A number of different hypotheses have been proposed to explain the origin of columnar joints. The most widely accepted theory suggests that the columns formed by contraction during cooling. It has also been proposed that thermal convection currents are in motion as the magma cools and that the columns are images of these convection cells. Recent studies on double-diffusive convection have resulted in the development of a third hypothesis for the origin of columnar joints. According to the third theory, the combined effect of temperature gradients and chemical gradients acting on melt density result in long, finger-like convection cells which define the boundaries of the cooling joints. Later in the cooling process, contraction causes the joints to form along these boundaries. Recent alkali olivine basalt flows in the Garibaldi region of British Columbia exhibit columnar jointing. Flows showing typical two- and three-tiered arrangements of joints can also be seen. Basaltic flows range in thickness from approximately 1 to 10 metres and occurrences of columnar jointing in the region are varied. Shapes and sizes of columns and the degree to which they are developed change markedly among flows. The presence and spacing of chisel structures is also variable. The electron microprobe was used in conjunction with standard thin section examination and wet chemical techniques to provide detailed physical, petrographic, mineralogical and chemical studies of samples from a number of different jointed flows. The data caused the theory of simple convection to be rejected and found very little evidence to support a double-diffusive origin to the columns. A purely contractive origin for the joints is favored by the data. Mathematical modelling of the cooling of a typical flow allowed calculations of the Rayleigh number for a range of flow thicknesses. Theoretically, if a critical value of the Rayleigh number is exceeded, double-diffusive convection is possible, provided that this value is exceeded for sufficient time to establish the convective currents. Calculations showed that such a process could, in theory, occur in flows whose thickness was greater than 2 metres.

Lu, Z., 1993. Landslides and geotechnical properties of volcanic tuff on Mount Cayley, British Columbia; Ph.D. thesis, University of Alberta, Edmonton, Alberta, 263 p.

Abstract: A major rockslide and debris flow occurred on Mount Cayley in June, 1984. 3.2 million cubic metres of volcanics travelled 2.0 km down Avalanche Creek at velocities up to 35 m/s to dam the confluence of Avalanche and Turbid Creeks. The breaking of the landslide dam caused an extremely fast debris flow. The velocity of the debris flow and associated wind gusts, up to 34 m/s, caused superelevations, hurled rocks and wood through the air, uprooted trees, and spattered mud 16 m up trees. The 1963 rock slide began at the head of Dusty Creek, and terminated at the new confluence of Dusty and Turbid Creeks. About 5 x 10^6 m^3 of columnar-jointed dacite and poorly consolidated pyroclastic rocks slid 2.4 km downstream. The deposits of the 1963 rock slide have distinct layers which can be traced to bedrock units in the depleted zone. Volcanic tuff constitutes the basal rupture zones of the 1963 and the 1984 rock slides. The tuff has a low dry density, 13.6 kN/m^3, high porosity, 36%, and very low slake durability, 25%. Two yield points are recognized frm stress-strain, volume change-strain and pore pressure-streain curves of uniaxial and triaxial tests. The yield points define the starts of crushing and shearing, the destruction of the natural structure and the development of microfracturing of the tuff. The tuff shows a rapid drop of the strength after passing peak. The peak friction angle of dry tuff is 35°, saturated tuff has peak values of Φ'=29°, c'=216 kPa and residual values of Φ_r=17°, c_r=65 kPa.

Moore, D.P., 1976. Rubble Creek landslide, Garibaldi, British Columbia; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 84 p.

Abstract: During the late winter of 1855-56 or early spring of 1856 about 33,000,000 cubic yards of volcanic rock slid from the high cliff known as The Barrier, near Garibaldi, B.C. This debris travelled down a rather sinuous path along Rubble Creek valley to its confluence with Cheakamus River about 4 miles from the Barrier and about 3400 feet lower. The initial material appears to have travelled as a high velocity tongue of debris which swept from one side of the valley to the other as the debris stream rounded curves eventually to be deposited on Rubble Creek fan. Velocities calculated from the superelevation of the debris as it rounded three different curves indicate that the debris was moving between 88 and 110 feet per second. A minimum velocity of 80 feet per second was calculated using the principle of conservation of energy where the debris overtopped a small hill at the apex of the fan. All of the trees in the path of this slide were uprooted and carried away. The trees adjacent to the slide were scarred and bruised by moving debris. The initial high velocity tongue was apparently followed by mud flows which deposited large rounded boulders and poorly sorted, volcanic debris on an area of the fan which was not covered by the initial slide. The slide deposit is formed of angular poorly sorted volcanic clasts weighing up to about 250 tons. Deposits of debris similar to the debris of the 1856 slide, beneath some of the fan deposits, show that an earlier slide may have occurred. The mechanism which triggered the landslide is not known, but blockage of a subsurface drainage system, which drains the area behind The Barrier and escapes as springs at its toe, could have raised groundwater pressures enough to trigger the slide. In addition, as the area is one of recent volcanic activity, a local earthquake may have been the immediate cause. In any event the underlying cause for the landslide was that the excessively steep and high cliff face of lava was apparently deposited against glacial ice, and subsequently, lost support when the ice melted. There has been at least one destructive slide in the area of Rubble Creek fan in the recent past and because it cannot be demonstrated that conditions have changed substantially since the 1856 slide it is only prudent to accept the possibility of the occurrence of another slide in the near future.

Mullineaux, D.R., 1976. Preliminary overview map of volcanic hazards in the 48 conterminous United States. Miscellaneous Field Studies Map MF-786, Volcanic Hazards, United States; United States Geological Survey, scale: 1: 7 500 000.

Summary: This map identifies areas of the conterminous United States where volcanic hazards, including ash fall, pose some degree of risk, and shows possible areal distribution of several kinds of hazardous phenomena. The map is focused on the United States but the depiction of some ash fall hazard zones crosses the border with Canada, so it has a crude qualitative relevance to Canadian hazard assessments.

Nooksack River International Task Force, 1991. Preliminary report on Nooksack River trans-boundary flooding, December 1991; multiple agency report, 46 p.

Summary: This report summarizes the 1990 weather-related flooding of the Nooksack River in Washington which spilled over a drainage divide at Everson, Washington and crossed into Canada, flooding the Sumas Prairie area, and indicates that the frequency of such overspill floods is increasing. Although the report does not discuss lahar-related floods, a Mount Baker lahar that entered the Nooksack River could cross into Canada via this route, and therefore poses a potential hazard to Canada.

Park., M., 2011. Glacial and geothermal dynamics in Sherman Crater, Mount Baker, Washington; M.Sc. thesis, Western Washington University, Bellingham, Washington, 88 p.

Abstract: Although quiescent since a significant thermal event in 1975, Mount Baker, in Washington, continues degassing from fumaroles in Sherman Crater, indicating the presence of a connection to an active magmatic system at depth. The apparent equilibrium condition of the crater glacier between 2003 and 2008, despite lying well above the regional equilibrium line altitude, suggests that melting of basal ice by heat flux from fumaroles and heated ground must balance the glacier's positive surface mass-balance. My investigation of glacial and geothermal dynamics in Sherman Crater between 2009 and 2010 provides the first rigorous quantitative assessment of the Sherman Crater glacier: ice volume, flow direction and velocity, annual mass balance and characteristics of the material below its base. Heat flux is derived from these constraints by two methods: the glacier calorimetry method of Welch et al. (2007) and the thermal grounds method of Frank et al. (1977). Ground-Penetrating Radar (GPR) transects across the crater glacier yield a maximum ice thickness of ~40 m W.E. and volume of ~1.3 million m^3 W.E. for 2009 and ~66 m W.E. and volume of ~2.1 million m^3 W.E. for 2010, assuming a standard velocity of EM-waves through ice of 0.151 m/ns and an average ice density of 700 kg/m^3. The measured annual mass balance in 2009 of ~4.0 m of snow and ice and derived heat flux range of ~18 to ~28 W/m^2 are comparable to values at active but quiescent volcanoes. The glacier flows northward at a rate of ~3 cm/day and rests on a base of hydrothermally altered regolith with thin meltwater layers. Because the glacier's total volume in 2009 is ~2/3 of the inferred volume of ice melted during the 1975 unrest event (which did not produce a debris flow), the risk from meltwater-induced debris flow from Sherman Crater is low. The large fluctuation in calculated glacier volume between 2009 and 2010, however, highlights the potential for this situation to change rapidly. An increase in annual-mass balance or decrease in heat flux could affect both ice volume and the distribution of thermally exposed surfaces in the crater. The present glacier mass-gradient driving the flow of ice northward towards large areas of thermally exposed ground could be overwhelmed by an eastward directed mass-gradient, towards the East Breach, a source of debris flows since the mid-Holocene. Sherman Crater might therefore become more of a threat if volcanic activity subsides.

Phoenix Geophysics Limited, 1984. Magnetotelluric survey data, Mount Cayley area, British Columbia; Geological Survey of Canada, Open File 1018, 96 p.

Summary: This is a summary of a magnetotelluric survey conducted at five sites in the vicinity of Mount Cayley, British Columbia.

Powell, J.H., Jr., 2006. Quaternary magmas of the Raffuse Creek-Mamquam River area, southwest British Columbia; M.Sc. thesis, University of Alabama at Tuscaloosa, Tuscaloosa, Alabama, 170 p.

Modified abstract: Late Cenozoic volcanic rocks of the Raffuse Creek-Mamquam River (RCMR) area of Southwestern British Columbia, Canada are associated with subduction of the Juan de Fuca plate beneath southwestern British Columbia. Mulligan Mountain, Paul Ridge, Mamquam River and Skookum Creek basaltic andesites erupted as domes on valley walls adjacent to the Holocene Ring Creek dacite lava. Petrology and geochemistry of these early to post-glacial effusive suites place important constraints on genesis of calc-alkaline magmas within the northern Cascadia Subduction System. Many of the RCMR lavas contain fragments of partially fused basement rock, and/or cognate xenoliths, with mineral assemblages similar to those of the host lavas. RCMR lavas are medium-K, calc-alkaline andesites and dacites characterized by low Nb contents. Observed intrasuite compositional variations are compatible with crystal fractionation along either hydrous or anhydrous crystallization paths. Trace element characteristics are consistent with the presence of a slab or crustal component in these magmas. RCMR magmas are unlikely to represent partial melts of amphibolitic to granulitic lower crust or subducted eclogitic oceanic lithosphere. Parental RCMR magmas were most probably generated in the mantle wedge overlying the subducted Juan de Fuca plate.

Read, P. B., 1977. Meager Creek volcanic complex, southwestern British Columbia; Geological Survey of Canada, Paper 77-1, p. 277-281.

Introduction: Nearly 65 years ago hot springs were discovered along Meager Creek and Lillooet River west of their confluence in the west half of map-sheet 92J (Robertson 1911). During 1974 and 1975 a program consisting of water geochemistry, resistivity and self potential surveys, and diamond drilling totalling 2523 feet has contributed data for an assessment of the geothermal potential of the area. In the summer of 1976, nearly two months were devoted to mapping of the Pliocene and Recent volcanic rocks outcropping west of the junction of Meager Creek and Lillooet River. L. Hammerstrom, Department of Geological Sciences, University of British Columbia, is engaged in a detailed study of spring water geochemistry. Nine volcanic assemblages of the Garibaldi Group form the Meager Creek Volcanic Complex. Andesite and dacite flows predominate and range in age from Pliocene and (?) Miocene to postglacial. The complex overlies a basement composed of Mesozoic plutonic and metamorphic rocks which are unconformably overlain by low grade metavolcanic rocks all of which are intruded locally by quartz monzonite stocks of presumed Miocene age. The hot springs issue from basement.

Reader, J.F. and Croft, S.A.S., 1983. Report on 1982 temperature gradient drilling on Shovelnose Creek at Mount Cayley, southwestern British Columbia; Geological Survey of Canada, Open File 1017, prepared by Nevin Sadlier-Brown Goodbrand Ltd., 32 p.

Summary: During August-September, 1982, Nevin Sadlier-Brown Goodbrand Ltd. on behalf of the Geological Survey of Canada, managed a helicopter-supported, geothermal gradient drilling program at the Mount Cayley Volcanic Complex in southwestern British Columbia. The drill site was located at elevation 1540m in the upper reaches of Shovelnose Creek which drains the southeastern side of the complex. Using diamond drilling equipment, one hole (Shovelnose One) was abandoned at 516’ (157.3m) when rods were stuck in the hole during cementing to alleviate severe hole conditions. After moving the rig by hand, Shovelnose Two was completed uneventfully to 1500’ (457.3m). The holes penetrated a quartz diorite of the Coast Plutonic Complex cut by at least three stages of volcanic intrusion. Numerous dykes of dacite and andesite composition are visible throughout the core. Alteration and precipitate assemblages are typical of extensive hydrothermal activity similar to that at the Meager Creek volcanic complex to the north. The highest temperature measured was 48.9°C at total depth in Shovelnose Two. Measured gradients display the influence of a warm water flow which enters the hole at 835’ (254.6m). A background thermal gradient of approximately 95°C/km is interpreted from the bottom hole temperatures. Water from the flowing zone was sampled at the surface and is seen

to be highly saline with Na^+, Cl^-, Mg^{2+}, HCO^{3-} being the dominant ions. A clear, colourless, non-flammable gas observed bubbling up the well is assumed to be dominantly carbon dioxide. Geothermometer estimates are variable with the most encouraging being the quartz conductive model which yields temperatures of 85.3°C and 115.7°C in two samples. Chalcedony precipitation and surface groundwater dilution probably yield a lower estimate of equilibrium temperatures.

Roddick, J.A. and Hutchison, W.W., 1968. Coast Mountains Project, British Columbia; Geological Survey of Canada, Paper 68-1a, p. 37-41.

Summary: This is a description of ongoing mapping in British Columbia's Coast Mountains, including a short description of the Silverthrone volcanic complex, about which very little has been published.

Roddick, J. C. and Souther, J.G., 1987. Geochronology of Neogene volcanic rocks in the northern Garibaldi Belt, British Columbia; Radiogenic age and isotopic studies, Report 1, Geological Survey of Canada, Paper 87-2, p. 21-24.

Abstract: Five samples of volcanic rocks from the Bridge River upland, the northernmost segment of the American high Cascades continental calc-alkaline arc have K-Ar ages ranging from 400-800 ka. Though several samples may contain excess argon, the ages are in good agreement with related segments of the arc and support the suggestion that late Pleistocene volcanism in the Cordillera may have been triggered by isostatic adjustment associated with major fluctuations in Pleistocene ice thicknesses.

Ryder, A.J.D., 1983. A reconnaissance hydrogeochemistry survey of the southwestern drainages of Mount Cayley, British Columbia; Geological Survey of Canada, Open File 1016, prepared by Nevin Sadlier-Brown Goodbrand Ltd., 20 p.

Summary: A reconnaissance hydrogeochemistry survey was conducted of the southwestern drainages of Mount Cayley, to identify anomalously mineralized surface waters possibly associated with hydrothermal fluids. Conductivity measurements were taken in surface waters, and samples were collected for chloride (Cl^-) and sulphate ($SO4^{2-}$) analysis. In addition samples from selected sites were submitted for more complete major element analysis, to characterize local thermal fluids and groundwaters. Thermal waters of variable composition exist over a considerable vertical range and areal extent at Mount Cayley. These waters include near-neutral pH sodium bicarbonate waters at high elevation, encountered in the Shovelnose-2 drill hole, sodium chloride/bicarbonate/sulphate waters at the Turbid Creek hot springs, and sodium sulphate waters at the EMR 304-2 drill hole in the Squamish River Valley. Turbid Creek and Shovelnose Creek show distinct chemical "signatures" of the thermal effluent discharged to them from the hot springs in their respective drainages. Other anomalously mineralized surface waters were identified in the upper Shovelnose Creek drainage, in Hook Creek, and in the vicinity of the Cayley-1 drill hole. Sulphate concentrations in Terminal Creek are marginally below the calculated "threshold" value for local surface waters. Waters of high conductivity identified in the headwaters of Shovelnose Creek may be related to the high-bicarbonate thermal waters encountered at Shovelnose-2. They appear to be associated with a late stage subvolcanic dacite dome.

Shore, G.A., 1981. Report on resistivity survey in the vicinity of Mount Cayley; Geological Survey of Canada, Open File 1020, 12 p.

Summary: This is a summary of a resistivity survey conducted as part of geothermal reconnaissance by the Geological Survey of Canada in the area around Mount Cayley.

Shore, G.A., 1983. Report on E-SCAN multiple pole-pole resistivity survey at Mt. Cayley, British Columbia; Geological Survey of Canada, Open File 1019, 12 p.
Summary: This is a summary of resistivity survey results, and defines an anomaly of potential geothermal significance.

Simpson, K. A., Stasiuk, M.V., Clague, J.J., Evans, S.G., and Friele, P., 2003. Preliminary drilling results from the Pemberton Valley, British Columbia; Geological Survey of Canada, Current Research 2003-A5, 6 p.
Abstract: The Mount Meager volcanic complex experiences frequent landslides and is a potentially active volcano that last erupted 2350 years ago. The combination of loose, altered volcanic material and steep topography is thought to be responsible for the significant landslide hazard. Sediments obtained from drilling in the Pemberton Valley record both landslide events and volcanic eruptions from the Mount Meager volcanic complex over the past 6500 years. Three major debris-flow deposits were identified, ranging from 0.6 to 8 m in thickness. Two of the debris-flow deposits were dated at approximately 2600 and 6200 years ago. The third debris-flow deposit is inferred to be approximately 4000 years old. The remainder of the drill-core sediments record typical meandering-river-valley sedimentation. Long-term sedimentation rates for the Pemberton Valley range from 1 to 7 mm per year. This paper is intended as an update for the Pemberton Valley landowners, rather than as a detailed scientific communication.

Souther, J. G., 1980. Geothermal reconnaissance in the central Garibaldi Belt, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 80-1, p. 1-11.
Abstract: The central part of the Cenozoic Garibaldi Belt includes seven volcanic complexes that extend south from Meager Mountain. They have erupted lavas ranging in composition from augite, olivine basalt through hypersthene andesite and dacite, to biotite rhyodacite. Many of the centres are characterized by subglacial, ice-contact features but preglacial and postglacial phases are also present. The north-northwesterly trend of the belt reflects young structures in the underlying Mesozoic to Tertiary plutonic and metamorphic rocks of the Cpast Plutonic Complex. Hydrothermal alteration associated with these structures plus the discovery of thermal springs near Mt. Cayley suggest that reservoirs of residual heat, similar to those being developed at Meager Mountain, may also be present in the central Garibaldi Belt.

Stasiuk, M. V. and Russell, J.K., 1989. Petrography and chemistry of the Meager Mountain volcanic complex, southwestern British Columbia; *in* Current Research, Part E; Geological Survey of Canada, Paper 89-1E, p. 189-196.
Abstract: The Meager Mountain volcanic complex is located at the northern end of the Garibaldi volcanic belt and is representative of Canadian Cascade volcanism. It is a dominantly calc-alkaline Quaternary volcano with lavas and pyroclastic rocks ranging in composition from andesite to dacite and Pliocene to Recent in age. Subordinate volumes of peripheral but contemporaneous Pleistocene mafic to intermediate alkaline rocks occur as lava flows and breccias.

Stasiuk, M. V. and Russell, J.K., 1990. The Bridge River Assemblage in the Meager Mountain volcanic complex, southwestern British Columbia; *in* Current Research, Part E; Geological Survey of Canada, Paper 90-01E, p. 227-233.
Abstract: The Meager Mountain volcanic complex erupted 2350 BP to produce the Bridge River Assemblage. This assemblage comprises at least three primary volcanic lithologies representing different eruption styles. The oldest stratigraphic unit is a pyroclastic airfall produced by five discrete phases of eruption, each beginning with phreatomagmatic activity and progressing to magmatic pyroclastic eruptions. The second unit is a pyroclastic block and ashflow deposit which has entrained large, charred logs and pumice blocks and outcrops up to 7 km from the vent area.

The third and youngest unit is represented by dacite lavas that form steep bluffs in the present-day Lillooet valley. Although the origin of these welded volcanic breccias remain somewhat enigmatic, they are interpreted to represent hot breccias intimately associated with the production of dacite lavas at the vent. These primary volcanic deposits are partly covered by a volcanic debris flow.

Stasiuk, M. V. and Russell, J.K., 1994. Preliminary studies of Recent volcanic deposits in southwestern British Columbia using ground penetrating radar; *in* Current Research1994-A, Geological Survey of Canada, p. 151-157.

Abstract: Ground penetrating radar data were collected from traverses over five well-exposed, Recent volcanic rock deposits from Mount Meager volcano and the Cheakamus valley, in southwestern British Columbia. The traverses overlie pyroclastic and lava flow deposits, including: a thick accumulation of pumice talus, a welded glassy lava breccia, a bed of airfall pumice, a pyroclastic block and ash flow, and a basalt lava flow. The volcanic rocks are dacite and basalt in composition and glassy to holocrystalline. Data were collected via a pulseEKKO IV ground penetrating radar system with a focused radar signal of 100 MHz. Other experimental conditions varied: i) sample intervals were 0.5 to 1.0 m, ii) ground penetrating radar data was collected with total time windows of 512 or 2048 ns, iii) the number of stacks used was between 64 and 512. Preliminary results suggest that ground penetrating radar is an effective means of delineating important stratigraphic contacts and can resolve complex internal structures in young volcanic deposits.

Stasiuk, M. V., Russell, J.K., and Hickson, C.J., 1994. Influence of magma chemistry on eruption behaviour from the distribution and nature of the 2400 y.B.P. eruption products of Mount Meager, British Columbia; Geological Survey of Canada, Open File 2843, 38 p.

Abstract: The Bridge River Volcanic Assemblage (BRVA) comprises the eruptive products of a 2400 B.P. eruption of Mount Meager including airfall pumice, pyroclastic flows, lahars and lava flow. There is also a unique form of welded block and ash breccia derived from collapsing fronts of the lava flow. Rock avalanches comprising mainly blocks of Plinth Assemblage volcanic rocks are found underlying and overlying BRVA deposits, but appear to be unrelated to the eruptive events. This report presents a new geologic map for the BRVA that includes more units, deposits that were not previously recognized, new stratigraphic relationships, and new origins for some of the deposits. Rocks of the BRVA are dacitic with phenocrysts of plagioclase, orthopyroxene, amphibole, biotite and minor oxides in a glassy groundmass. Sieve-textured plagioclase is pervasive in all BRVA rock types. The presence of banded pumices suggests mingling of mafic and dacitic magma prior to eruption and perhaps represents the trigger mechanism for the Recent volcanism. Pearce element ratio diagrams demonstrate that the BRVA rocks record a chemical variation that correlates with mode of eruption. Pumices from airfall deposits and pumice blocks from pyroclastic flows are richer in water and tend to be more differentiated than do the BRVA lavas. These slight chemical variations correlate with a change in eruptive style from explosive to extrusive.

Stasiuk, M. V., Russell, J.K., and Hickson, C.J., 1996. Distribution, nature, and origins of the 2400 BP eruption products of Mount Meager, British Columbia; linkages between magma chemistry and eruption behaviour; Geological Survey of Canada, Bulletin 486, 27 p.

Abstract: The Bridge River Volcanic Assemblage comprises the eruptive products of a 2400 BP eruption of Mount Meager including airfall pumice, pyroclastic flows, lahars, and lava flow. There is also a unique form of welded block and ash breccia derived from collapsing fronts of the lava flow. Rock avalanches comprising mainly blocks of Plinth Assemblage volcanic rocks are found underlying and overlying Bridge River Volcanic Assemblage deposits, but appear to be unrelated to the eruptive events. This report presents new units that were not previously recognized, new stratigraphic relationships, and new origins for some of the deposits. Rocks of the Bridge River Volcanic Assemblage are dacitic with phenocrysts of plagioclase, orthopyroxene, amphibole, biotite and minor oxides in a glassy groundmass. Sieve-textured plagioclase is pervasive in all Bridge River Volcanic Assemblage rock types. The presence of banded pumices suggests mingling of mafic and dacitic magma prior to eruption and perhaps represents the trigger mechanism for Recent volcanism. Pearce element ratio diagrams demonstrate that the Bridge River Volcanic Assemblage rocks record a chemical variation that correlates with mode of eruption. Pumices from airfall deposits and pumice blocks from pyroclastic flows are richer in water and tend to be more differentiated than do the Bridge River Volcanic Assemblage lavas. These slight chemical variations correlate with a change in eruptive style from explosive to extrusive.

Stewart, M.L., 2002. Dacite block and ash avalanche hazards in mountainous terrain: 2360 yr. BP eruption of Mount Meager, British Columbia; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 109 p.

Abstract: The Mount Meager volcanic complex hosts deposits from the youngest known explosive volcanic eruption in Canada (2360 yr. BP). These deposits reflect the consequences of erupting dacite magmas into a region of extreme topographic relief. Regions of this kind represent one of the most hazardous and, potentially, high risk natural environments on the planet. Mapping of the Pebble Creek Formation deposits has elucidated a unique distribution of hazardous events of varying intensity, timing, and frequency associated with the 2360 yr. BP eruption event. For example, lavas erupted onto the steep slopes of the volcano failed under gravitational stresses producing hot block and ash avalanches. During the later stages of this extrusive activity, cold rock avalanches were produced on the oversteepened slopes of the volcano, in one case mixing with a hot block and ash avalanche. Both volcanic and rock avalanches were highly mobile, travelling down the slopes of the volcano, following the valley and running up the opposite valley wall. Deposits from these events preserve features that are diagnostic of their hot volcanic or cold mass wasting origins and allow these two deposit types to be distinguished in the field. Discrimination is essential because these deposits are superficially very similar in appearance and may be complexly interlayered, but they have different hazard implications. The steep narrow valleys surrounding the Mount Meager volcano provide an efficient catchment for volcanic and rock avalanches. During the 2360 yr. BP eruption cycle thick block and ash avalanche deposits formed a natural dam against the flow of the Lillooet River, a major drainage system. Volume estimates and flow rates of the current Lillooet River suggests there was an ongoing competition between building of the pyroclastic dam and filling of the lake. Gradual buildup of the dam was periodically interrupted by overtopping and catastrophic failure of the dam by the encroaching lake. This catastrophic failure released high volumes of water, flooding the Lillooet valley as far as Pemberton, B.C. and produced highly destructive debris flows. Properly assessing the distribution and nature of volcanic and associated hazards in mountainous regions features is requisite for formulating a risk model for areas such as Mount Meager. Mapping of the deposits elucidates the distribution, and frequency of past hazardous events. The detailed stratigraphic analysis presented in this study demonstrates the destructive potential of these events based on the intensity and time of onset for analogous modern events.

Stewart, M. L., Russell, J.K., and Hickson, C.J., 2001. Discrimination of hot versus cold avalanche deposits; implications for hazards assessment at Mount Meager, British Columbia; Geological Survey of Canada, Current Research 2001-A10, 10 p.

Abstract: Avalanche deposits within the Mount Meager volcanic complex are nearly monolithological and comprise mainly intermediate volcanic rock clasts up to 10.5 m, lack internal structure, and are very poorly sorted. Despite these physical similarities, the deposits originate from two distinct processes, cold rock-avalanche deposits from mass wasting and hot block-and-ash avalanche depositions derived from gravitational collapse of active lava domes and flows. Hot block-and-ash deposits are recognized by the presence of features indicative of high emplacement

temperatures. Clasts within rock-avalanche deposits preserve predepositional weathering and jointing surfaces as well as fragmentation surfaces from transport. The ability to discriminate between hot and cold avalanche deposits and the recognition of multiple volcanic events are critical to hazard assessment in volcanic terranes. Misidentification can lead to underestimating the risk of one (i.e. volcanic) hazard whilst overestimating the other (i.e. mass wasting).

Stewart, M. L., Russell, J.K., and Hickson, C.J., 2002. Revised stratigraphy of the Pebble Creek Formation, British Columbia; evidence for interplay between volcanism and mountainous terrain; Geological Survey of Canada, Current Research 2002-E3, 6 p.

Abstract: The Mount Meager volcanic complex hosts rocks from the youngest explosive volcanic eruption in Canada (2360 BP). Products of that eruption constitute the Pebble Creek Formation. We present a revised stratigraphy based on field work from the 2000 and 2001 field seasons. This stratigraphy is based on volcanic and related deposits described by Hickson et al. (1999). New stratigraphic units include reworked fallout, paleolake deposits, a mixed volcanic and rock-avalanche deposit, and an intervolcanic avalanche deposit. The nature and distribution of the Pebble Creek deposits attest to interactions between volcanism and a high-relief landscape hosting a prominent river system.

Stewart, M. L., Russell, J.K., and Hickson, C.J., 2008. Geology, Pebble Creek Formation, British Columbia; Geological Survey of Canada, Open File 5533, scale 1:10,000.

Summary: This geologic map depicts volcanic rocks of the Pebble Creek Formation, produced by the eruption of Mount Meager, British Columbia, at approximately 2360 B.P.

Todd, S., 2000. Genesis, geology and geomorphology of four major Holocene landslide deposits in Meager Creek valley, southwestern British Columbia; B.Sc. thesis, Simon Fraser University, Burnaby, British Columbia, 38 p.

Abstract: This study was conducted in the Meager Creek valley located 150 kilometres north of Vancouver, British Columbia. Slopes bordering Meager Creek valley are highly unstable and have experienced numerous mass movements since deglaciation. Field description of ten measured sections in Meager Creek valley led to the recognition of at least four major mass movements. All of the mass movements are dominated by volcanic lithologies derived from the Mount Meager volcanic complex in the vicinity of Pylon and Devastator peaks. The types of mass movements include three debris flows and a rock avalanche. Six new radiocarbon dates in addition to the four currently available for this area, provide chronological control on these mass movements. The oldest mass movement in the study area dates to about at 8120+ or -70 ^{14}C yr BP. It deposited a massive, compact diamicton, which looks like till. The next failure was a debris avalanche. This is the largest failure in the study area. Although undated, it is younger than 8120+ or -70 ^{14}C yr BP. The rock avalanche deposit has lithologic zoning and a hummocky surface. A second large debris flow around 4000 ^{14}C yr BP, traveled approximately seven kilometers, the greatest distance of all of the documented mass movements. The youngest mass movement is a debris flow that ran up South Meager Creek. The surface of this landslide is a prominent terrace at 720 masl.

Waddell, B.E., 1994. Crustal contamination of calc-alkaline andesites, southwest British Columbia, Canada; M.Sc. thesis, University of Alabama, Tuscaloosa, Alabama, 175 p.

Abstract: The Loggers Lake complex, northernmost eruptive center in the Garibaldi Lake volcanic field of the Late Cenozoic Garibaldi Volcanic Belt, comprises several 100 to 200 m thick, esker-like, subglacial andesitic lavas extruded onto an irregular surface carved in Cretaceous Cloudburst quartz diorites. The andesites are porphyritic with 10-15% phenocrysts of oscillatorynormal zoned plagioclase (An_{48-71}) with sieve-textured cores (An_{24-44}), strongly resorbed pargasitic hornblende, and rare orthopyroxene (En_{62-75}). Some lavas contain weakly resorbed megacrysts (1-3 cm) of tschermakitic pargasite (Mg/Mg+Fe) = 0.59-0.70; Al^{IV} = 1.8-2.2; Al^{VI} = 0.16-0.72) and/or xenocrysts of augite-rimmed quartz and biotite (Mg/(Mg+Fe) = 0.6-0.8; Al^{IV} = 2.2-2.5). Many of these andesites also enclose rounded, 5-30 cm quartz diorite xenoliths, the mineralogy of which is similar to that of the underlying quartz diorites. Pale brown rhyolitic glass occurs interstitial to partially to strongly resorbed xenolith feldspar (An_{24-44}), quartz, and biotite. Glasses within xenolith melt channels have compositions comparable to minimum melts generated progressively at 2-7 kb pressures, but show asymmetric distribution with respect to channel cross-sections. Many Loggers Lake lavas have mottled matrices characterized by sheared-out patches of pale brown glass similar to that in xenolith melt channels. Loggers Lake lavas exhibit decreases in TiO_2, Al_2O_3, total FeO, MgO, CaO, P_2O_5, and Sr, and increases in Ba, Na_2O, K_2O, Hf, Th, U, Ta, La, Sm, and Yb with increasing silica content (58.46-61.33 wt% SiO_2). Observed geochemical variations can be explained in terms of fractional crystallization (Pl + Hb + Mt) of andesitic magmas, accompanied by assimilation of rhyolitic glass, biotite, and plagioclase derived from quartz diorite xenoliths at mid-crustal to near-surface conditions (<7 kb; 950-1050°C). Magma-xenolith interactions indicate that considerable compositional and mineralogical heterogeneity can be introduced into lavas at shallow crustal levels.

Wilson, H.A., 2006. Physical properties as a means for investigating changes in the dynamics of the 2360 B.P. eruption of Mount Meager, British Columbia; B.Sc. thesis, University of Calgary, Calgary, Alberta, 91 p.

Abstract: The Mount Meager Volcanic Complex is a stratovolcano, located approximately 69 km northwest of Pemberton, British Columbia. It is the northernmost volcano in the Garibaldi Volcanic Belt, the Canadian segment of the Cascades Volcanic Belt. The 2360 BP eruption of Mount Meager has the distinction of being the most recent explosive volcanic event in Canada. This eruptive episode produced a sequence of volcanic deposits, the Pebble Creek formation, comprising airfall deposits, pyroclastic flows, lava flows, and associated debris flow deposits. These rocks represent a change from explosive to effusive behaviour, however, the details of the transition are unclear. The physical properties of the juvenile clasts and the components of the flow derived from the fragmenting magma should vary with eruption style. This study examines changes in the physical properties of the pyroclastic flows to elucidate the transition. Work focused on deposits derived from plume/fountain collapse or dome collapse. I collected bulk samples from various intervals within the Pebble Creek Fm. pyroclastic flows and processed them for grain-size distributions, sorting, clast components, bulk densities, solid densities, ash densities, and porosity variations. Results indicate that the various physical properties changed as the eruption progressed, implying changes in style and dynamics of the eruption. Grain-size distributions and sorting can be used to differentiate airfall from pyroclastic flows, but do not prove to be very helpful distinguishing between the poorly sorted pyroclastic flows. Solid densities show an increasing variance up section. Ash densities display an interesting dispersion, with densities ranging from 2.42 g/cm^3 in the first pyroclastic flow interval to 2.73 g/cm^3 higher in the section. Clasts from within the deposit also show an increasing density trend, as well as a decrease in porosity as the eruption continued. This can be related to eruption style, and the mechanisms by which the magma fragmented. I propose that the pyroclastic flows studied, represent not one, but three phases in eruptive activity comprising Plinian fountain collapse, Vulcanian activity, and finally, fragmentation of lava flows or domes.

Conference Proceedings, Abstracts, and Symposium Volumes

Andrews, G.D.M., Russell, J.K., and Stewart, M.L., 2009. Lahar formation by catastrophic collapse of a pyroclastic dam; history, volume, and duration of the

2360 BP Salal Lake, Mount Meager, British Columbia, Canada; Geological Society of America, Abstracts with Programs, v. 41, no. 7, p. 717.

Abstract: Mount Meager is situated at the northern end of the Canadian portion of the Cascade Arc (Garibaldi Belt), and produced the youngest explosive eruption in Canada. The 2360 BP eruption occurred in an area of high relief and produced airfall, pyroclastic density currents, and block and ash flow deposits that inundated and partly-filled the Lillooet River valley immediately beneath the vent. A direct consequence of the 2360 BP eruption of Mount Meager was that the Lillooet River, which drains the Lillooet Icefield 20 km upstream of Mount Meager, was dammed at least twice by the rapid accumulation of block and ash flow deposits. The first damming-event was caused by formation of a >100 m high dam of welded to non-welded block and ash flow deposit. Uniquely, we demonstrate that the filling of a temporary lake (Salal Lake), and its subsequent draining, occurred during welding of the pyroclastic dam, such that the upper non- to incipiently-welded part of the dam was removed. During a hiatus in volcanism, outflow from the paleo-lake (estimated volume 0.2 km^3) formed a river that used the top of the welded pyroclastic deposits (e.g., dam) as a natural spillway without significant erosion. Subsequently volcanism waxed again, producing a second, largely non-welded block and ash flow dam on top of the remnants of the first dam (>150 m total height). An additional 0.35 km^3 of water was added to the lake behind the heightened dam, together with minor deltas where tributaries entered the lake. This time, however, the entire dam failed catastrophically removing most of the second dam and excavating a 2 km long canyon in the still hot, welded deposit beneath. This catastrophic dam failure and deluge completely drained Salal Lake and formed a lahar that travelled at least 50 km downstream, inundating the present site of the village of Pemberton. We have modeled the duration of the second dam-building and failure event using field observations that constrain the size of the impounded lake and the volumes of water and sediment transported by lahars. Our calculations are also used to estimate the amount of compaction during welding of the pyroclastic dam, the maximum time available for welding of the first dam (e.g., prior to failure), and the effective viscosity of the pyroclastic deposits during welding.

Bach, A.J., 2008. Field guide to Mount Baker and the Nooksack Valley; 50th Annual Meeting of the Western Division, Canadian Association of Geographers, Bellingham, Washington, 16 p.

Summary: This conference field guide describes the geography of Mount Baker, particularly, the Nooksack River valley. It includes a discussion of the Nooksack River's Late Holocene avulsion from its previous Sumas Valley channel, which caused it to drain north into Canada and the Fraser River, to its current course along a remnant outwash channel into Bellingham Bay. This recent major drainage change has important implications with regard to cross-border flooding, and is relevant to evaluations of the cross-border lahar hazard from Mount Baker (although that is not specifically discussed).

Bruno, S. J., Stelling, P., and Hickson, C.J., 2007. An examination of the morphology and petrology of the Ring Creek lava flow, south-west British Columbia, Canada; American Geophysical Union, EOS Transactions, v. 88, no. 52, V13E-08.

Abstract: The Ring Creek lava flow is the youngest event in a series of Quaternary volcanic activity in Mount Garibaldi Volcano of south-west British Columbia, Canada, occurring between 10.7 – 9.3 ka. The lava flow erupted from parasitic Opal Cone and extends south 6.5 km before making a sharp turn and continues another 11.5 km. At this turn, the flow width reaches approximately 2.5 km. Examination of outcrops along the southern flow margin yield thickness estimates in excess of 200 m. The centre of the flow contains lava blocks up to 2 m in diameter, linear ridges parallel to flow direction ranging from 9 – 11 m in amplitude with a 26m peak to peak distance, and pressure ridges perpendicular to flow direction ranging from 4 – 13 m height with 21 – 35 m wavelength. Flow front breccia approximately 200 m in thickness is observed at the toe of the flow. The presence and magnitude of these features coupled with the mineral assemblage (pl+hbl+bt ± pyx ± mt) are typical of high viscosity flows. The Ring Creek lava flow is anomalous

in that it was able to travel 18 km down-valley. This apparent contradiction is even more striking when compared to other flows on Mount Garibaldi with similar mineralogy, which are typically short thick flows or domes. This suggests that a factor other than viscosity has played an important role in determining the behaviour of the Ring Creek lava flow. Our investigation will address alternative governing factors of the Ring Creek flow, how they relate to other flows, and the implications of this anomalous activity for volcanic hazards.

Easterbrook, D.J., Kovanen, D., and Slaymaker, O., 2007. New developments in Late Pleistocene and Holocene glaciation and volcanism in the Fraser Lowland and north Cascades, Washington; *in* Floods, faults, and fire; geological field trips in Washington State and southwest British Columbia, (ed.) P. Stelling and D.S. Tucker; Geological Society of America, Field Guide, v. 9, p. 31-56.

Abstract: As the Vashon glacier retreated from its terminal position in the southern Puget-Lowland and thinned rapidly, marine waters invaded the central and northern lowland, floating the ice and depositing Everson glaciomarine drift over a wide area from southern Whidbey Island to southern British Columbia. The Everson deposits are characterized by vast areas of massive, poorly sorted stony silt and clay commonly containing marine shells. At Bellingham Bay and elsewhere in the Fraser Lowland, Deming sand is overlain by massive, poorly sorted, Bellingham glaciomarine drift to elevations of 180-210 m above present sea level and is underlain by Kulshan glaciomarine drift. Following deposition of the Everson glaciomarine drift, ice readvanced into northern Washington and deposited Sumas Drift and meltwater channels were incised into the glaciomarine deposits. Four moraine-building phases are recognized in the Sumas, the last two in the Younger Dryas. Rapid deglaciation between 14,500 and 12,500 ^{14}C yr B.P. resulted in lowering of the surface the Cordilleran Ice Sheet below ridge crests in the Nooksack drainage and glacial activity thereafter became topographically controlled. Local valley glaciers in the upper Nooksack Valley were fed by alpine glaciers on Mount Baker, Mount Shuksan, and the Twin Sisters Range that were no longer connected to the Cordilleran Ice Sheet Remnants of the Cordilleran Ice Sheet persisted in the Fraser Lowland at that time but were separated from the Nooksack Valley glaciers by several ridges 1200 m higher than the surface of the ice sheet. Alpine glaciers deposited drift in the Middle and North forks of the Nooksack drainage 25-45 km down-valley from their sources. Large mega-landslides in the Nooksack drainage are associated with an area of unusually high seismic activity, whereas nearby areas having the same geology, topography, climate, and vegetation have no such mega-landslides, suggesting that the landslides are seismically induced. Five Holocene tephras have been recognized in the region around Mount Baker-Schreibers Meadow scoria, Mazama ash, Rocky Creek ash, Cathedral Crag ash, and the 1843 tephra.

Friele, P.A. and Clague, J.J., 2006. Volcanic landslide hazards at Mount Meager, British Columbia. *in* Sea to Sky Geotechnique, 59th Canadian Geotechnical Conference and 7th Joint CGS/IAH-CNC Groundwater Specialty Conference, Vancouver, British Columbia, Canada. p. 997-1004.

Abstract: Landslides are frequent on the unstable slopes of the Mount Meager volcanic massif in the southern Coast Mountains of British Columbia. We compile data on historic and prehistoric landslides to determine the risk to people involved in recreation, geothermal power development, and forestry in valleys proximal to Mount Meager, and also to residents in the Lillooet River valley at distances up to 75 km from the volcano. Landslides 10^6-10^7 m^3 in size will have direct impacts in Meager Creek and upper Lillooet River valleys and indirect impacts, including channel aggradation and flooding, at more distant locations. Landslides larger than 10^7 m^3, although relatively rare, may trigger volcanic debris flows that will reach populated areas in the Lillooet River valley, 32-75 km downstream from the source. Without warning, the loss of life from such an event could be high.

Green, N.L., 1990. Late Cenozoic volcanism in the Mount Garibaldi and Garibaldi Lake volcanic fields, Garibaldi volcanic belt, southwestern British Columbia; *in* Special symposium commemorating the 10th anniversary of the eruption of Mount St. Helens, May 18, 1980, Geological Association of Canada – Mineralogical Association of Canada, Geoscience Canada, v. 17, no. 3, p.171-174.

Summary: At least twelve Pleistocene-Holocene calc-alkaline eruptive complexes were formed in the Mount Garibaldi and Garibaldi Lake volcanic fields during the intervals 1.1-1.3 Ma, 0.4-0.7 Ma, 0.2-0.3 Ma, and 0.10 Ma to present. Mildly alkalic basalts, which resemble extensional magma types, were erupted only during the last 100,000 years. Evolution of basaltic andesite and andesite magmas can be explained by polybaric crystal fractionation of more mafic parental magmas. The dacitic and rhyodacitic magmas probably originated by continued fractionation of andesitic liquids accompanied by extensive assimilation of heterogeneous crustal contaminants. Erupted basalts and calc-alkaline rocks, however, can not be related by fractionation processes.

Green, N.L., 2003. Relation of convergent margin volcanism to slab age and thermal structure; possible influences on andesitic magmatism of the northern Cascadia subduction system; Geological Society of America, Abstracts with Programs, v. 35, no. 6, p. 562.

Abstract: The Cascadia subduction system of western North America represents the type example of a continental margin underthrust by extremely young (<25 m.y.) and presumably hot oceanic lithosphere. Although the High Cascades volcanic arc of the southern Cascadia system overlies a subducted Juan de Fuca plate of nearly uniform age (15-17 m.y.), more northerly Garibaldi belt andesitic to rhyodacitic volcanoes developed above oceanic crust that apparently decreases in age from about 22 m.y. beneath Glacier Peak to roughly 14 m.y. below the Bridge River Cones. Individual intermediate to silicic eruptive suites of the 15-km-wide Garibaldi belt exhibit sub-parallel to overlapping trends of decreasing TiO_2, FeO_t, CaO, MgO, Ni, V, and Cr, and increasing K_2O, Rb, and Ba with increasing silica content. Within most of these suites, Al_2O_3, Na_2O, P_2O_5, and to a lesser extent, Sr initially increase as SiO_2 increases to about 58 wt. %, then steadily decline with increasing silica contents. Major- and trace-element compositions of Cascadia basaltic lavas have been shown to exhibit significant correlations with slab age, suggesting magma generation was strongly influenced by along-strike variations in the thermal state of the underlying subducted plate. Garibaldi belt mafic andesites also appear to exhibit relationships to the age of the subducted oceanic crust, but correlations are not as strong and some relationships are opposite to those observed between associated basalts and slab age. Arc-parallel variations in compositions of these medium-K andesitic magmas typically include: 1) slight increases in Al_2O_3, Na_2O, K_2O, P_2O_5, K/Rb, Ba/Ta, Ba/Th, Ba/U, Sm/Yb, and Sr/Nd; 2) near constant CaO, FeO_t, Nb/Ta (~17), Ce/Ce* (~1), and Ba/Sr; 3) wide but similar ranges in Rb, Sr, La, Zr, Hf, La/Yb (<25), Zr/Hf (>35), Th/Rb, Ba/La, Ba/Zr, Ba/Nb, Eu/Eu*, K/Sr, La/Nb, (La/Sm)N, and Sr/Y (20-110): 4) modest decreases in TiO_2, MgO, Th, V, Y, Yb, Th, Rb/Ba, Th/Nb, Zr/Nb, and Mg# (0.7-0.5); and 5) decreases in maximum Cr, Ni, Nb, Nb/Zr, and (Sr/P)N. Compositions of more evolved Garibaldi belt magmas (siliceous andesite-to-rhyodacite) tend to lack similar correlations with slab age. These variations may place constraints on processes operating within and above the Cascadia subduction zone and on any genetic connections between mafic and evolved magmas.

Green, N.L., 2005. Thermal structure and melting conditions associate with 'hot' subduction; implications from thermobarometry of Garibaldi Belt basalts, northern Cascadia subduction system; American Geophysical Union, EOS Transactions, v. 86, no. 52, V41A-1432.

Abstract: The northern Cascadia margin of North America is the classic example of a "hot" subduction system. The downgoing Juan de Fuca plate decreases in age from ca. 10 m.y. off the central Washington coast to less than 5 m.y. off central Vancouver Island; beneath the Garibaldi volcanic belt (GVB) 250 km east of the convergent margin, inferred age of the oceanic lithosphere decreases northward from ca. 22 m.y to 13 m.y. Primitive and near-primitive mafic lavas, which primarily occur trenchward of the GVB volcanic front, range northward from high-Al olivine tholeiites, Mg-andesites and LILE- and LREE-enriched calc-alkaline basalts at Glacier Peak, through transitional basalts in the Cheakamus Valley to alkali olivine basalts and trachybasalts at Meager Mountain, Salal Glacier and Bridge River. The more northerly GVB basaltic magmas show the least evidence of slab-derived components in their source regions. Application of various olivine-melt and pyroxene-melt thermobarometers to GVB basalts indicates a general increase in magmatic temperatures from 1150-1200° C in Mount Baker and Glacier Peak basalts to 1225-1300° C in Bridge River and Salal Glacier lavas. Fe-Ti oxide thermobarometry suggests that northernmost basalts equilibrated under oxygen fugacities conditions between QFM and NNO, whereas Glacier Peak lavas equilibrated at higher oxygen fugacities (ca. 1 log unit above NNO). Estimated P and T conditions of mantle segregation suggest that GVB basalts ascended from increasingly greater depths northward along the volcanic arc. Similar variation is indicated by calculated P-T of basalt equilibrations with both Mg- and Fe-rich peridotite mineral assemblages, based on diopside and albite activity-composition relations. Estimated mantle equilibration temperatures correlate positively with some HFSE abundances (e.g., Hf), but negatively with those of fluid mobile elements (e.g., Cs and B). These relationships are considered in terms of the influence of slab thermal structure on subduction fluxes and mantle sources of arc basalts.

Green, N. L. and Kenyon, P.M.,1992. Crustal contamination by disaggregation of partially fused xenolith margins; American Geophysical Union, EOS Transactions, v. 73, no. 14, p. 353.

Modified abstract: Weakly porphyritic dacite flows and crosscutting dikes of the Late Cenozoic Watts Point and Monmouth Creek volcanic complexes in S.W. British Columbia contain xenoliths of underlying biotite-granodiorite in varied states of fusion and disaggregation. Xenolith feldspars exhibit a diffusion-controlled transition from low- to high-temperature ternary solvii compositions; partially resorbed biotites, which exhibit a cryptic Mg-Fe zonation with respect to the melting front, become more magnesian closer to xenolith margins. Magma-xenolith interactions, which occurred at 950-1025°C based on pyroxene and Fe-Ti oxide geothermometry, indicate that contamination has introduced considerable compositional heterogeneity in the host magma as a result of entrainment of material derived from partially fused xenolith margins.

Jones, A. G. and Dumas, I., 1993. Electromagnetic images of a volcanic zone; *in* The V. R. S. Hutton symposium, electromagnetic studies of the continents, Edinburgh, United Kingdom, (ed.) A.G. Jones and V. Haak, Physics of the Earth and Planetary Interiors, v. 81, no. 1-4, p. 289-314.

Abstract: Data from 20 magnetotelluric (MT) soundings in the Coast belt of southwestern British Columbia, Canada, in the vicinity of volcanic Mounts Meager and Cayley (approximately 150 km north of Vancouver), are analysed to determine both the internal electrical conductivity structure of the Garibaldi volcanic belt and the regional conductivity structure. Galvanic distortion effects on the data are removed using Groom-Bailey tensor decomposition, and the regional 2D responses are determined in a survey-consistent reference coordinate frame for 1D and 2D modelling and inversion. The remaining unknowns, the site gain at each location, are estimated by requiring the long-period asymptotes of the E-polarization rho (sub a) curves to be the same, and alternatively are derived as part of the 2D inversion procedure. Positive correlations are observed between an increased temperature gradient at a depth of about 200 m, a zone of enhanced electrical conductivity and drilling results. The zone of enhanced conductivity is interpreted to be due to montmorillonite-dominated clay alteration minerals which form the cap rock of the geothermal reservoir. Below this cap, the zone is electrically resistive owing to the chlorite and sericite which form the reservoir itself. The volcanic belt is underlaid by highly resistive (more than 10 000 Omega m) crystalline rock, beneath which is a deep conductive region (less than 70 Omega m) beginning at a depth of 12 km. The cause of this crustal zone of enhanced conductivity is thought

to be free saline water possibly released by metamorphic devolatilization from the downgoing Juan de Fuca slab. Within this conductive layer is a region of high conductivity directly beneath the volcanic belt, which we interpret as the magma source body for the belt. Sensitivity studies imply that the upper crustal resistive zone underlies the whole complex, although a weakly conductive, thin, vertical channel, representative of a magma conduit from the deep source body to the near surface, cannot be excluded.

Kelman, M.C., Hickson, C.J., and Russell, J.K., 2003. Quaternary glaciovolcanism along the Whistler corridor; Geological Society of America, Cordilleran Section, Annual Meeting, Vancouver, British Columbia, p. 147-159.

Summary: Southwestern British Columbia's Garibaldi Volcanic Belt (GVB) extends from Watts Point, a small lava mass near the head of Howe Sound, northward through Mount Garibaldi, Mount Cayley, Mount Meager, and the Salal Glacier volcanic complex, all the way to Silverthrone Mountain. Quaternary volcanism in the region results from subduction of the Juan de Fuca plate beneath the Pacific plate. Volcanic deposits range in age from Miocene to Holocene and in composition from high-alumina basalt to rhyolite. Numerous examples of glaciovolcanism (volcano-ice interaction) exist. This field guide describes a number of localities between Vancouver, B.C. and Whistler, B.C. where there is evidence for volcano-ice interaction.

Kelman, M. C., Russell, J.K., and Hickson, C.J., 2003. Glaciovolcanism in the Garibaldi volcanic belt; topographic and compositional controls on morphology; Geological Association of Canada – Mineralogical Association of Canada, Program with Abstracts, v. 28, p. 88-89.

Abstract: Southwest British Columbia's Garibaldi Volcanic Belt (GVB) is a Quaternary volanic chain dominated by intermediate composition lavas in a setting that has been intermittently subjected to widespread glaciation. Thus, it contains numerous examples of the interaction between volcanoes and ice. Glaciovolcanism in the GVB is distinctive for the paucity of features indicative of subaqueous eruption (e.g. hyaloclastite, pillows) and for the dominance of subglacial domes, flow-dominated tuyas, and impoundment features. These features result primarily from lava composition and topography. Lava composition influences edifice morphology because eruption temperature, viscosity and glass transition temperature are strongly correlated to silica content. The GVB is dominated by intermediate lavas (andesite and dacite). Dacitic lavas have substantially lower liquidus temperatures (approximately 950-1050°C), higher viscosities (10^9-10^{11} Pa s) and higher or equal glass transition temperatures (approximately 800-1000°C) relative to the basaltic lavas that dominate Iceland or Antarctica. Andesitic lavas have liquidus temperatures, viscosities, and glass transition temperatures that fall in between those of dacite and basalt. Examination of the heat balances for cooling of lava masses beneath ice shows that, over the entire cooling interval, dacite can release no more than 80% of the heat released by cooling basalt (and may release much less). This results in dacitic subglacial volcanoes melting less water during eruptions than do their basaltic counterparts. Additionally, the presence of steep topography and high-altitude vents (whose elevation leads to thinner overlying ice than for low-altitude vents) promotes drainage of the meltwater that is produced. Thus, these subglacial edifices have shapes that are strongly influenced by the surrounding ice. Steep topography can also lead to the formation of numerous impoundment features: during periods of glacial attrition, lavas from high altitude vents may flow downslope and pond against the stagnant ice that fills valleys.

Linneman, S., Pittman, P., and Vaugeois, L., 2007. Lively landscapes: Major Holocene geomorphic events in the Nooksack-Sumas Valley; *in* Floods, faults, and fire; geological field trips in Washington State and southwest British Columbia, (ed.) P. Stelling and D.S. Tucker; Geological Society of America, Field Guide, v. 9, p. 99-119.

Abstract: The Nooksack River Basin is situated in the steep western slopes of the North Cascade Mountains and low glacial plains of northwest Washington State. The basin drains west from the north and west sides of volcanically active Mount Baker and meets the sea at Bellingham Bay near the southern end of the Strait of Georgia. The dramatic topographic relief of the region is the result of tectonic activity along the Cascadia Subduction Zone. Pleistocene continental and alpine glaciations sculpted and scoured the region, modifying topography and mantling many areas with deposits of tills, outwash and glaciomarine drift. The Holocene saw the retreat of glaciers, rebounding of land, and the peopling of North America with indigenous cultures and then with Euro-American settlement. The Nooksack Basin has had a long history of cultural occupation as it provided both a transportation corridor and a prolific resource area. Although geomorphologically quiescent since Euro-American settlement, the landscape of the Nooksack Valley has experienced numerous landscape-altering events during the Holocene that very likely impacted, if not dramatically altered, the cultures that were present there. The purpose of this field trip is to show evidence for some Holocene geologic events and to contemplate human culture amidst this lively landscape.

Mathews, W.H., 1987. Garibaldi Area, Southwestern British Columbia; Volcanoes Versus Glacier Ice; Cordilleran section of the Geological Society of America, Centennial Field Guide, v. 1, Boulder, Colorado, p. 403-406.

Summary: This is a field trip guide with a site by site description of a number of stops in the Garibaldi region of southwestern British Columbia. Each stop includes geological and geomorphological features indicative of volcanic activity or landslide activity in volcanic materials, with an emphasis on features indicating volcano-ice interaction. Many of these features are of Pleistocene or Holocene age.

Michol, K. A. and Russell, J.K., 2005. 'Strain under scrutiny'; multi-scale analysis of deformation in welded block and ash flow deposits, Meager Mountain, British Columbia; American Geophysical Union, EOS Transactions, v. 86, no. 52.

Abstract: The 2400BP eruption of Mt. Meager has produced a variety of pyroclastic deposits including pumice fall deposits, lavas, and pumiceous pyroclastic flows. The most unique and enigmatic of these is a 100m-thick, valley-filling, welded block and ash flow deposit. Pyroclasts in this deposit range in size from ~1m blocks to fine ash, but the dominant clast size ranges from 5-15cm. Clasts mainly (85-95%) comprise angular to subrounded, variably vesicular fragments of dacitic lava. The welding intensity ranges from a densely welded, vitrophyric breccia to a weakly welded or indurated deposit, to an unconsolidated deposit of blocks and ash. The variably welded aspect of the deposit provides an excellent opportunity to study the unique conditions and processes that have contributed to the welding of this pyroclastic flow. Our approach has been to collect and analyze field data from the block and ash flow deposit, with the intent of quantifying the strain accumulated during the welding process. The main dataset derives from thirteen, hand-drawn, texture maps of 1 m square areas from select outcrops of the block and ash flow deposit. These textural sketch-maps have been scanned into digital images, which have been used for image analysis purposes. For each map, image analysis provides quantitative estimates of clast numbers, sizes, orientations, eccentricities, and proportions of clasts to matrix. These metrics are then used to quantify the total strain in the deposit at the map scale and explore the degree of coupling between clasts and matrix during deformation. Future work involves parallel strain analysis on scanned images of rock slabs and thin sections to investigate how strain is partitioned at these scales. Our analysis will also elucidate the extent to which strain is accommodated as: i) volume strain, as evidenced by a reduction in porosity versus ii) pure shear strain, as indicated by more flattening than can be accommodated by porosity loss alone. Further analysis at smaller scales will serve to reinforce these trends and produce more specific values of strain, as well as determine the proportions of shear to volume strain.

Pittman, P.D., Maudlin, M.R., and Collins, B.D., 2003. Evidence of a major late Holocene river avulsion; Geological Society of America, Abstracts with Programs, v. 35, no. 6, p. 334.
Abstract: The late Holocene avulsion of a major river from one basin to another has great implication for international interest because of concerns with cross-border flooding, volcanic hazards and future avulsion potential, but has had little study to date. The Sumas Valley, located in the eastern portion of the Fraser Lowland, encompasses portions of Washington State and British Columbia. The valley has a complex Quaternary geologic history consisting of continental glaciation, structural activity, and more recent alluvial deposition by three major river systems. Earlier work demonstrated that thick deposits of bedload originating from the Mount Baker volcano underlie the Sumas River valley, which suggests that the Nooksack River, which heads on Mount Baker, flowed north through the Sumas Valley into the Fraser River for much of the Holocene. The Nooksack River drains more than 1400 square kilometers at the point where it would flow north to the Fraser, making it one of the larger tributaries to the Fraser. At some point in the Late Holocene the Nooksack River avulsed from the Sumas Valley into a remnant glacial outwash channel that is its present channel course into Bellingham Bay, some 58 kilometers south of where the Fraser meets the Pacific Ocean. Numerous relict channels and oxbows in the Sumas valley, consistent in size and radius of curvature with the modern Nooksack River, the depth and distribution of flood deposits, as well as alluvial fans that have been truncated by channel migration, further suggest the Nooksack's northward Holocene course through the Sumas Valley to the Fraser. Two much smaller streams, the Sumas River and Johnson Creek, now flow northward in the Sumas Valley within these oversized relict channels. The abundance and morphological newness of the remnant channels, Native American legend, and various radiocarbon dates indicate that the Nooksack River avulsed from the Fraser basin to its modern course to Bellingham Bay in the late Holocene.

Read, P.B., 1981. Geological hazards, Meager Creek geothermal area, British Columbia; Geological Association of Canada – Mineralogical Association of Canada, Program with Abstracts, p. A48.
Abstract: Andesite and rhyodacite, erupted over the last 2 million years, forms the bulk of Meager Volcanic Complex. Three main eruptive phases are: (a) 3 km^3 of a formerly much more extensive rhyodacite tuff, flow and hypabyssal intrusive sequence erupted between 1.0 and 1.9 Ma; (b) widespread andesite flows, breccias and intrusions totalling a minimum of 15 km^3 formed between 0.5 and 1.0 Ma; and (c) rhyodacite lava domes and encircling extrusive rocks which form most of the major peaks in the complex, aggregate at least 20 km^3, and are mostly inter- to postglacial. All phases, particularly the rhyodacite ones, will have airfall material not accounted for in the minimum volume estimates. Two major valleys, the Lilllooet River valley on the north and northeast sides of the complex, and Meager Creek valley on the south side, contain records of the postglacial geologic hazards of the area which include products of volcanism, evidence of the resulting fire and disruption of drainage, and later debris flows. Potential volcanic hazards are most probable in the north and east sections of the complex and adjacent Lillooet River valley. The probable rhyodaccite composition of any future volcanic activity means that airfall tephra and nuées ardentes are likely. All slopes, particularly east facing ones, and valleys are potentially dangerous areas. Potential debris flow hazards are highest in Devastation Creek and the lower part of Meager Creek. The highly altered, early rhyodacite is the best source material. Two km^2 of unstable slopes, mainly on the northwest side of the Devastator, are underlain by this material. The high frequency of debris flows in Devastation and lower Meager Creek valleys render human activities in the valley bottom risky and in 1975, fatal.

Read, P. B., 1990. Mount Meager Complex, Garibaldi Belt, southwestern British Columbia; *in* Special symposium commemorating the 10th anniversary of the eruption of Mount St. Helens, May 18, 1980, Geological Association of Canada –

Mineralogical Association of Canada, Geoscience Canada, v. 17, no. 3, p. 167-170.
Summary: The Mount Meager Complex of Pliocene to Recent age contains rocks ranging in composition from basalt to rhyolite. Products of three periods of volcanism dominate the complex; early and late periods of rhyodacite bound a middle episode of andesite. In the early episode rhyodacite tephra and flows, from <1.9±0.2 Ma to >1.0±0.1 Ma, covered remnants of a basal breccia and overlying dacite flows on the southwestern edge of the complex. Products from the middle episode of andesite volcanism, from 1.0±0.1 Ma to 0.5±0.1 Ma, underlie the southern and central parts of the complex; The Devastator was their principal source. The late episode of rhyodacite volcanism, from 0.1±0.02 Ma to 2340±50 years B.P., produced rhyodacite flows, tephra and lava domes from vents in the northeastern part of the complex. The vent at the 1650 m (5400 foot) level on the northeast flank of Plinth Peak is the source of the Bridge River tephra. Meager and Pebble Creek hot springs issue from the Mesozoic basement near vents.

Roche, A.D., Guthrie, R.H., Roberts, N.J., Ellis, E., and Friele, P., 2011. Once more into the breach: a forensic analysis of the August 2010 landslide dam outburst flood at Meager Creek; Proceedings, fifth Canadian conference on geotechnique and natural hazards, Kelowna, British Columbia, 10 p.
Abstract: A major debris flow on August 6, 2010 dammed Meager Creek and caused a short-duration blockage of the Lillooet River above Pemberton, BC. About 20 hours after the initial event, the landslide dam was overtopped and an outburst flood resulted. An unusually robust portfolio of available data documents this event, including hydrometric data, field observations, seismic records, and satellite imagery. The data are used to perform a forensic analysis that includes hydrodynamic modelling of the outburst flood.

Russell, J. K., Hickson, C.J., and Andrews, G., 2007. Canadian Cascade volcanism; subglacial to explosive eruptions along the Sea to Sky Corridor, British Columbia; *in* Floods, faults, and fire; geological field trips in Washington State and southwest British Columbia, (ed.) P. Stelling and D.S. Tucker; Geological Society of America, Field Guide, v. 9, p. 1-29.
Abstract: Here we describe a two-day field trip to examine Quaternary volcanism in the Canadian Cascade are, named the Garibaldi volcanic belt. Day 1 of the trip proceeds along the Whistler corridor from Squamish to Pemberton and focuses on Quaternary glaciovolcanic deposits. Interactions between volcanoes and ice in the Garibaldi volcanic belt have been common during the past two million years and this has resulted in a diverse array of landforms, including subglacial domes, tuyas, impounded lava masses, and sinuous lavas that exploited within-ice drainage systems. On Day 2, the trip heads northwest of Pemberton, British Columbia, along logging roads to see deposits from the 2360 yr B.P. eruption of the Mount Meager volcanic complex. This eruption began Plinian-style, generating pyroclastic fall and flow deposits and ended with the production of block and ash pyroclastic flows by explosive (Vulcanian) collapse of lava domes (e.g., Soufriere Hills). Many of the traits of the deposits seen on this two day trip are a reflection of, both, the style of eruption and the nature of the surrounding landscape. In this regard, the trip provides a spectacular window into the nature and hazards of effusive and explosive volcanism occurring in mountainous terrains and the role of water and ice.

Russell, J.K., Hickson, C.J., Stewart, M.L., and Stasiuk, M.V., 2003. Field guide to the 2360 B.P. eruption of Mount Meager, Pemberton, B.C.; Geological Society of America, Cordilleran Section, Annual Meeting, Vancouver, British Columbia, p. 161-186.
Summary: This guidebook was prepared in support of a one-day field trip to examine deposits resulting from the 2360 BP volcanic eruption of the Mount Meager volcanic complex (MMVC). This Plinian-style eruption cycle generated pyroclastic fall and flow deposits and was immediately

followed by the production of lava flows/domes and associated block and ash pyroclastic flows. Many of the characteristics of these deposits are shaped by the combination of eruptive style and the nature of the surrounding landscape. In this regard, the trip provides a spectacular window into the nature and hazards of explosive volcanism occurring in the mountains terrains. We have included most of the stops that we consider necessary to reconstruct the sequence of events comprising the 2360 BP eruption. The guide includes extensive directions on how to reach each outcrop and abundant images that illustrate the critical elements of each stop.

Scott, W. E., 1990. Patterns of volcanism in the Cascade Arc during the past 15,000 years; *in* Special symposium commemorating the 10th anniversary of the eruption of Mount St. Helens, May 18, 1980, Geological Association of Canada – Mineralogical Association of Canada, Geoscience Canada, v. 17, no. 3, 179-183.

Summary: About 110 well-dated and 70 poorly dated eruptive periods less than 15,000 years old at individual volcanoes in the Cascade arc constitute a data set for identifying spatial and temporal patterns of eruptive activity. Key features of the record include: (1) the mean frequency of eruptive periods during the past 4,000 years is approximately two per century; however, the variance about the mean may be large; (2) at most major centres, episodes of activity lasting several thousand years are defined by groups of eruptive periods separated by apparent dormant intervals of roughly similar duration, (3) arc-wide clustering of eruptive activity may exist at 0-4 ka, 6-8 ka, and 10-14 ka. Such clustering would be remarkable in light of significant along-arc changes in crustal structure, stress field, and subduction-zone geometry.

Tucker, D.S., Scott, K.M., Grossman, E.E., and Linneman, S. Mount Baker lahars and debris flows, ancient, modern, and future; *in* Trials and tribulations of life on an active subduction zone; field trips in and around Vancouver, Canada, (ed.) S. Dashtgard and B. Ward; Geological Society of America, Field Guide, v. 38, p. 33-52.

Abstract: The Middle Fork Nooksack River drains the southwestern slopes of the active Mount Baker stratovolcano in northwest Washington State. The river enters Bellingham Bay at a growing delta 98 km to the west. Various types of debris flows have descended the river, generated by volcano collapse or eruption (lahars), glacial outburst floods, and moraine landslides. Initial deposition of sediment during debris flows occurs on the order of minutes to a few hours. Long-lasting, down-valley transport of sediment, all the way to the delta, occurs over a period of decades, and affects fish habitat, flood risk, gravel mining, and drinking water. Holocene lahars and large debris flows (>10^6 m^3) have left recognizable deposits in the Middle Fork Nooksack valley. A debris flow in 2013 resulting from a landslide in a Little Ice Age moraine had an estimated volume of 100,000 m^3) , yet affected turbidity for the entire length of the river, and produced a slug of sediment that is currently being reworked and remobilized in the river system. Deposits of smaller-volume debris flows, deposited as terraces in the upper valley, may be entirely eroded within a few years. Consequently, the geologic record of small debris flows such as those that occurred in 2013 is probably very fragmentary. Small debris flows may still have significant impacts on hydrology, biology, and human uses of rivers downstream. Impacts include the addition of waves of fine sediment to stream loads, scouring or burying salmon-spawning gravels, forcing unplanned and sudden closure of municipal water intakes, damaging or destroying trail crossings, extending river deltas into estuaries, and adding to silting of harbors near river mouths.

Clearwater-Quesnel Volcanic Province

Scientific Books and Articles

Canil, D. and Scarfe, C.M.,1989. Origin of phlogopite in mantle xenoliths from Kostal Lake, Wells Gray Park, British Columbia; Journal of Petrology, v. 30, no. 5, p. 1159-1179.

Modified abstract: Phlogopite has been recognized for the first time in ultramafic xenoliths from the Canadian Cordillera. The phlogopite-bearing xenoliths are hosted in post-glacial basanitoid flows and ejecta of the Kostal Lake volcanic center, British Columbia. The xenolith assemblage consists of 60% cumulate-textured wehrlites, and 40% coarse-textured lherzolites, harzburgites, dunites, and olivine websterites.

Hickson, C.J., 1990. Wells Gray – Clearwater; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 137-138.

Summary: The monogenetic Wells Gray – Clearwater volcanic field of east-central British Columbia is summarized briefly.

Hickson, C. J., Moore, J.G., Calk, L., and Metcalfe, P., 1995. Intraglacial volcanism in the Wells Gray-Clearwater volcanic field, east-central British Columbia, Canada; Canadian Journal of Earth Sciences, v. 32, no. 7, 838-851.

Abstract: Small-volume, subaerial, subaqueous and subglacial basaltic eruptions occurred in the Wells Gray–Clearwater area during Quaternary time. Part of this time, significant thicknesses of glacial ice were present. Dating of intraglacial volcanic features corroborates other evidence of an Early Pleistocene, Cordilleran-wide ice sheet. Of the intraglacial volcanoes investigated, three were studied in detail and of these, two probably erupted during the Fraser glaciation (11–20 ka), when maximum ice level exceeded 2100 m elevation. Major-element and sulphur concentrations were measured in glass from the volcanoes to provide insight into vent conditions at the time of eruption. Hyalo Ridge (2102 m elevation, whole-rock K–Ar age of 0.02 ± 0.01 Ma) is a small volcanic edifice capped by lava flows with coherent pillowed lavas and interbedded hyaloclastite exposed over nearly 400 m altitude on its east flank. Low sulphur content (<0.03 wt.%) in pillow rim glasses indicates that the lavas are degassed. It is interpreted that the vent built above the water (or ice) surface then fed lava flows that crossed a shoreline and produced pillowed flows. Pyramid Mountain is a volcanic cone 240 m high, comprised of glassy, vesicular, lapilli-tuff breccia. The highly alkalic glass contains 0.1 wt.% S (considered high), and indicates a high original volatile content and drastic quenching, probably during phreatomagmatic eruption from a meltwater-flooded vent. East of the Clearwater River a sequence of massive pillowed flows and pillow joint-block breccias is exposed from 880 to 1320 m elevation (0.27 ± 0.05 Ma). The vent location is unknown. Moderate S content (0.040–0.055 wt.%) indicates that the lavas were erupted in shallow water and are largely degassed. The S content of glass in dykes cutting the pillow breccias is low. The dykes are interpreted as lava that has flowed laterally or down into cracks.

Hickson, C. J. and Souther, J.G., 1984. Late Cenozoic volcanic rocks of the Clearwater-Wells Gray area, British Columbia; Canadian Journal of Earth Sciences, v. 21, no. 3, p. 267-277.

Abstract: Succession of alkali olivine basalt flows that lie east of the extensive Chilcotin lavas and define the eastern end of the Anahim volcanic belt. The rocks are petrographically similar to but less altered than the Chilcotin basalts. The volcanic activity spanned at least two episodes of glacial advance and produced both subaerial flows and a subaqueous facies comprising pillow

lava, pillow breccia, and tuff breccia, locally intercalated with fluvial gravels and sand. Four morphological assemblages have been recognized. An early glacial assemblage, characterized by tuyalike forms, gives K-Ar dates of 0.27-3.5 Ma. These circular features are surrounded by a deeply dissected valley-filling assemblage of subaerial and minor subaqueous flows and tuff breccia that rest locally on lag gravel and till. Subaerial flows in this assemblage give K-Ar dates of 0.15-0.56 Ma. Whitehorse Bluffs, a volcanic center composed of crudely laminated tuff cut by high-level dikes, may be a source of some of these valley-filling flows. A late interglacial assemblage is composed of subaerial pyroclastic material, transitional deposits, and deposits that are clearly subaqueous. Volcanic activity in the area culminated with the formation of pyroclastic cones, blocky lava flows, and pit craters that postdate the last Cordilleran glaciation.

Littlejohn, A.L. and Greenwood, H.J., 1974. Lherzolite nodules in basalts from British Columbia, Canada; Canadian Journal of Earth Sciences, v. 11, no. 9, p. 1288-1308.

Modified abstract: Lherzolite nodules in basaltic rocks from three localities in British Columbia include metamorphic tectonites and crystal cumulates. Chemical analyses show that trace element concentrations and distribution coefficients differ from suite to suite. Distribution of iron and magnesium between coexisting phases is regular and characteristic of each suite. Distribution of iron and magnesium between spinel and olivine indicates temperatures of last equilibration of approximately 840 °C for the cumulate nodules from Nicola Lake, 1085 °C for the tectonite nodules from Jacques Lake, and in excess of 1600 °C for the tectonite nodules from Castle Rock.

Neuffer, D. P., Schultz, R.A., and Watters, R.J., 2006. Mechanisms of slope failure on Pyramid Mountain, a subglacial volcano in Wells Gray Provincial Park, British Columbia; Canadian Journal of Earth Sciences, v. 43, no. 2, p. 147-155.

Modified abstract: Pyramid Mountain is a subglacial volcano in Wells Gray Provincial Park in east-central British Columbia. Landslides deform the north and east flanks of the volcano. Field strength testing and rock mass classification designate the hyaloclastite breccia in which the landslides originated as a weak, massive rock mass: uniaxial compressive strengths (UCS) range from 24 to 35 MPa, and geologic strength index (GSI) and rock mass rating (RMR) values are 60-70. The shear strength of fracture surfaces in the hyaloclastite breccia, as measured by laboratory direct shear tests, can be characterized by a friction angle phi of 18° and cohesion c of 0.11-0.66 MPa. Limit-equilibrium slope stability analyses show that the landslides were probably triggered by the rapid drawdown of a surrounding englacial lake with no seismic ground acceleration required. Slope measurements and slope stability modeling indicate that Pyramid Mountain was asymmetric prior to failure: the north and east flanks had slope angles of 35-40°, and the south and west flanks had slope angles of 21-33°. Slope asymmetry may result from closer ice confinement on up-gradient (north and east) flanks due to higher ice flux in this direction relative to down-gradient (south and west) flanks. At the time of failure, the volcanic edifice was at least partially lithified, with cohesive strengths of 0.19-0.52 MPa. Failures of lithified subglacial and subaqueous volcanic edifices may be triggered by rapid drawdown of surrounding water without seismic loading.

Reports, Government Publications, and Theses

Bailey, D.G., 1990. Geology of the Central Quesnel Belt, British Columbia (Parts of NTS 93A, 93B, 93G and 93H); British Columbia Ministry of Energy, Mines, and Petroleum Resources, Open File 1990-31, 13 p.

Summary: The Central Quesnel belt, centred about the town of Likely in south-central British Columbia, comprises that part of Quesnellia Terrane extending from 52° 15’ north to about 53° 10’ north. The accompanying 1:1 000 000-scale geological map mainly covers the volcanic stratigraphy of the Central Quesnel belt and is compiled from the work by Bailey (1976,1988a, 1988b, 1989a, 1989b), Panteleyev (1987, 1988) and Panteleyev and Hancock (1989). These notes and the accompanying geological map are preliminary to a more comprehensive publication by Panteleyev (in preparation) which will include a description, not only of the volcanic component of the Central Quesnel belt, but also of the eastern sedimentary facies.

Bishop, S.T., 1985. The petrology of the Flourmill volcanic centre in the Clearwater-Wells Gray area, east-central British Columbia. Canada; B.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 49 p.

Abstract: The Flourmill Cones represents one of the most recent components of the late Cenozoic volcanic succession in the Clearwater-Wells Gray area of east-central British Columbia. The pristine morphology of the pyroclastic cones, the unaltered basalt flows, and the lack of any surficial deposits suggest that the Flourmills center postdates the last Cordilleran glaciation. Field examination of the center indicates that separate lava flows issued from each of the three cones. Petrographic, mineralogical, and chemical determinations of the three samples reveal identical mineralogy and similar mineral compositions. The flows of this center are composed of porphyritic alkali olivine basalt. Olivine phenocrysts appear to be in greater abundance in hand specimen, but modal analysis reveals an equal, or slightly greater, percentage of the Ti rich clinopyroxene phenocrysts. Groundmass phases have compositions similar to their phenocryst counterparts. Many of the clinopyroxene phenocrysts exhibit strong chemical zonation and partial resorption textures which reflect changes in pressure, temperature and magma composition. Although the lavas issued from different cones, they share the same magmatic origin. Progressive magmatic extrusion possibly altered the near surface conduit system to produce the three separate cones. The partial melting of a mantle pyrolite is a possible source for the lavas of the Flourmill center.

Campbell, R.B., 1978. Geological map of the Quesnel Lake map-area, British Columbia; Geological Survey of Canada, Open File 574, scale 1:125 000.

Summary: This map depicts the geology of the Quesnel Lake region, including several Pleistocene to Holocene centres in the Quesnel Cones Group, which have not been mapped or studied in detail.

Getsinger, J.S., 1982. Metamorphism and structure of Three Ladies Mountain area, Cariboo Mountains, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 82-1A, p. 317-320.

Summary: This is a detailed summary of metamorphism and structures of the Three Ladies Mountain area, and also contains a short description of Recent volcanic rocks of the Grain Creek area.

Getsinger, J.S., 1985. Geology of the Three Ladies Mountain/Mount Stevenson area, Quesnel Highland, British Columbia; Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 166 p.

Modified abstract: In late Proterozoic to early Paleozoic time, continent-derived clastic sediment and minor carbonate of the Snowshoe group were deposited in a continental slope to shelf environment, and shallow marine clastics and carbonates of the Cariboo Group were deposited nearer to the shore of North America. The Snowshoe Group is divided into a lower sequence of micaceous quartzite, pelite, and minor amphibolite, all interlayered with quartz diorite sheets; and an upper sequence of micaceous quartzite, pelite, and carbonate with minor calc-silicate and amphibolitic rocks. Metamorphic events are dated and described in detail. A brief description of lava flows and volcaniclastic rocks of the Grain Creek Centre, part of the Quesnel Cones Group is included.

Hickson, C.J., 1987. Quaternary volcanism in the Wells Gray-Clearwater area, east central British Columbia; Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 357 p.

Abstract: Basaltic volcanism in the form of small-volume, subaerial and subaqueous eruptions have occurred in the Wells Gray – Clearwater area of east central British Columbia. These eruptions have been dated by the K-Ar method and by relationships to dated glaciations. The oldest known eruption may be as old as 3.2 Ma but is more likely 2 Ma or less. The youngest eruptions are less than 7560±110 radiocarbon years. The most extensive basalts are valley-filling and plateau-capping flows of the Clearwater unit, which are Pleistocene in age and greater than 25 km^3 in volume. The deposition of flows of the Clearwater unit has overlapped at least three periods of glaciation. The interaction of glacial ice and basaltic magma has been recorded in the form of tuyas, ice ponded valley deposits and subglacial mounds (SUGM). In a few places glacial till has been preserved beneath basalt flows. Flows of Wells Gray-Clearwater suite appear to have erupted from vents that are both spatially and temporally separated. The individual eruptions were of low volume (<1km^3) and chemically distinct from one another. Major element composition is variable but the lavas are predominantly alkalic. Olivine is the predominant phenocryst phase. Plagioclase and augitic clinopyroxene rarely occur as phenocrysts, but both minerals are ubiquitous in the groundmass. Orthopyroxene was not seen in any of the samples. Flows appear to have erupted with minimal crystal fractionation or crustal contamination. The range of compositions seen in the suite is best explained by a process of partial melting and the progressive depletion of the mantle source by earlier melts. Progressive depletion of the mantle source was coupled with enrichment of parts of the mantle in K as well as some lithophile and siderophile elements. Increasing alkali content may have triggered the highly enriched eruptions of Holocene age that, despite very low degrees of partial melting, were capable of reaching the surface. Overprinting the effects of partial melting are inherited heterogeneities in the source zone of the magmas. Based on whole-rock chemistry the magma source appears to be a highly depleted region similar to that which produces the most depleted mid-ocean ridge basalts (MORB). The zone is, however, capable of producing large volume (~15%) partial melts and has not been isotopically depleted to the same extent as MORB source regions. Isotope analyses of $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and whole-rock Pb indicate that the magmas may be derived from a remnant of subducted oceanic lithosphere which has been variously depleted by the prior generation of basaltic melts. Isotopic enrichment above the level seen in MORB's is due in part to crustal contamination. The isotopic results are very different from those obtained from samples erupted through thin, allochthonous crust in the Intermontane Belt and may be explained in part by generation of the magmas in oceanic material which was subducted when allochthonous crust lay against the parautochthonous rocks underlying the Wells Gray-Clearwater area. The alkali olivine basalts of the Wells Gray-Clearwater area have erupted onto a tectonically active surface. A peneplain (erosion surface), formed in Eocene-Miocene time has been uplifted since the Miocene and uplift may be continuing. This uplift is in response to an elevated geothermal gradient which may be due to crustal extension. This crustal extension may be similar to that which occurred in the Eocene. The elevated geothermal gradient and reduced pressures attendant with recent uplift and erosion may have initiated basaltic volcanism in the region, rather than a fixed mantle hot spot as proposed in earlier work.

Metcalfe, P., 1987. Petrogenesis of Quaternary alkaline lavas in Wells Gray Provincial Park, British Columbia and constraints on the petrology of the subcordilleran mantle; Ph.D. thesis, University of Alberta, Edmonton, Alberta, 395 p.

Modified abstract: Basaltic volcanism in the area of Wells Gray Provincial Park, east-central British Columbia, represents some of the youngest volcanic material in the Canadian Cordillera. Basalts were erupted from eleven of the centres in the area over a period of time from 0.3 Ma to as little as 300 B.P.. The centres are pre-, syn- and postglacial, are usually polygenetic and are, with one exception, of central type. The maximum volume of lava erupted from any centre is 0.3km^3, suggesting that the volcanoes separated by greater than 10 km have discrete source regions.

Lava erupted from these later centres are mainly alkaline and olivine-clinopyroxene phyric and contain olivine and clinopyroxene xenocrysts. One centre has erupted lavas of transitional tholeiitic composition which are olivine-plagioclase phyric. The chemical, mineralogical and isotopic heterogeneity of the Wells Gray alkaline lavas is interpreted as being representative of heterogeneity in the subcordilleran mantle. The discovery of volatile-rich phases indicates that at least one metasomatic event has enriched the source regions in incompatible elements and has probably resulted in the formation of an amphibole source phase. This enrichment is a necessary precursor to the generation of lavas with high concentrations of these elements, from small, discrete source volumes in the subcordilleran mantle.

Panteleyev, A., Bailey, D.G., Bloodgood, M.A., and Hancock, K.A., 1996. Geology and mineral deposits of the Quesnel River – Horsefly map area, central Quesnel trough, British Columbia (NTS map sheets 93A/5, 6, 7, 11, 12, 13; 93B/9, 16; 93G/1; 93H/4); British Columbia Geological Survey, Bulletin 97, 156 p.
Summary: This is a detailed summary of geological work in the Quesnel River – Horsefly area. It includes several volcanic cones mapped as Miocene or younger, whose degree of dissection suggests they are Pleistocene to Holocene (this has been confirmed by later field observations and a single Ar-Ar date [Kelman, unpublished data]).

Schiarriza, P. and Boulton, A., 2006. Geology and mineral occurrences of the Quesnel Terrane, Canim Lake area (NTS 092P/15), south-central British Columbia; British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 2006-1, p. 163-184.
Summary: This paper presents preliminary results from the first year of bedrock mapping for the Takomkane Project. Most of the bedrock underlying the area is pre-Pleistocene in age, however, the mapping included flat-lying basalt flows that are outliers of the Clearwater-Quesnel volcanic province, some of which are Pleistocene or younger.

Sun, M., 1985. Sr isotopic study of ultramafic nodules from Neogene alkaline lavas of British Columbia, Canada, and Josephine Peridotite, southwestern Oregon, U.S.A.; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 133 p.
Summary: This thesis provides a detailed analysis of ultramafic nodules from the Josephine Peridotite in Oregon, and a number of alkaline lavas of probable Neogene age from British Columbia. The Canadian samples include nodules from Jacques Lake, in the Quesnel cones portion of the Clearwater-Quesnel volcanic province. Because very little is known about the Quesnel cones (including their ages), this thesis is included here as one of the few publications that discusses them in any capacity, even though the focus of the thesis is on mantle nodules.

Conference Proceedings, Abstracts, and Symposium Volumes

Fiesinger, D. W. and Nicholls, J., 1977. Petrography and petrology of Quaternary volcanic rocks, Quesnel Lake region, East-central British Columbia; *in* Symposium on volcanic regimes in Canada, (ed.) W.R.A. Baragar, L.C. Coleman, and J.M. Hall; Geological Association of Canada, Special Paper, v. 16, p. 25-38.
Abstract: The Pliocene to Recent volcanic rocks in the Quesnel Lake region of east-central British Columbia occur as scattered flows and cinder cones. Although these rocks have chemical characteristics of both the alkali olivine and tholeiitic basalt suites, the lack of a reaction relationship between olivine and lime-poor pyroxene suggests that these rocks belong to the

alkali olivine basalt suite. Xenoliths of lherzolite and gabbro are found in the nephelinite and basanitoid lavas of this region. The former xenoliths have olivine compositions indicative of a high pressure source, presumably in the mantle. The latter xenoliths are out of equilibrium with the host lavas. The chemical variation between the two samples from one volcanic centre can be explained by low pressure fractionation. No sequential fractionation process at either high or low pressures appears to account for the chemical variation in the remaining lavas. These lavas, however, could have been produced by five to twenty percent partial melting of pyrolite.

Anahim Volcanic Belt

Scientific Books and Articles

Balfour, N. J., Cassidy, J., and Dosso, S. 2008. Mapping faults and studying volcanoes; applications of double-difference relocations in British Columbia; Seismological Research Letters, v. 79, no. 2, p. 294-295.

Abstract: This paper applies double-difference earthquake relocation techniques to investigate a number of sources of seismicity in British Columbia, the most seismically active region of Canada. Southwest British Columbia is a complex region of deformation located above a bend in the subducting Juan de Fuca plate. The region experiences all forms of seismicity associated with subduction zones: megathrust earthquakes at the subduction interface (up to M ~9), large intra-slab earthquakes (up to M ~7), and events from faults in the overlying crust (up to M ~7.3). Each of these types of earthquakes poses significant hazard to major population centres but particularly the crustal events due to their frequency and proximity to the surface and urban areas. By investigating seismicity patterns and the state of stress, we seek a better understanding of the forces driving earthquake activity, the locations of active structures, and the resulting seismic hazard. We present evidence for new active structures in the region using double difference earthquake relocation. Preliminary results show lineations in areas of clustered seismicity and have significantly reduced uncertainties over routine catalogue locations. The lineations that we identify appear to be 'hidden' structures that do not extend to the surface. British Columbia also has a number of volcanic belts, including the Anahim hot spot track, where recent swarms of earthquakes have raised questions regarding renewed volcanic activity. Swarm activity was first detected on October 9, 2007, in the vicinity of the Anahim Volcanic Belt, and may represent the reawakening of this seemingly inactive region. Double-difference relocation is applied to microseismic events to investigate how seismicity progresses with time during the swarm. The importance of station geometry in constraining earthquake depths in volcanic regions is also discussed, as this is critical information for monitoring volcanic activity and assessing associated hazards.

Bevier, M.L., 1981. The Rainbow Range, British Columbia: A Miocene peralkaline shield volcano; Journal of Volcanology and Geothermal Research, v. 11, no. 2-4, p. 225-251.

Abstract: The Rainbow Range is a Late Miocene shield volcano (30 km diameter, 370 km^3) whose stratiform flanks surround a complex central zone. Over a 2-m.y. interval, extrusion of low viscosity, silicic peralkaline lavas and minor basaltic lavas built up the gently sloping (5–8°) flanks, forming a shield volcano rather than a composite cone. Comenditic trachytes are the lowest flows exposed on the north flank of the volcano. Thin mugearite flows rest unconformably on the comenditic trachytes. Comendites unconformably overlie the mugearites and account for at least 75% of the volume of flows within the flank zone. These lavas are distinguished from the comenditic trachytes by lower Al_2O_3 (13%), higher total iron as Fe_2O_3, (7%), and extremely depleted Sr (1–10 ppm) and Ba (10–100 ppm). Strontium isotopic studies combined with petrologic data suggest that Rainbow Range lavas originated from alkali basalt magma trapped in an intracrustal magma chamber and tapped at several intervals after it underwent crystal fractionation. A best-fit mathematical model for the origin of the suite involves step-wise derivation of the lavas in the order hawaiite → mugearite → comenditic trachyte → comendite, with the major phases precipitating in the order: olivine, clinopyroxene, plagioclase, iron-titanium oxides, and alkali feldspar.

Bevier, M.L., 1989. A lead and strontium isotopic study of the Anahim Volcanic Belt, British Columbia: Additional evidence for widespread suboceanic mantle beneath western North America; Geological Society of America Bulletin, v. 101, no. 7, p. 973-981.

Abstract: Mantle-derived alkali basalts and their peralkaline differentiates of the late Cenozoic Anahim volcanic belt occur in a 500-km-long, east-west-trending belt that cuts across the predominantly north-northwest structural grain of the accreted terranes in southern British Columbia. Pb and Sr isotopic ratios of these rocks indicate that heterogeneous, suboceanic depleted mantle is present in their source region beneath Alexander, Stikinia, and Kootenay terranes. This widespread suboceanic mantle source is characterized $^{206}Pb/^{204}Pb$ = 18.62-19.18, $^{207}Pb/^{204}Pb$ = 15.52-15.63, $^{208}Pb/^{204}Pb$ = 38.15-38.68, and $^{87}Sr/^{86}Sr$ = .7026-.7033. These values are similar to those of the source for northeast Pacific Ocean seamounts; that is, the Anahim source is not as depleted as the MORB-source in the northeast Pacific. No evidence exists for the presence of radiogenic, subcontinental mantle in the zone of melting beneath the Anahim belt. Locally, very radiogenic initial isotopic ratios from Bella Bella and King Island centers on the coast, and the Wells Gray-Clearwater centers on the far eastern end of the Anahim belt, reflect contamination from a radiogenic, Precambrian(?) crustal component derived from Alexander and Kootenay terranes, respectively. The mantle source for Anahim belt volcanic rocks appears isotopically continuous with the source for alkali basalts in the Basin and Range of the western United States and distinct from the subcontinental mantle source proposed for some Snake River Plain and Columbia River Basalt Group lavas.

Bevier, M.L., 1990. Rainbow Range; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 131-132.

Summary: The Late Miocene Rainbow Range, in British Columbia’s Anahim Volcanic Belt, is summarized briefly; this summary is relevant to understanding the Pleistocene to Recent history of the Anahim Volcanic Belt.

Bevier, M.L., Armstrong, R.L., and Souther, J.G., 1979. Miocene peralkaline volcanism in West-central British Columbia; its temporal and plate-tectonics setting; Geology, v. 7, no. 8, p. 389-392.

Abstract: The 600-km-long Anahim volcanic belt of upper Miocene-Quaternary alkalic and peralkalic volcanic centers trends east-west along approximately lat 52°N in British Columbia, in contrast to the Miocene Pemberton volcanic belt of calc-alkalic centers and the Pliocene-Quaternary Garibaldi volcanic belt of calc-alkalic centers, which follow the northwest-trending continental margin. Anahim belt rock types range from alkali basalt and nephelinite, found as small cinder cones and flows, to oversaturated (and undersaturated) peralkalic varieties found in evolved central volcanoes and in their erosion-exposed roots. In contrast to the usual subduction-related calc-alkaline volcanism in the Pemberton and Garibaldi belts, volcanic activity in the Anahim belt has been linked with lithospheric fracturing above the northern edge of the subducted Juan de Fuca plate or interpreted as an edge effect of the subducted plate in the mantle. Available isotopic ages from the oldest centers in the Anahim belt become younger eastward at a rate of 2 to 3.3 cm/yr, suggesting that volcanic activity there may well be related to a mantle hot spot beneath British Columbia. Volcanic chemistry and isotopic composition do not distinguish between either a rift or a hot-spot setting.

Cassidy, J. F., Balfour, N., Hickson, C.J., Kao, H., Mazzotti, S., Rogers, G.C., Bird, A., Bentkowski, W., Al-Khoubbi, I., Esteban, L., White, R., Caplan-Auerbach, J., and Kelman, M.C., 2008. The upper Baezaeko River, British Columbia, earthquake sequence; unusual seismic activity in the Anahim Volcanic Belt; Seismological Research Letters, v. 79, no. 2, p. 334.

Abstract: On October 9, 2007, an unusual sequence of earthquakes began near the upper Baezaeko River in central British Columbia. Within 24 hours, eight earthquakes of magnitude 2–2.7 occurred in a region where no earthquakes had previously been recorded in more than 40 years of monitoring. This cluster of events is about 30 km to the west of the Nazko cone – the most recent (circa 7200 years) volcanic centre in the Anahim Volcanic Belt. Within three weeks, more than 1000 microearthquakes occurred at depths of 25-35 km, most within a radius of 5 km, and with magnitudes of 1 to 2. Through November the rate of activity decreased significantly. The clear P- and S-wave arrivals indicated that these are “normal” earthquakes, and a moment tensor solution for the largest event suggests normal faulting. The calculated “b-value” of 2 is anomalous for crustal earthquakes, but consistent with volcanic-related events. Analysis of receiver functions indicates a Moho at 35-40 km, with a lower-crustal low-velocity zone (LVZ). Precise relocation of the seismicity using double-difference methods suggests a horizontal migration at the rate of about 0.2 km/day, and places most of the events within this LVZ. Crustal strength profiles suggest that brittle failure should not occur at this depth under standard tectonic deformation. Neither harmonic tremor, or long-period events were recorded as a part of this sequence; however, some “spasmodic bursts” (continuous seismic signals consisting of numerous high-frequency events) were co-located with the earthquake hypocentres. This sequence is similar to the deep earthquake sequence beneath Lake Tahoe in 2003-2004. As with that sequence, we interpret the Upper Baezaeko River sequence as an injection of magma in the lower crust beneath the Anahim Volcanic Belt. The magma fractures rock, producing mainly high-frequency volcanic-tectonic (VT) earthquakes and some “spasmodic bursts” and explains the nature and depth of this unusual earthquake sequence.

Cassidy, J.F., Balfour, N., Hickson, C.J., Kao, H., White, R., Caplan-Auerbach, J., Mazzotti, S., Rogers, G.C., Al-Khoubbi, I., Bird, A.L., Esteban, L., Kelman, M.C., Hutchinson, J., and McCormack, D., 2011. The 2007 Nazko, British Columbia, earthquake sequence: injection of magma deep in the crust beneath the Anahim Volcanic Belt; Bulletin of the Seismological Society of America, v. 101, no. 4, p. 1732-1741.

Abstract: On 9 October 2007, an unusual sequence of earthquakes began in central British Columbia about 20 km west of the Nazko cone, the most recent (circa 7200 yr) volcanic center in the Anahim volcanic belt. Within 25 hr, eight earthquakes of magnitude 2.3–2.9 occurred in a region where no earthquakes had previously been recorded. During the next three weeks, more than 800 microearthquakes were located (and many more detected), most at a depth of 25–31 km and within a radius of about 5 km. After about two months, almost all activity ceased. The clear P- and S-wave arrivals indicated that these were high-frequency (volcanic-tectonic) earthquakes and the b value of 1.9 that we calculated is anomalous for crustal earthquakes but consistent with volcanic-related events. Analysis of receiver functions at a station immediately above the seismicity indicated a Moho near 30 km depth. Precise relocation of the seismicity using a double-difference method suggested a horizontal migration at the rate of about 0.5 km/d, with almost all events within the lowermost crust. Neither harmonic tremor nor long-period events were observed; however, some spasmodic bursts were recorded and determined to be colocated with the earthquake hypocenters. These observations are all very similar to a deep earthquake sequence recorded beneath Lake Tahoe, California, in 2003–2004. Based on these remarkable similarities, we interpret the Nazko sequence as an indication of an injection of magma into the lower crust beneath the Anahim volcanic belt. This magma injection fractures

rock, producing high-frequency, volcanic-tectonic earthquakes and spasmodic bursts.

Charland, A., 1990. Itcha Range; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 134-135.

Summary: The Itcha Range, youngest of three overlapping felsic shield volcanoes in British Columbia's Anahim Volcanic Belt, is summarized briefly.

Charland, A., Francis, D., and Ludden, J., 1993. Stratigraphy and geochemistry of the Itcha volcanic complex, central British Columbia; Canadian Journal of Earth Sciences, v. 30, no. 1, p. 132-144.

Abstract: The Itcha Volcanic Complex is the youngest and easternmost felsic shield volcano of the Anahim Volcanic Belt of central British Columbia. The main body of the shield erupted over an area of ~300 km^2 forming Itcha Mountain and Mount Downton. Volcanism associated with the Itcha Shield extended 20 km south to the Satah Mountain area, where lavas erupted along a north-northwest – south-southeast fault system and covered an additional area of 250 km^2. The Itcha Volcanic Complex is characterized by a bimodal population of volcanic rocks, which are dominated by felsic lavas. There were two stages of volcanism: (*i*) an early felsic shield-building stage dominated by felsic lavas ranging in composition from phonolite to minor quartz-normative trachytes, which erupted as flows, domes, and pyroclastic deposits to form a low-angled shield; and (*ii*) a late mafic capping stage, which comprises a thin veneer of hawaiite and more primitive mafic lavas ranging in composition from alkali olivine basalt to basanite. The late mafic capping stage lavas erupted from satellite cinder cones and fissures concentrated on the eastern side of the shield. The hawaiites that dominate the late mafic capping stage cannot have been derived from the more primitive basalts with which they are associated by low-pressure crystal fractionation but may instead have originated from the fractionation of a clinopyroxene-dominated assemblage at high pressures. The presence of mafic xenocrysts in a megacrystic trachyte unit, whose eruption terminated the felsic shield-building stage, and anorthoclase xenocrysts in the most evolved alkali olivine basalts of the mafic capping stage indicate that the mafic and the felsic magmas interacted prior to eruption. An overlap in $^{87}Sr/^{86}Sr$ ratios and a similarity in the high-field-strength element ratios of the felsic and the mafic lavas suggest that they are genetically related. Elevated ratios of large-ion lithophile elements to high-field-strength elements (e.g., Rb/Zr) in the trachytes, however, indicates that the felsic magmas were not derived by closed-system fractional crystallization from the mafic magmas and may instead suggest the assimilation of a crustal component.

Charland, A., Francis, D., and Ludden, J., 1995. The relationship between the hawaiites and basalts of the Itcha volcanic complex, central British Columbia; Contributions to Mineralogy and Petrology, v. 121, no. 3, p. 289-302.

Abstract: Volumetrically subordinate alkaline mafic lava flows form a late capping stage over the earlier felsic lavas that form the shield of the Itcha Volcanic Complex (IVC), of the Anahim Volcanic Belt (AVB) in central British Columbia (B.C.). The mafic capping stage of the IVC is dominated by hawaiites which are the earliest of the mafic lavas, and are succeeded by alkali olivine basalts (AOB) and then by basanites. The alkali olivine basalts can be subdivided into high-, intermediate- and low-MgO AOB groups, all of which share similar HFSE ratios (e.g. Nb/Zr) with the hawaiites. High Al contents and Sr/Zr ratios indicate that hawaiites and Fe-rich evolved AOB were derived from primitive AOB parental magmas by crystal fractionation of a wehrlitic assemblage at pressures on the order of 8 to 10 kbar. High Si and low Fe contents indicate that the majority of the evolved AOB lavas, however, do not represent an intermediate stage in the liquid line of descent to hawaiites, but were most likely produced by gabbroic fractionation from primitive AOB magmas at relatively low pressures. The parental magmas of the majority of these lavas were distinct from those of the observed high-MgO basalts, having higher HFSE contents and being more Si-under-saturated. The high Al, high Sr/Zr signature of high-pressure fractionation of a clinopyroxene-dominated assemblage in the IVC is shared by hawaiites of other alkaline volcanic suites of the Canadian Cordillera, such as the Edziza Volcanic Complex in northern B.C. and appears to be a feature of hawaiites in many localities, including Hawaii and Iceland. Viscosities calculated for both high- and low-pressure crystal fractionation models suggest that aphyric hawaiites are residual liquids escaped from a wehrlitic crystalline network, at elevated pressures, possibly at the base of the crust.

Dolmage, V., 1924. Post-Pleistocene volcanics of the British Columbia coast; Journal of Geology, v. 32, no. 1, p. 36-48.

Modified abstract: In 1921 and 1922 the writer discovered ten separate post-Pleistocene extrusions on a group of coast islands in the vicinity of Milbanke Sound, about 340 miles north of Vancouver. Both tuffs and lavas are described in detail. The post-glacial age of the tuffs is shown by the fact that they rest on glaciated surfaces and on deposits of till and contain in their basal members many large glacial boulders which rest on the underlying granodiorite. (Almost nothing more recent has been published about these small volcanic centres.)

Ellis, R.M., Dragert, H., and Ozard, J.M., 1976. Seismic activity in the McNaughton Lake area, Canada; Engineering Geology, v. 10, no. 2-4, p. 227-238.

Abstract: Filling of McNaughton Lake, with a capacity at full load of 25 x $10^9 m^3$ and maximum depth 191 m, was initiated on March 29, 1973. An earthquake swarm of 747 events (ML > 0) with largest event ML = 4.7 occurred within 17 km of the reservoir just prior to loading. Subsequent to this, three swarms of 194, 292 and 22 events with maximum ML = 4.1 occurred in the same region; however, no earthquakes have occurred between the reservoir and the swarm area. The level of regional seismic activity is similar to that observed prior to loading. The distribution of this activity, excluding swarm events, exhibits a spatial pattern similar to that recorded earlier by regional seismic stations, except that several events appear to be associated with the fault underlying the Rocky Mountain Trench in which the lake is formed. During a loading-unloading cycle in which the maximum water depth varied from 98 m to 171 m to 131 m, the change ofvp was less than 2%. This indicates that no significant change in dilatancy or degree of water saturation occurred in the upper crustal layer during this cycle.

Rogers, G. C., 1981. McNaughton Lake seismicity; more evidence for an Anahim hotspot? Canadian Journal of Earth Sciences, v. 18, no. 4, p. 826-828.

Abstract: The only notable concentration of earthquakes in the Canadian Cordillera away from the coastal zone occurs in the McNaughton Lake region of British Columbia, off the eastern end of the Anahim volcanic belt. The association of these two phenomena strengthens the hypothesis that the origin of the Anahim belt is due to North America overriding a mantle hotspot and provides a possible explanation for the concentration and character of the seismicity.

Rogers, G. C. and Souther, J.G., 1983. Hotspots trace plate movements; Geos [Ottawa], v. 12, no. 2, p. 10-13.

Summary: This short nontechnical paper discusses the hypothesis that a mantle plume is responsible for the volcanism in central British Columbia’s Anahim Volcanic Belt.

Souther, J.G., 1990. Ilgachuz Range; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 132-134.

Summary: The 4-6 million year-old Ilgachuz Range, an older portion of British Columbia’s Anahim Volcanic Belt, is summarized briefly.

Souther, J.G., 1990. Milbanke Sound cones; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 130-131.
Summary: The Milbanke Sound cones, at the west end of British Columbia's Anahim Volcanic Belt, are summarized briefly.

Souther, J.G., 1990. Nazko; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 135-136.
Summary: Nazko cone, the youngest known eruptive centre in British Columbia's Anahim Volcanic Belt, is summarized briefly.

Souther, J.G., Clague, J.J., and Mathews, R.W., 1987. Nazko cone, a Quaternary volcano in the eastern Anahim Volcanic Belt; Canadian Journal of Earth Sciences, v. 24, p. 2477-2485.
Abstract: Nazko cone, located in central British Columbia at the eastern end of the Anahim Volcanic Belt, is the product of at least three episodes of Quaternary volcanic activity. An eroded Pleistocene subaerial flow at the base of the pile is overlain by a subglacial mound of hyaloclastite that is, in turn, partly covered by a younger composite pyroclastic cone and associated lava flows. A whole-rock K–Ar date of 0.34 ± 0.03 Ma on the oldest flow is consistent with a hotspot model for the Anahim Belt and implies absolute late Neogene motion of 2.6 cm/year for North America. The hyaloclastite mound was erupted beneath the Cordilleran Ice Sheet during the Late Pleistocene, perhaps during the Fraser Glaciation (25 000 – 10 000 years BP). Radiocarbon dates from peat above and below Nazko tephra in a bog near the cone suggest that the volcano last erupted about 7200 years BP.Nazko basalt has 10–15% normative nepheline and is classified as basanite. This is significantly more undersaturated than basalts farther west in the Anahim Belt and may indicate an eastward shift toward a deeper or less depleted mantle source.

Stout, M. Z. and Nicholls, J., 1983. Origin of the hawaiites from the Itcha Mountain Range, British Columbia; Canadian Mineralogist, v. 21, Part 3, p. 575-581.
Abstract: Hawaiites are intermediate-to-mafic volcanic rocks, dominated by plagioclase that have been erupted in continental and oceanic settings. Those from the Northern Itcha Mountain Range, British Columbia, are associated in space and time with nearly aphyric alkali olivine basalts and basanites. The hawaiites are strongly porphyritic with plagioclase phenocrysts; they usually carry plagioclase megacrysts that have a calcic overgrowth on a relatively Na-rich core. They also contain sparse, partly digested granitic xenoliths. In contrast, the type hawaiites are typically aphyric and do not carry xenoliths of any kind. The presence of granitic xenoliths in the Itcha Mountain hawaiites and their high concentrations of phenocrysts and megacrysts require a period of crystallization and probable reaction with the country rocks prior to eruption, likely in the crust. Therefore, the hypotheses proposed in the literature to explain the origin of hawaiites, either by primary melting in the mantle or solely by fractionation of basalt magma, are likely invalid for the Itcha Mountain Range rocks although they may account for the origin of the oceanic varieties. As a hypothesis for the origin of the Itcha Mountain Range hawaiite, assimilation of granitic rocks combined with olivine and augite fractionation from an alkali basalt magma meet the requirements of mass and energy-balance calculations.

Reports, Government Publications, and Theses

Baer, A.J., 1973. Bella-Coola – Laredo Sound map areas, British Columbia; Geological Survey of Canada, Memoir 372, 122 p.

Summary: Bella Coola and Laredo Sound map areas span the Coast Mountains of British Columbia between latitudes 52° and 53°N. This paper summarizes the results of geologic mapping of the area. The geology has been studied on a reconnaissance basis and forms part of a general geological investigation of the Coast Mountains. Most of the region is covered in pre-Pleistocene rocks. Crystalline and metamorphic basement rocks are overlain by metasediments and volcanic rocks. Volcanic and metavolcanic rocks are dominantly of intermediate composition, and range in age from pre-Middle Jurassic to Pleistocene. On King Island, rhyolite and associated rocks grade vertically downwards into granite of Late Tertiary age. There are several occurrences of volcanic rocks that may be Pleistocene, and several occurrences of postglacial (Holocene) volcanic rocks; later studies have grouped these rocks into the Milbanke Sound volcanics.

Charland, A., 1994. Stratigraphy, geochemistry and petrogenesis of the Itcha volcanic complex, central British Columbia; Ph.D. thesis, McGill University, Montréal, Québec, 448 p.

Abstract: The Itcha Volcanic Complex (IVC) is the easternmost shield of a series of bimodal central volcanic complexes which comprise the Anahim Volcanic Belt (AVB) in central British Columbia. The IVC lavas are distinctly bimodal, with a compositional gap between 52 and 58 wt% SiO_2, comprising late basaltic and hawaiitic lavas and early felsic lavas of Si-undersaturated to Si-oversaturated character. The hawaiite lavas dominate the late capping stage of the IVC. Their high Sr/Zr ratios indicate that they were derived by crystal fractionation of a clinopyroxene-dominated assemblage at high pressures (~10 kbar) from parental magmas with compositions similar to the most primitive alkali olivine basalts in the IVC. The majority of later evolved basalts have low Sr/Zr ratios indicating they formed by crystal fractionation at lower pressures. The similarity of isotopic and the incompatible element ratios suggests that the felsic and mafic magmas of the IVC are co-genetic. The early basal trachytes were derived by an AFC process in crustal magma chambers and appear to have assimilated a significant (15-20%) crustal component. Later, more evolved felsic lavas exhibit a wider range of Si-saturation, which appears to require parental basaltic magmas with a range of silica saturations with less, and more selective, crustal contamination. The compositional gap between the mafic and the felsic lavas of the Itcha shield appears to be related to the difficulty of erupting crystal-rich viscous lavas of intermediate composition. Viscosity models indicate that the rise in viscosity with decreasing Mg is slower at high pressures, which would favour the eruption of lavas of more evolved composition. Late basanites have distinct Nb/Zr and isotopic signatures (low $^{87}Sr/^{86}Sr$), requiring a mantle source distinct from that of the alkali olivine basalts.

Hickson, C. J., Kelman, M. C., Chow, W., Shimamura, K., Servranckx, R., Bensimon, D., Cassidy, J., Trudel, S., and Williams-Jones, G., 2009. Nazko region volcanic hazard map; Geological Survey of Canada, Open File 5978, 1:650 000.

Summary: This is a poster summarizing potential volcanic hazards associated with the 2007 earthquake swarm near Nazko cone, British Columbia (which did not lead to eruption and ended after several months of unrest). It includes a preliminary hazard map of the Nazko cone region.

Hora, Z. D. and Hancock, K.D., 1995. Nazko cinder cone and a new perlite occurrence; Geological Fieldwork 1994, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1995-1, p. 405-407.

Summary: A detailed physical description of the Nazko cone tephra is provided, along with a brief description of commercial mining operations at the Nazko site.

Hutchinson, J., 2012. Relocation and analysis of the 2007 Nechako, B.C., seismic swarm; evidence for magmatic intrusion in the lower crust; M.Sc. thesis, Western Washington University, Bellingham, Washington, 73 p.

Abstract: On October 9, 2007, a seismic swarm, known as the Nechako swarm, began in south-central British Columbia, approximately 20 km west of the Nazko polygenetic cinder cone. After lasting for well over a month, seismic activity tapered off by November 21, 2007. This study analyzes data from several temporary broadband seismometers deployed by the Geological Survey of Canada near the epicentral locations of initial events from the swarm. Over 4400 events were observed during this period, from which 1048 absolute locations were calculated, with depths ranging from 26-35 km. All of the events recorded by the temporary seismometers were high frequency, volcano-tectonic earthquakes. A previous study by members of the Geological Survey of Canada reported a b-value (the slope of the magnitude-frequency relationship) of 1.9, indicating magmatic activity as the source for seismic unrest. Algorithmic double-difference programs HypoDD and TomoDD allowed for precise relocations of earthquake multiplets (earthquakes with similar waveforms) from the swarm, suggesting two distinct spatial and temporal pulses of seismic activity. The first pulse recorded by the temporary seismometers began on Oct. 21, migrating southeast at a rate of 0.44 km/day from 26.5-28.3 km deep, until Oct. 29. The second pulse began on Oct. 29 at a depth of 29-31 km, approximately 3 km to the southeast of the first pulse. No clear migration of events between the areas could be observed. On Nov. 2 the first region of activity resumed seismic unrest. Both regions remained active for the remainder of the swarm. Distinct waveforms and hypocenters from spasmodic bursts (rapidly occurring events with overlapping waveforms) and earthquake multiplet clusters lend further credence to the simultaneous rupturing of the two regions. The proximity of high-frequency volcano-tectonic events to the crust-mantle boundary (approximately 30 km deep); the presence of spasmodic bursts, high b-value, and two distinct regions of simultaneous seismic activity provide strong evidence that the Nechako swarm was generated by the expansion and propagation of magma in the lower crust. Inverted, nearly identical waveforms are interpreted as originating from the brittle fracturing of solidified magma plugs, driven by the force of magma injection along a dike. From the evidence provided, I have concluded that the two spatially distinct regions of activity are representative of two large sills at the base of the crust, emplaced by crustal underplating, with branching dikes. The swarm was initiated by the brittle failure and fracturing of rock in the lower crust around these regions by either buoyantly rising magma in preexisting sills/dikes, or an injection of new magma from a mantle source.

Souther, J. G., 1984. The Ilgachuz Range, a peralkaline shield volcano in central British Columbia; Geological Survey of Canada, Paper 84-1A, p. 1-10.

Abstract: The Ilgachuz Range is one of three moderately dissected, late Tertiary shield volcanoes in the east-trending Anahim Volcanic Belt of central British Columbia. It is the product of two pulses of magmatic activity: an early dome and shield-formign stage which culminated in the collapse of a central caldera, and a late-stage effusion of basalt which formed the outer part of the shield. The pile is chemically bimodal, with a pronounced SiO_2 and alkali gap separating oversaturated, peralkaline rocks of the early stage from hawaiite of the late stage. Five new K-Ar dates from the Ilgachuz confirm the progressive decrease in the age of volcanic centres eastward along the Anahim Belt, and support the concept of an easterly migrating hotspot.

Souther, J. G. and Souther, M.E.K., 1994. The Ilgachuz Range and adjacent parts of the Interior Plateau, British Columbia; Geological Survey of Canada, Bulletin 462, 75 p.

Abstract: Christensen Creek (93C/11) and Carnlick Creek (93C/14) map areas encompass the Ilgachuz Range, a highly dissected late Tertiary shield volcano that rises 1200 m above the general level of the Interior Plateau of central British Columbia. The drift-covered plateau surface adjacent to the Ilgachuz Range contains isolated exposures of Mesozoic volcanic and sedimentary rocks, early Tertiary felsic volcanic and subvolcanic rocks, and mylonitic orthogneiss of the Eocene Tatla Lake Metamorphic Core Complex. Undeformed late Tertiary volcanic rocks rest unconformably on all of the older strata. They include Chilcotin Group basalt flows and Ilgachuz Group alkaline volcanic and subvolcanic rocks which form the Ilgachuz Range shield volcano. The Ilgachuz Range is a composite volcanic shield comprising a thick lower section of highly alkaline to peralkaline felsic flows, domes, and hypabyssal intrusions, overlain by a relatively thin veneer of alkaline basalt. A small central caldera is filled with pyroclastic deposits, lacustrine beds, and ponded lava. K-Ar dates indicate that the entire volcanic edifice was built between 6 Ma and 4 Ma. The Ilgachuz Range is one of three large shield volcanoes in the central part of the east-trending Anahim Volcanic Belt. Volcanoes along this belt become progressively younger from west to east and are believed to have formed on the American continental plate as it moved westward over a mantle hotspot. The chemistry and stratigraphy of the Ilgachuz Group rocks suggest that they are the product of crustal melting and crystal fractionation, accompanied by underplating with mantle-derived basaltic magma.

Tipper, H.W., 1969. Geology, Anahim Lake, British Columbia; Geological Survey of Canada, Map 1202A, scale 1:253 440.

Summary: The map is a compilation of geologic mapping done from 1954-1957, and includes volcanics of probable Pleistocene age in the vicinity of Itcha Mountain.

Woodsworth, G.J., 1991. Neogene to Recent volcanism along the east side of Hecate Strait, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 90-10A, p. 325-335.

Abstract: Mafic volcanic rocks are preserved in several small areas on islands east of Hecate Strait; much of southeast Hecate Strait may be underlain by similar rocks. K-Ar dates show that the volcanics are 19-26 Ma in age and are contemporaneous with the main phase of Masset volcanism on Queen Charlotte Islands. Petrographic, chemical and isotopic data suggests that the rocks are nonmarine olivine basalt and andesite, are transitional to slightly alkaline in chemistry, have a mantle origin, and were erupted in a back-arc or incipient rift setting. The volcanic rocks probably formed in localized basins. Episodic extensional reactivation of older structures appears to have been the dominant structural style along the west side of the Coast Mountains from Late Oligocene to Recent time. Younger (postglacial) volcanic centres are present at Kitasu Hill, Lake Island, Lady Douglas Island, and Price Island. They are more alkaline than volcanic rocks to the north, and likely reflect a more limited amount of partial melting or a deeper mantle source.

Conference Proceedings, Abstracts, and Symposium Volumes

Cassidy, J.F., Hickson, C.J., McCormack, D., and Bolton, M., 2009. Lessons learned from the 2007 Anahim Volcanic Belt earthquake sequence: applications of "real-time science" to emergency management and response; Sixth annual Canadian Risks and Hazard Network (CHRNet) symposium, Edmonton, Alberta, p. 1.

Abstract: On October 9, 2007, an unusual sequence of earthquakes began near the community of Nazko, British Columbia. Within 24 hours, eight earthquakes of magnitude 2-3 occurred in a region where no earthquakes had previously been recorded in more than 40 years of monitoring. This cluster of earthquakes was located near the Nazko Cone in the Anahim Volcanic Belt of central British Columbia and immediately raised concerns that this could be the precursor to a volcanic eruption. There was a high-level of concern in local communities, and a very high-level of interest from the media (several of whom did "live from Nazko Cone" news broadcasts). Questions that were raised included: "What do these earthquakes mean?"; "Will there be a volcanic eruption?"; "What would be the impact in local communities?"; "When might a volcanic eruption occur?", and "What would be the warning signs?". Within a few days a Technical Advisory Group was formed to address these and other questions. The group was comprised of seismologists, geologists, volcanologists, and emergency managers from academia, federal and provincial governments. In this presentation we summarise: 1) the important role of "real-time

science" - that is obtaining the necessary data and interpreting those data for decision-making; and 2) the critical interactions between scientists and emergency managers.

Hickson, C. J., 1989. Whither the Anahim volcanic belt? American Geophysical Union, EOS Transactions, v. 70, no. 9, p. 137.

Abstract: Rocks of the Wells Gray-Clearwater (WG-CLW) volcanic suite are Quaternary in age and alkalic in chemical affinity. All have a single, augitic, pyroxene and the majority are nepheline-normative. Pleistocene flows in the region were previously correlated with the Chilcotin Group Basalts and Holocene centres were considered to be the eastern termination of the Anahim Volcanic Belt (AVB). The AVB is thought to be the result of a mantle hot spot. Besides the WG-CLW area, the belt was considered to consist of plutonic rocks on King Island (KI), and the volcanic centres; the Rainbow Range (RR), Ilgachuz (ILR) and the Itcha (IR) Ranges. Using the most recently available K-Ar dates (KI 13 Ma; RR 8.7 Ma; ILR 6.1 Ma; IR 3.5 Ma; WG-CLW 0.6 Ma), the calculated centre to centre velocities for each segment are: KI-RR 3.5 cm/yr; RR-ILR 1.3 cm/yr; ILR-IR 1.2 cm/yr; IR-WG-CLW 9.2 cm/yr. Cumulate, great circle velocities are more consistent with the predicted motion of the North American plate, but the IR-WG-CLW segment is still high. The best velocity match was obtained along a track from KI-RR-ILR-IR to a Holocene cinder cone 80 km east of the IR called Nazko Cone (NC). A further test of the track topology uses a maximum likelihood fit of the Euler pole to a given Euler pole. Several published poles were tested and none of the data fit any of the poles very well, however the best fit was obtained from the KI-NC track to the New England-Great Meteor track. It seems probable that the volcanic rocks from King Island to Nazko may be the result of a mantle hot spot but an alternative explanation is necessary for the basaltic rocks of the Wells Gray-Clearwater area.

Souther, J. G., 1986. The western Anahim Belt; root zone of a peralkaline magma system; *in* W. H. Mathews symposium; a celebration. Canadian Journal of Earth Sciences, v. 23, no. 6, p. 895-908.

Abstract: The Anahim Volcanic Belt extends easterly across central British Columbia, where it includes three large shield volcanoes and numerous small monogenetic cones and lava flows. Potassium–argon dates on the lavas suggest that the onset of volcanic activity progressed from approximately 8 Ma in the west to less than 1 Ma in the east. A western extension of the belt into the strongly uplifted and deeply dissected Coast Mountains is defined by an east-trending zone of chemically distinctive, high-level plutons, dyke swarms, and remnants of eruptive breccia that yield K–Ar dates of 10–14 Ma. The lavas and dykes include both basic (alkali basalt and hawaiite) and salic (trachyte and sodic rhyolite) suites, which have remarkably similar major-element abundances. In addition, moderately to strongly peralkaline rocks (comendite and pantellerite) constitute a major part of the volcanic piles and a lesser proportion of the dykes. Epizonal plutons show an upward zonation from hypersolvus syenite to miarolitic, alkaline to mildly peralkaline soda granite. The plutonic, hypabyssal, and eruptive rocks of the western Anahim Belt are considered to represent different levels of exposure in the root zone of an alkaline magma system that gave rise to peralkaline end members. Uplift rates, based on fission track dates, suggest that fractionation leading to mildly peralkaline soda granite took place in crustal reservoirs emplaced at depths of 2.5–4.5 km below the surface and that additional enrichment in alkalis took place at still shallower depths.

Northern Cordilleran Volcanic Province

Scientific Books and Articles

Abraham, A.-C., Francis, D., and Polvé, M., 2001. Recent alkaline basalts as probes of the lithospheric mantle roots of the northern Canadian Cordillera; Chemical Geology, v. 175, no. 3-4, p. 361-386.

Abstract: Tertiary to Recent alkaline lavas across the Northern Canadian Cordillera display chemical and isotopic characteristics that can be correlated with their position with respect to three of the five major tectonic belts that constitute the Canadian Cordillera: the Omineca Belt, the Intermontane Belt, and the Coast Belt. There is a discontinuous change in the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios in Recent alkaline basalts across the Tintina fault, a major Mesozoic to Tertiary strike-slip fault separating the Omineca Belt from North America. Important changes are also identified across both boundaries of the Intermontane Belt. Lavas erupted within the Intermontane Belt have lower $^{87}Sr/^{86}Sr$, higher $^{143}Nd/^{144}Nd$, and lower Rb concentrations compared to their equivalents in the Omineca Belt to the East, and in the Coast Belt to the West. Recent alkaline basalts in the Coast Belt, however, have distinctly lower Pb isotopic ratios and Th concentrations than Omineca Belt lavas. The changes observed in the signatures of the alkaline basalts correspond approximately to isotopically distinctive upper crustal domains defined on the basis of granitoids in the Northern Cordillera. Some lavas might have suffered small amounts of crustal contamination; however, the distinctive isotopic signatures of lavas erupted in each belt can not be explained by crustal contamination and appear to be inherited from the lithospheric mantle. The chemical and isotopic changes across the Tintina fault indicate that it is a deep feature that juxtaposes two distinct lithospheric mantles. There is spatial correspondence of isotopic discontinuities in both the Cretaceous Carmacks volcanics and the Recent alkaline basalts, suggesting that the Omineca-Intermontane Belt lithospheric mantle boundary has been conserved since the accretion of the Intermontane Belt to the North American continental margin, represented by the Omineca Belt. An eastern displacement from the tectonic boundary at the surface for the inferred mantle transition between the Intermontane Belt and the Coast Belt indicates that enriched lithosphere related to the Coast Belt basalts extends partly beneath the Intermontane Belt at latitude 60° N.

Abraham, A.-C., Francis, D., and Polvé, M., 2005. Origin of Recent alkaline lavas by lithospheric thinning beneath the northern Canadian Cordillera; *in* The Lithoprobe Slave-NORthern Cordillera Lithospheric Evolution (SNORCLE) Transect, (ed.) F.A. Cook and P. Erdmer; Canadian Journal of Earth Sciences, v. 42, no. 6, p. 1073-1095.

Abstract: Recent alkaline lavas that have erupted across the disparate terranes of the northern Canadian Cordillera provide natural probes with which to interrogate the underlying lithosphere. The lavas range between two compositional end members, olivine nephelinite (NEPH) and hypersthene-normative olivine (Hy-NORM) basalt. The chemical signature of amphibole in the incompatible element enriched NEPH end member indicates that it is derived in the lithospheric mantle. The Hy-NORM end member is characterized by lower incompatible trace element contents but is still relatively enriched relative to primitive mantle. Although the Hy-NORM end member is always more radiogenic in Pb and Sr isotopes and less radiogenic in Nd isotopes than the NEPH end member, its isotopic signature varies with tectonic belt. In particular, Hy-NORM basalts in the Omineca Belt are strikingly more radiogenic in Sr and Pb isotopes and less radiogenic in Nd isotopes than otherwise equivalent Hy-NORM basalts in the adjacent Intermontane Belt, indicating the existence of a major lithospheric boundary between the two belts. Cordilleran and other continental Hy-NORM basalts have distinctly low Ca and high Na contents compared with their equivalents in oceanic hot spots or at mid-ocean ridges. A comparison with experimental melts of mantle peridotite indicates that these characteristics reflect smaller degrees of partial melting (<10%) in the stability field of garnet in the lower lithospheric mantle beneath the northern Cordillera. Contrary to the conclusion commonly drawn from experimental results, the Cordilleran NEPH lavas may be derived from similar or shallower depths than coeval Hy-NORM basalts.

Allen, C.C., 1990. Tuya Butte; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 119-121.
Summary: The ten volcanoes of the Tuya Butte volcanic field in northwestern British Columbia are summarized briefly.

Allen, C.C., Jercinovic, M.J., and Allen, J.S.B., 1982. Subglacial volcanism in north-central British Columbia and Iceland. Journal of Geology, v. 90, p. 699-715.
Abstract: The subglacial genesis of five volcanoes in British Columbia has been confirmed by field and laboratory studies and by comparison with the stapar (table mountains) of Iceland. Two Canadian “tuyas” are flat-topped piles of hyaloclastite overlain by basalt flows. These mountains are almost identical in form to their Icelandic counterparts. Three other tuyas are large conical piles of unconsolidated lapilli, two of which overlie vitric tuff and pillow basalt layers, and may be analogous to relatively rare Icelandic subglacial scoria cones. All fives volcanoes can be accounted for by eruption into englacial meltwater lakes. The differences in gross morphology and physical composition can be accounted for by minor variation in the relative importance of magmatic versus phreatomagmatic eruption.

Aumento, F. and Souther, J.G., 1973. Fission-track Dating of Late Tertiary and Quaternary Volcanic Glass from the Mount Edziza Volcano, British Columbia; Canadian Journal of Earth Sciences, v. 10, no. 7, p. 1156-1163.
Abstract: Seventeen specimens of Pliocene to Recent volcanic glass from Mount Edziza, British Columbia, were dated by the fission-track method. Results agree well with paleomagnetic, potassium–argon, carbon-14, and stratigraphic data, offering accurate dates with closer limits of confidence than can be obtained by other methods. The age data supports the petrological evidence for three principal stages of activity, each beginning with eruption of basalt and culminating with eruption of more acid magma.

Barbeau, M., 1935. Volcanoes on the Nass; Canadian Geographic Journal, v. 10, no. 5, p. 215-225.
Summary: This is a nontechnical account of a journey up the Nass River of northwestern British Columbia, with a description of some of the young volcanic deposits there, and an account taken from Nisga’a First Nations oral history that tells of the volcanic eruption that occurred in the region several hundred years ago. It is the only known historical account of a volcanic eruption in Canada.

Blondes, M. S., Reiners, P.W., Edwards, B.R., and Biscontini, A., 2007. Dating young basalt eruptions by (U-Th)/He on xenolithic zircons; Geology, v. 35, no. 1, p. 17-20.
Abstract: Accurate ages for young (e.g., Pleistocene) volcanic eruptions are important for geomorphic, tectonic, climatic, and hazard studies. Existing techniques can be time-consuming and expensive when many ages are needed, and in the case of K/Ar and $^{40}Ar/^{39}Ar$ dating, extraneous Ar often can limit precision, especially for continental basalts erupted through old lithosphere. We present a new technique for dating young basaltic eruptions by (U-Th)/He dating of zircons (ZHe) from crustal xenoliths. Single-crystal ZHe dates generally have lower precision than typical $^{40}Ar/^{39}Ar$ dates, but can be determined relatively easily on multiple replicate grain aliquots. We dated zircons from xenoliths from four volcanic centers in western North America: Little Bear Mountain, British Columbia (157±3.5 [2.2%] ka weighted 95% confidence interval [CI],

mean square of weighted deviates [MSWD] = 1.7) and Prindle Volcano, Alaska (176±16 [8.9%] ka, MSWD = 13), in the northern Cordilleran volcanic province, and Fish Springs (273±23 [8.6%], MSWD = 43) and Oak Creek (179±8.1 [4.5%] ka, MSWD = 12), in the Big Pine Volcanic Field, California. All ZHe ages are either equivalent to or younger than previously determined K/Ar or ^{40}Ar/ ^{39}Ar ages, indicating the possibility of inherited ^{40}Ar in some of the previous measurements. Zircons from upper crustal xenoliths in the Oak Creek and Fish Springs vents show poorer reproducibility and multiple apparent age distribution peaks, consistent with either intracrystalline U-Th zonation or <99.99% He degassing (assuming ca. 100 Ma pre-entrainment ZHe ages) of some zircons during magmatic entrainment. Removal of clear outliers in the older age-distribution peaks of the upper crustal xenoliths, most of which have extremely high U compared to other zircons of the same xenolith, improve the reproducibilities of Fish Springs to 4.7% (95% CI, MSWD = 4.8) and Oak Creek to 3.4% (95% CI, MSWD = 6.2). Coupled thermal and He diffusion modeling using appropriate xenolith sizes and magma temperatures and assuming published diffusion kinetics for zircon indicate that incomplete He degassing would require entrainment times <1 h. However, the observation of extremely high U in most zircons with older ages raises the possibility that zircons with high radiation dosages may have more retentive He diffusion characteristics.

Carignan, J., Ludden, J., and Francis, D., 1994. Isotopic characteristics of mantle sources for Quaternary continental alkaline magmas in the northern Canadian Cordillera; Earth and Planetary Science Letters, v. 128, no. 3-4, p. 271-286.

Abstract: Three mantle compositions are identified as potential source end members for Quaternary to recent alkaline volcanic rocks from Fort Selkirk, Llangorse-Hirschfeld, Alligator Lake and Mt. Edziza in the northern Canadian Cordillera. These are: (1) an amphibole-rich source, characterised by unradiogenic Sr, Nd and Pb, from which the olivine nephelinite lavas formed, (2) the continental lithospheric mantle which is characterised by high ^{207}Pb/ ^{204}Pb and appears to be involved in the formation of the alkali olivine basalts of Fort Selkirk, and (3) a mantle with radiogenic Pb and unradiogenic Sr (HIMU-type) represented by lavas from Mt. Edziza. The Mt. Edziza volcano is the largest of the volcanic centres in the region, and is considered to reflect melting of sublithospheric mantle of HIMU composition below central British Columbia. Incipient melting of amphibole-veined subcontinental mantle lithosphere resulted from plume upwelling and/or transtensional pressure release and produced the small nephelinite to olivine basalt centres of the northern Cordilleran Province. The source of the nephelinite magmas is slightly more radiogenic than present-day Pacific MORB, and is best represented by the most depleted component of the Aleutian magmas. This suggests enrichment of the subcontinental lithosphere in the northern Cordillera by melts of this isotopic composition during Cretaceous subduction. The Alligator Lake complex is anomalous and characterised by the most radiogenic lavas. Despite the presence of crustal xenoliths there is no clear geochemical signature for crustal contamination and, in contrast to the other volcanic centres which were erupted through the Intermontain Belt, the lavas of this centre may have been derived from a highly radiogenic lithospheric mantle beneath the Coast Plutonic complex.

Carignan, J., Ludden, J., and Francis, D., 1996. On the Recent enrichment of subcontinental lithosphere; a detailed U-Pb study of spinel lherzolite xenoliths, Yukon, Canada; Geochimica et Cosmochimica Acta, v. 60, no. 21, p. 4241-4252.

Modified abstract: Lead strontium, and osmium isotopic data have been obtained for whole rocks and mineral separates (olivine, orthopyroxene, clinopyroxene, and spinel) for spinel lherzolite xenoliths hosted by lavas of the Quaternary Alligator Lake volcanic centre, southern Yukon. Whole-rock xenolith samples display a large variation of lead concentrations. However, their lead isotope ratios are relatively homogeneous. The ^{238}U/^{204}Pb ratios display a large variation and do not correlate with indices of fertility such as calcium or aluminum content. Mineral separates yield even larger variations in lead isotopic composition and lead and uranium concentrations. Although whole rocks and cpx for individual samples yield almost identical ^{87}Sr/^{86}Sr, the xenoliths display a large variation of strontium isotopic compositions, and lead and strontium isotope ratios

of cpx and the distribution of the data in a U---Pb isochron diagram suggest that the subcontinental lithosphere under the Yukon was affected by a recent (< ~30 Ma) enrichment in uranium, lead, and strontium. The metasomatic fluid/magma might have had an isotopic composition close to that of some sediments in the northern Pacific Ocean. When compared to K_d values reported in the literature, olivine is enriched in lead relative to coexisting cpx and, depending on the K_d values used for the calculations, is either enriched or depleted in uranium compared to cpx. Mantle cpx from the subcontinental lithosphere that has suffered metasomatism is U- and Pb-rich when compared to “unmetasomatised” cpx suggesting that cpx scavanges these elements from metasomatic fluids. Fractionation of uranium and lead between fluids and cpx is not easy to constrain, but the data for Alligator Lake suggest a possible uranium enrichment over lead in metasomatised cpx. Three whole rock samples have variable $^{187}Os/^{188}Os$. In contrast to the lead and strontium data, the $^{187}Os/^{188}Os$ and $^{187}Re/^{188}Os$ ratios are positively correlated with calcium and aluminum contents of the xenoliths. Their $^{187}Re/^{188}Os$ ratios are slightly higher than the mean chondritic values, and an age of 650 Ma is obtained when the data are regressed in a Re---Os isochron diagram. This age may date partial melting of the lherzolite and/or re-fertilization with rhenium enrichment of the mantle lithosphere. The protolithic lithosphere would have had a γOs typical of depleted MORB (ca. −1.4) at 650 Ma.

Cassidy, J.F., Rogers, G.C., and Ristau, J., 2005. Seismicity in the vicinity of the SNORCLE corridors of the northern Canadian Cordillera; Canadian Journal of Earth Sciences, v. 42., p. 1137-1148.

Abstract: The Slave – Northern Cordillera Lithospheric Evolution (SNORCLE) corridors of the northern Cordillera sample some of the most, and least, seismically active regions of Canada. The earthquake history of this region is short. Precise determination of earthquake locations and depths is not possible even today. Nonetheless, significant gains in our knowledge of the seismicity of this region have been made in recent years from studies of historic earthquakes, microseismicity studies, and advances in waveform modelling techniques combined with broadband data that allow for determination of focal mechanisms and depths for moderate earthquakes. This article summarizes our current knowledge of the seismicity and seismic hazards across the region. These detailed analyses have shown that (i) the largest historical earthquakes have occurred in regions of ongoing microseismicity; (ii) the largest earthquakes have occurred in pairs or in swarms, suggesting that stress triggering is important in this region; (iii) the active faults are concentrated in the offshore region; (iv) there is a concentration of seismicity in the Fold and Thrust belt, several hundred kilometres from the active plate margin; and (v) there is no seismicity associated with the Quaternary volcanic zone in northern British Columbia. Potentially damaging (magnitude $M \geq 5$) earthquakes can be expected every few years in the vicinity of the northern Cordillera. The $Mw = 7.9$ Denali, Alaska, earthquake (where Mw is the moment magnitude) was a good reminder that the effects of a large earthquake can be substantial, even hundreds of kilometres from the epicentre. Detailed studies of seismicity, earth structure, and tectonics, with the latter made possible in large part by the SNORCLE transect, will allow for informed decision-making for resource development and the design of safe structures and infrastructure in the northern Canadian Cordillera.

Clark, I.D., Fritz, P., and Souther, J.G., Geochemistry and isotope hydrogeology of the Mount Edziza – Mess Creek geothermal area; Canadian Journal of Earth Sciences, v. 26, no. 6, p. 1160-1171.

Abstract: The Mount Edziza volcanic complex, a Recent volcano within British Columbia's northern Intermontane Belt, and the adjacent Mess Creek valley are investigated to evaluate the origin, geothermal history, and age of associated thermal waters. Samples of thermal and cold groundwaters, runoff, and glacier ice were collected for chemical and environmental isotope ($^{18}O/^{2}H$, ^{3}H, $H^{13}CO_3^-$, $S^{18}O^{16}O_3^{2-}$) analysis.Mount Edziza thermal waters, discharging at 36 and 46 °C from extensive travertine formations at the base of the volcanic pile, originate as glacier meltwater on the summit of the complex. Their Na(Ca,Mg)–HCO_3 chemistry is a product of alteration reactions with alkali basalts under a high CO_2 partial pressure. Chemical and isotopic

geothermometers suggest that subsurface temperatures are less than about 100 °C. Carbon-13 data show that the high carbon dioxide contents (close to 1 bar (100 kPa) pressure) likely originate through high-temperature decarbonation of marine carbonates at depth, and manifest a deep geothermal component in an essentially high-level geothermal flow system.Mess Creek thermal waters discharge at 43 °C from a fault-controlled flow system unrelated to the Mount Edziza complex, showing evidence of equilibrium with local basement rocks at temperatures less than about 100 °C. Deep circulation within a region of slightly higher than normal geothermal gradients is given as the mechanism for heating.The low ^3H contents suggest that the thermal waters are tritium free (>30 years old) and are mixing with between 10 and 40% nonthermal groundwater in the discharge areas.

Cousens, B. L. and Bevier, M.L., 1995. Discerning asthenospheric, lithospheric, and crustal influences on the geochemistry of Quaternary basalts from the Iskut-Unuk rivers area, northwestern British Columbia; Canadian Journal of Earth Sciences, v. 32, no. 9, p. 1451-1461.

Abstract: Pleistocene- to Holocene-age basaltic rocks of the Iskut–Unuk rivers volcanic field, at the southern terminus of the Stikine Volcanic Belt in the northern Canadian Cordillera, provide information on the geochemical composition of the underlying mantle and processes that have modified parental magmas. Basaltic rocks from four of the six eruptive centres are moderately evolved (MgO = 5.7–6.8%) alkaline basalts with chondrite-normalized La/Sm = 1.6–1.8, $^{87}Sr/^{86}Sr$ = 0.70336–0.70361, ε_{Nd} = +4.4 to +5.9, and $^{206}Pb/^{204}Pb$ = 19.07–19.22. The small range of isotopic compositions and incompatible element ratios imply a common "depleted" mantle source for the basalts, similar to the sources of enriched mid-ocean ridge basalts from northwest Pacific spreading centres or alkali olivine basalts from the western Yukon. Positive Ba and negative Nb anomalies that increase in size with increasing SiO_2 and $^{87}Sr/^{86}Sr$ indicate that the basalts are contaminated by Mesozoic-age, arc-related, Stikine Terrane crust or lithospheric mantle through which the magmas passed. Lavas from a fifth volcanic centre, Cinder Mountain, have undergone greater amounts of fractional crystallization and are relatively enriched in incompatible elements, but are isotopically identical to least-contaminated Iskut–Unuk rivers basalts. Iskut–Unuk rivers lavas share many of the geochemical characteristics of volcanic rocks from other Stikine Belt and Anahim Belt centres, as well as alkali olivine basalts from the Fort Selkirk volcanic centres of the western Yukon.

Dixon, J. E., Filiberto, J.R., Moore, J.G., and Hickson, C.J., 2002. Volatiles in basaltic glasses from a subglacial volcano in northern British Columbia (Canada); implications for ice sheet thickness and mantle volatiles; *in* Volcano-Ice Interaction on Earth and Mars, (ed.) J.L. Smellie and M.G. Chapman; Geological Society Special Publications, v. 202, p. 255-271.

Abstract: Dissolved H_2O, CO_2, S and Cl concentrations were measured in glasses from Tanzilla Mountain, a 500 m-high, exposed subglacial volcano from the Tuya-Teslin region, north central British Columbia, Canada. The absence of a flat-topped subaerial lava cap and the dominance of pillows and pillow breccias imply that the Tanzilla Mountain volcanic edifice did not reach a subaerial eruptive phase. Lavas are dominantly tholeiitic basalt with minor amounts of alkalic basalt erupted at the summit and near the base. Tholeiites have roughly constant H_2O (c. 0.56±0.07 wt%), CO_2 (<30 ppm), S (980±30 ppm) and Cl (200±20 ppm) concentrations. Alkalic basalts have higher and more variable volatile concentrations that decrease with increasing elevation (0.62-0.92 wt% H_2O, <30 ppm CO_2, 870-1110 ppm S and 280-410 ppm Cl) consistent with eruptive degassing. Calculated vapour saturation pressures for the alkalic basalts are 36 to 81 bars corresponding to ice thicknesses of 400 to 900 m. Maximum calculated ice thickness (c. 1 km) is at the lower end of the range of predicted maximum Fraser glaciation (c. 1-2 km), and may indicate initiation of volcanism during the waning stages of glaciation. Temporal evolution from tholeiitic to alkalic compositions may reflect compositional gradients within a melting column, instead of convective processes within a stratified magma chamber. The mantle source region for the subglacial volcanoes is enriched in incompatible elements similar to that for enriched mid-oceanic ridge basalt (e.g. Endeavour Ridge) and does not contain residual amphibole. Thus, metasomatic enrichment most likely reflects small degree partial melts rather than hydrous fluids.

Edwards, B. R. and Russell, J.K., 1999. Northern Cordilleran volcanic province; a northern Basin and Range?; Geology, v. 27, no. 3, p. 243-246.

Abstract: On the basis of new petrological, radiometric, and other geotectonic data, we rationalize the character and onset of Neogene-Quaternary volcanism in the northern Cordilleran volcanic province of British Columbia. From 20 Ma to present, volcanism across the northern Cordillera is attributable to incipient rifting of the continental margin of northwestern North America. Our tectonic model is consistent with the observed petrology of these volcanic rocks; magmatism is dominantly alkaline and chemically bimodal. The model also explains the temporal distribution of volcanic activity. The majority of magmatism falls in two distinct pulses (8-4 Ma and 2-0 Ma), and the mean rate of magma production was higher from 7 to 5 Ma than from 2 to 0 Ma (250 km^3 /m.y. vs. 100 km^3 /m.y.). The first pulse of magmatism correlates with a period of net extension along the Pacific-North American plate margin. The second pulse (2-0 Ma) resulted from local domains of extension during a period of net compression between the Pacific and North American plates.

Edwards, B. R. and Russell, J.K., 2000. Distribution, nature, and origin of Neogene-Quaternary magmatism in the northern Cordilleran volcanic province, Canada; Geological Society of America Bulletin, v. 112, no. 8, p. 1280-1295.

Abstract: The northern Cordilleran volcanic province encompasses a broad area of Neogene to Quaternary volcanism in northwestern British Columbia, the Yukon Territory, and adjacent eastern Alaska. Volcanic rocks of the northern Cordilleran volcanic province range in age from 20 Ma to ca. 200 yr B.P. and are dominantly alkali olivine basalt and hawaiite. A variety of more strongly alkaline rock types not commonly found in the North American Cordillera are locally abundant in the northern Cordilleran volcanic province. These include nephelinite, basanite, and peralkaline phonolite, trachyte, and comendite. The most MgO-rich nephelinites, basanites, and alkaline basalts from throughout the northern Cordilleran volcanic province show trace element abundances and isotopic compositions that are consistent with an asthenospheric source region similar to that for average oceanic island basalt and for post-5 Ma alkaline basalts from the Basin and Range. Our petrologic observations help constrain the origin of northern Cordilleran volcanic province magmatism as well as lithosphere changes between the four major basement terranes that underlie the province. Results from phase equilibria calculations and the spatial distributions of volcanic rock types and magmatic inclusions are more consistent with the existence of thicker lithosphere beneath Stikinia, which underlies the southern part of the northern Cordilleran volcanic province, than beneath the Cache Creek and Yukon-Tanana terranes, which underlie the northern part of the northern Cordilleran volcanic province. Our results support a model for initiation of northern Cordilleran volcanic province magmatism due to incipient rifting of the northern Cordillera, driven by changes in relative plate motion between the Pacific and North American plates ca. 15-10 Ma.

Edwards, B. R. and Russell, J.K., 2002. Glacial influences on morphology and eruptive products on Hoodoo Mountain Volcano, Canada; *in* Volcano-Ice Interaction on Earth and Mars, (ed.) J.L. Smellie and M.G. Chapman; Geological Society Special Publications, v. 202, p. 179-194.

Abstract: Hoodoo Mountain volcano (HMV), a Quaternary composite volcano in northwestern British Columbia, is a well-exposed example of peralkaline, phonolitic ice-contact and subglacial volcanism. Its distinctive morphology and unique volcanic deposits are indicative of subglacial, within-ice, and/or ice-contact volcanic eruptions. Distinct ice-contact deposits result from three different types of lava-ice interaction: (1) vertical cliffs of lava, featuring finely jointed flow fronts up to 200 m in height, resulted from lava flows being dammed and ponded against thick masses of ice; (2) pervasively-jointed, dense lava flows, lobate intrusions, and domes associated with

mantling deposits of poorly-vesiculated breccia are derived from volcanic eruptions contained beneath relatively thick ice; and (3) an association of pervasively-jointed, highly-vesicular lava flows or dykes encased by vesicular hyaloclastite of identical composition formed by eruption under and/or through relatively thin ice. The distribution of these three deposit types largely explains the distinctive morphology of Hoodoo Mountain and can be used to reconstruct variations in ice thickness surrounding the volcano since c. 85 ka. Our analysis suggests that at c. 85 ka Hoodoo Mountain erupted underneath ice cover of at least several hundred metres. At c. 80 ka eruptions were no longer subglacial, but the edifice was surrounded by ice at least 800 m high that dammed lava flows around the perimeters of the volcano. After a period of eruptions showing no apparent evidence for ice interaction, from 40 ka, subglacial eruptions began again, signalling the build-up of regional ice levels. Local ice thickness during these eruptions may well have been over 2 km thick.

Edwards, B. R., Russell, J.K., and Anderson, R., 2002. Subglacial, phonolitic volcanism at Hoodoo Mountain Volcano, northern Canadian Cordillera; Bulletin of Volcanology, v. 64, no. 3-4, p. 254-272.

Abstract: Hoodoo Mountain volcano (HMV) is a Quaternary phonolitic volcano situated on the north side of the Iskut River, in the Coast Mountains of northwestern British Columbia, Canada. Its activity spans the last 100,000 years, it may have erupted as recently as 9 ka, and it encompasses a volume of approximately 17 km^3. Throughout its history, much of the volcanic activity has been directly affected by glaciers, which accounts for its striking morphology and volcanic deposits. The physical development of the volcano includes at least six stages: (1) subglacial eruptions at about 85 ka; (2) ice-confined eruptions at about 80 ka; (3) subaerial(?) pyroclastic eruptions between about 80 and 54 ka; (4) subaerial effusive eruptions at about 54 ka; (5) subglacial eruptions between 54 and 30 ka; and (6) subaerial, post-glacial eruptions at about 9 ka. The chemical and mineralogical compositions of HMV lavas remained limited throughout the 100,000-year history of the HMV. All samples are phonolite or trachyte with (micro-) phenocrysts of alkali-feldspar, clinopyroxene, and magnetite. Samples are almost exclusively nepheline and acmite normative. Compared with primitive mantle values, samples from HMV are 10-100 times enriched in rare earth element concentrations and have moderate negative Eu anomalies. Field observations, petrological data sets, and thermodynamic modeling support derivation of the phonolite magmas at HMV from alkali olivine basalt by a combination of fractional crystallization and crustal assimilation at mid-crustal pressures. The attendant changes in magma density related to differentiation permitted the continued buoyant ascent and eruption of phonolitic magmas derived from basaltic parental magmas that stalled in the crust. In this environment, the slight changes in lithostatic pressure accompanying fluctuations in Cordilleran ice sheets could amplify volcanism by "glacial pumping" of the magma-charged crustal lithosphere.

Edwards, B.R., Russell, J.K., and Simpson, K., 2011. Volcanology and petrology of Mathews Tuya, northern British Columbia, Canada; glaciovolcanic constraints on interpretations of the 0.730 Ma Cordilleran paleoclimate; Bulletin of Volcanology, v. 73, no. 5, p. 479-496.

Abstract: Petrological, volcanological and geochronological data collected at Mathews Tuya together provide constraints on paleoclimate conditions during formation of the edifice. The basaltic tuya was produced via Pleistocene glaciovolcanism in northern British Columbia, Canada, and is located within the Tuya volcanic field (59.195°N/130.434°W), which is part of the northern Cordilleran volcanic province (NCVP). The edifice comprises a variety of lithofacies, including columnar-jointed lava, pillow lava, massive dikes, and volcaniclastic rocks. Collectively these deposits record the transition from an explosive subaqueous to an effusive subaerial eruption environment dominated by Pleistocene ice. As is typical for tuyas, the volcaniclastic facies record multiple fragmentation processes including explosive, quench and mechanical fragmentation. All samples from Mathews Tuya are olivine-plagioclase porphyritic alkali olivine basalts. They are mineralogically and geochemically similar to nearby glaciovolcanic centers from the southeastern part of the Tuya volcanic field (e.g., Ash Mountain, South Tuya, Tuya Butte) as well as the

dominant NCVP rock type. Crystallization scenarios calculated with MELTS account for variations between whole rock and glass compositions via low pressure fractionation. The presence of olivine microphenocrysts and the absence of pyroxene phenocrysts constrain initial crystallization pressures to less than 0.6 GPa. The eruption of Mathews Tuya occurred between 0.718 ± 0.054 Ma and 0.742 ± 0.081 Ma based on $^{40}Ar/^{39}Ar$ geochronology (weighted mean age of 0.730 Ma). The age determinations provide the first firm documentation for large (>700 m thick), pre-Fraser/Wisconsin glaciers in north-central British Columbia approximately 0.730 Ma, and correlate in age with glaciovolcanic deposits in Russia (e.g., Komatsu et al. Geomorph 88: 352-366, 2007) and with marine isotopic evidence for large global ice volumes approximately 0.730 Ma.

Edwards, B. R., Skilling, I.P., Cameron, B., Haynes, C., Lloyd, A., and Hungerford, J.H.D., 2009. Evolution of an englacial volcanic ridge; Pillow Ridge tindar, Mount Edziza volcanic complex, Northern Cordilleran Volcanic Province, British Columbia, Canada; *in* Volcano-ice interactions on Earth and Mars; the state of the science, (ed.) B.R. Edwards, I.P. Skilling, H. Tuffen, and L. Wilson; Journal of Volcanology and Geothermal Research, v. 185, no. 4, p. 251-275.

Abstract: Glaciovolcanic deposits are critical for documenting the presence and thickness of terrestrial ice-sheets, and for testing hypotheses about inferred terrestrial ice volumes based on the marine record. Deposits formed by the coincidence of volcanism and ice at the Mount Edziza volcanic complex (MEVC) in northern British Columbia, Canada, preserve an important record for documenting local and possibly regional ice dynamics. Pillow Ridge, located at the northwestern end of the MEVC, formed by ice-confined, fissure-fed eruptions. It comprises predominantly pillow lavas and volcanic breccias of alkaline basalt composition, with subordinate finer-grained volcaniclastic deposits and dykes. The ridge is presently nearly equal 4 km long, nearly equal 1000 m in maximum width, and nearly equal 600 m high. Fifteen syn- and post-eruptive lithofacies are recognized in excellent exposures along the glacially dissected western side of the ridge. We recognize five lithofacies associations: (1) poorly sorted tuff breccia and dykes, (2) proximal pillow lava, dykes and tuff breccia, (3) distal pillow lava, poorly sorted conglomerate and well-sorted volcanic sandstone, (4) interbedded tuff, lapilli tuff, and tuff breccia units, and (5) heterolithic volcanogenic conglomerate and sandstone. Given the abundance of pillow lavas and the lack of surrounding topographic barriers capable of impounding water, we agree with Souther [Souther, J. G., 1992. The late Cenozoic Mount Edziza volcanic complex. Geol. Soc. Can. Mem., vol. 420. 320 pp.] that the bulk of the edifice formed while confined by ice, but have found evidence for a more complex and variable eruption history than that which he proposed. Preliminary estimates of water-ice depths derived from FTIR analyses of H_2O give ranges of 300 to 680 m assuming 0 ppm CO_2, and 857 to 1297 m assuming 25 ppm CO_2. Variations in depth estimates among samples may indicate that water/ice depths changed during the evolution of the ridge, which is consistent with our interpretations for the origins of different lithofacies associations. Given that the age of the units are likely to be ca. 0.9 Ma [Souther, J. G., 1992. The late Cenozoic Mount Edziza volcanic complex. Geol. Soc. Can. Mem., vol. 420. 320 pp.], Pillow Ridge may be the best documentation of a regional high stand of the Cordilleran Ice Sheet (CIS) in the middle Pleistocene, and an excellent example of the lithofacies and stratigraphic complexities produced by variations in water levels during a prolonged glaciovolcanic eruption.

Eiché, G. E., Francis, D.M., and Ludden, J.N., 1987. Primary alkaline magmas associated with the Quaternary Alligator Lake volcanic complex, Yukon Territory, Canada; Contributions to Mineralogy and Petrology, v. 95, no. 2, p. 191-201.

Abstract: The Alligator Lake complex is a Quaternary alkaline volcanic center located in the southern Yukon Territory of Canada. It comprises two cinder cones which cap a shield consisting of five distinct lava units of basaltic composition. Units 2 and 3 of this shield are primitive olivine-phyric lavas (13.5-19.5 cation % Mg) which host abundant spinel lherzolite xenoliths, megacrysts, and granitoid fragments. Although the two lava types have erupted coevally from adjacent vents and are petrographically similar, they are chemically distinct. Unit 2 lavas have considerably higher

abundances of LREE, LILE, and Fe, but lower HREE, Y, Ca, Si, and Al relative to unit 3 lavas. The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios of these two units are, however, indistinguishable. The differences between these two lava types cannot be explained in terms of low pressure olivine fractionation, and the low concentrations of Sr, Nb, P, and Ti in the granitoid xenoliths relative to the primitive lavas discount differential crustal contamination. The abundance of spinel lherzolite xenoliths and the high Mg contents in the lavas of both units indicate that their compositional differences originated in the upper mantle. The Al and Si systematics of these lavas suggest that, compared to unit 3 magmas, the unit 2 magmas may have segregated at greater depths from a garnet lherzolite mantle. The identical isotopic composition and similar ratios of highly incompatible elements in these two lava units argue against their differences being a consequence of random metasomatism or mantle heterogeneity. The lower Y and HREE contents but higher concentrations of incompatible elements in the unit 2 lavas relative to unit 3 can be most simply explained by differential partial melting of similar garnet-bearing sources. The unit 2 magmas thus appear to have been generated by smaller degrees of melting at a greater depth than the unit 3 magmas. The contemporaneous evolution of two distinct but volumetrically restricted primary magmas from adjacent vents at the Alligator Lake volcanic complex suggests that volcanism in the region of the Canadian Cordillera is controlled by localized, small batch processes.

Francis, D., 1987. Mantle-melt interaction recorded in spinel lherzolite xenoliths from the Alligator Lake volcanic complex, Yukon, Canada; Journal of Petrology, v. 28, no. 3, p. 569-597.

Abstract: Magmas which have equilibrated with the Earth's upper mantle are generally assumed to be compositionally buffered by spinel lherzolite as represented by Cr-diopside series xenoliths found in alkaline lavas. The fact that the mineral equilibria preserved in such xenoliths typically reflect re-equilibration at sub-solidus mantle conditions, however, has discouraged attempts to use the compositional variation observed in spinel lherzolite xenoliths to constrain the compositions of melts extracted from the upper mantle. A suite of mantle-derived xenoliths from the Alligator Lake volcanic center in the southern Yukon, Canada, exhibits a bimodal xenolith population consisting of lherzolites, the most fertile of which approach pyrolite in composition, and relatively depleted harzburgites. If a source-residue relationship is assumed between the two, then the extracted melt was a picritic magma (~17 wt. per cent MgO, 23 Mg cation units) with low Fe but relatively high Si contents, similar to picritic lavas associated with subduction margins. The compositional variation within the lherzolite xenoliths, however, is not towards the majority of the harzburgite xenoliths, but towards relatively rare, Fe-rich harzburgites. Reactions observed between the xenoliths and their alkaline host lavas may provide an analogue for the upper mantle process which produced this trend. The observed reactions result in the loss of an Al and Si-rich melt associated with the preferential destruction of pyroxene and spinel and a concomitant rise in the Fe content of residual olivine. The result of such an interaction in the upper mantle would be the development of a Fe and oli vine-rich residue similar to the observed Fe-rich harzburgites. In turn, the magma responsible would be forced to evolve towards more Si-rich, but Fe-poor compositions than would otherwise be possible by closed system, crystal fractionation. A comparison with other mantle xenolith suites indicates that the compositional spectra of many of those associated with continental alkaline basalts can be interpreted in terms of the extraction of picritic magmas similar to that calculated for Alligator Lake. Xenolith suites from oceanic islands such as Hawaii, in contrast, contain fertile lherzolites which are considerably more Fe-rich than pyrolite. The associated refractory xenoliths, however, are similar to those at Alligator Lake and their derivation from such fertile lherzolites would require the extraction of a picritic melt which was both Fe and Si-rich, similar to the observed tholeiitic picritcs of the shield-building stage of Hawaiian volcanism. Alternately, the Fe-rich lherzolites may represent samples of upper mantle which have reacted extensively with the relatively Fe-rich Hawaii magmas. Xenolith suites from kimberlites, on the otheT hand, are dominated by refractory harzburgites which are richer in Si but poorer in Fe than the Alligator Lake harzburgites. They suggest that the lower continental lithosphere is both more orthopyroxene-rich and more depleted than the upper mantle sampled by alkaline basalts. In general, the derivation of depleted harzburgite xenoliths by the partial

melting of a pyrolite mantle source seems to require the extraction of picritic magmas. If the majority of terrestrial basaltic magmas are not derived from picritic parental magmas, they require the existence of mantle source regions more Fe-rich than standard pyrolite models.

Francis, D., 1990. Volcano Mountain; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 118-119.

Summary: The volcanic field at Volcano Mountain in the Yukon Territory is summarized briefly.

Francis, D. and Ludden, J., 1990. The mantle source for olivine nephelinite; basanite, and alkaline olivine basalt at Fort Selkirk, Yukon, Canada; Journal of Petrology, v. 31, no. 2, p. 371-400.

Abstract: Olivine nephelinite, basanite, and transitional alkaline basalt lavas of the Quaternary Fort Selkirk volcanic complex in the central Yukon represent three distinct alkaline magma series which have evolved along diverging paths. They cannot be related by low-pressure crystal-liquid fractionation, and systematic isotopic differences make it difficult to derive them by variable degrees of melting of a common mantle source. Field evidence requires, however, that these three magma series are intimately related in time and space, and they share a number of anomalous chemical characteristics including low Ca/Na ratios with respect to the majority of terrestrial equivalents. When the effects of differential olivine fractionation are ignored, the compositional spectrum of the Fort Selkirk lavas approximates a binary mixing line between transitional alkaline basalt and olivine nephelinite. A population gap along this mixing line, located between the compositions of the nephelinite and basanite lavas, coincides with the compositions of amphibole and/or amphibole–garnet–clinopyroxene assemblages observed in mantle xenoliths. This compositional gap may represent a thermal divide separating two minimum-melt compositions in a mantle source consisting of a lherzolite host cut by amphibole–garnet–clinopyroxenite veins. The olivine nephelinite endmember may have been derived by early melting in the amphibole–garnet–clinopyroxenite veins, whereas the transitional alkaline basalt would represent more extensive melting of the host lherzolite.

Francis, D. and Ludden, J., 1995. The signature of amphibole in mafic alkaline lavas, a study in the northern Canadian Cordillera; Journal of Petrology, v. 36, no. 5, p. 1171-1191.

Abstract: Despite evidence for its involvement, the importance of amphibole in controlling the compositions of mafic alkaline magmas remains under-appreciated. Relatively small variations in large ion lithophile elements (LILE) with respect to other incompatible elements, such as light rare-earth elements (LREE) or Th, require that amphibole was an important residual phase during the production of Late Tertiary to Recent olivine nephelinite (Ol-NEPH) magmas beneath the northern Canadian Cordillera. The erupted mafic magma types define a continuous array from Ol-NEPH to hypersthene-normative olivine basalt (Hy-NORM AOB). The overall compositional array has a sense of curvature which is counter to binary mixing, but can be modeled by two distinct linear melting trends: one from Ol-NEPH to basanite (BASAN) compositions, during which amphibole controlled the composition of the melt, and the ratios of LILE/LREE change significantly, but the ratios of high field strength elements (HFSE) remain relatively constant; the other from BASAN to Hy-NORM AOB corresponding to the melting of a lherzolite assemblage, following the exhaustion of amphibole, across which the ratios of LILE/LREE remain relatively constant, but the ratios of HFSE change significantly. Other intraplate alkaline suites, such as those of the Hawaiian Islands, show similar evidence for the involvement of residual amphibole in the genesis of Ol-NEPH to BASAN magmas. The melting of any amphibole-bearing mantle assemblage is likely to be a two-step process, regardless of whether the amphibole is segregated as veins or distributed interstitially. In a water-undersaturated environment, the first stage of melting is controlled by the breakdown of amphibole, which produces silica-saturated liquids below 12 kbar and silica-undersaturated liquids at greater depths, with little contribution from

other mineral phases. In the second stage, following the exhaustion of amphibole, the major element compositions of subsequent melts change rapidly to equilibrate with a lherzolite mineralogy, but the incompatible trace-element characteristics of the former amphibole persist.

Hamilton, T.S.,1990. Level Mountain; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 121-123.

Summary: The Level Mountain volcanic complex in the Yukon Territory is summarized briefly.

Hamilton, T.S. and Evans, M.E., 1983. A magnetostratigraphic and secular variation study of Level Mountain, northern British Columbia; Geophysical Journal of the Royal Astronomical Society, v. 73, p. 39–49.

Modified abstract: Palaeomagnetic results are reported from 50 flows erupted by Level Mountain, which is a composite volcano in northern British Columbia. Fourteen magnetic polarity zones are represented, and these allow a magnetostratigraphy to be established which indicates that eruptive activity began about 6.5 Myr ago and continued up to very recent times with several hiatuses of up to 1 Myr or more. Most of the flows yield acceptable normal or reversed palaeopoles, but two of them record the Gauss/Matuyama polarity transition, and a further four yield a tight group of divergent directions, which are here interpreted as a geomagnetic excursion near the base of the Gauss Epoch. This observation lends support to an earlier suggestion (Bingham and Stone) that the geomagnetic field was abnormally disturbed about 3.5 Myr ago, at least locally in north-western North America. The angular dispersion, the occurrence of geomagnetic excursions, and an anomalous palaeopole offset, combine to suggest that a local long-lived source of geomagnetic perturbations may exist in the outermost core beneath this region.

Harder, M. and Russell, J.K., 2006. Thermal state of the upper mantle beneath the Northern Cordilleran Volcanic Province (Northern Cordilleran Volcanic Province), British Columbia, Canada; *in* Mantle to magma; lithospheric and volcanic processes in western North America, (ed.) B.R. Edwards and J.K. Russell; Lithos, v. 87, no. 1-2, p. 1-22.

Abstract: Data are presented for a suite of peridotitic mantle-derived xenoliths collected from basanite lavas within the Llangorse volcanic field, northwest British Columbia. The xenoliths comprise spinel lherzolite and subordinate spinel harzburgite. Two-pyroxene thermometry based on the Brey and Kohler (1990) [Brey, G. P., Kohler, T., 1990. Geothermobarometry in four-phase lherzolites II. New thermobarometers, and practical assessment of existing thermobarometers. Journal of Petrology, 31, 1353-1378.] calibration was applied to 44 xenolith samples. The resulting geothermometry define minimum (800-850° C) and maximum (1050-1100°C) temperatures of equilibration for the xenolith suite which are estimates of thermal conditions in the underlying lithospheric mantle. We take the minimum temperatures as indicative of the maximum MOHO temperature; the maximum xenolith temperatures provide a minimum temperature for the transition from lithospheric to asthenospheric mantle. The geothermometry data are combined with published heat flow data to produce a set of model geotherms for this portion of the northern Cordillera. The model geotherms constrain the thickness of the mantle lithosphere in the northern Canadian Cordillera to between 16 and 30 km, corresponding to depths to the lithosphere/asthenosphere boundary of 52-66 km. We show that this model is consistent with an underlying convecting asthenospheric mantle with an average temperature and viscosity of 1210-1250° C and $10^{19.4}$ Pa s, respectively. We conclude by exploring the implications this model has for the source regions of alkaline magmas erupted over this portion of the northern Cordilleran volcanic province.

Harder, M. and Russell, J.K., 2007. Basanite glaciovolcanism at Llangorse Mountain, northern British Columbia, Canada; Bulletin of Volcanology, v. 69, no. 3, p. 329-340.

Abstract: The Llangorse volcanic field is located in northwest British Columbia, Canada, and comprises erosional remnants of Miocene to Holocene volcanic edifices, lava flows or dykes. The focus of this study is a single overthickened, 100-m-thick-valley-filling lava flow that is Middle-Pleistocene in age and located immediately south of Llangorse Mountain. The lava flow is basanitic in composition and contains mantle-derived peridotite xenoliths. The lava directly overlies a sequence of poorly sorted, crudely bedded volcaniclastic debris-flow sediments. The debris flow deposits contain a diverse suite of clast types, including angular clasts of basanite lava, blocks of peridotite coated by basanite, and rounded boulders of granodiorite. Many of the basanite clasts have been palagonitized. The presence and abundance of clasts of vesicular to scoriaceous, palagonitized basanite and peridotite suggest that the debris flows are syngenetic to the overlying lava flow and sampled the same volcanic vent during the early stages of eruption. They may represent lahars or outburst floods related to melting of a snow pack or ice cap during the eruption. The debris flows were water-saturated when deposited. The rapid subsequent emplacement of a thick basanite flow over the sediments heated pore fluids to at least 80–100°C causing in-situ palagonitization of glassy basanite clasts within the sediments. The over-thickened nature of the Llangorse Mountain lavas suggests ponding of the lava against a down-stream barrier. The distribution of similar-aged glaciovolcanic features in the cordillera suggests the possibility that the barrier was a lower-elevation, valley-wide ice-sheet.

Hart, C. J. R. and Villeneuve, M., 1999. Geochronology of Neogene alkaline volcanic rocks (Miles Canyon Basalt), southern Yukon Territory, Canada; the relative effectiveness of laser $^{40}Ar/^{39}Ar$ and K-Ar geochronology; Canadian Journal of Earth Sciences, v. 36, no. 9, p. 1495-1507.

Abstract: Miles Canyon basalt is an informal term used to describe numerous exposures of young alkaline olivine basalt flows in southern Yukon. The volcanic rocks are part of the Northern Cordilleran volcanic province. K-Ar and Ar-Ar whole-rock dates indicate that the Miles Canyon succession of flows at the Whitehorse Rapids are clearly Late Miocene in age (ca. 8.4 Ma). The largest exposure of the Miles Canyon basalt occurs at the Alligator Lake volcanic complex where two nearly concordant Pliocene Ar-Ar dates indicate eruption at ca. 3.2 Ma. K-Ar analyses from other sites yield dates of 2.4 and 7.1 Ma and indicate an episodic Neogene volcanic history for the region. There is no evidence of Quaternary or postglacial volcanism. The dates are older than assumed by previous workers, and in some cases the K-Ar dates are strongly discordant from Ar-Ar determinations. More accurate Ar-Ar determinations may result from the method's ability to select smaller amounts of better material for analysis. Excess ^{40}Ar was not encountered. As a result, the accuracy of any single or several discordant K-Ar determinations for Neogene subaerial volcanic rocks, particularly low-K rocks such as basalts, should be questioned and resulting interpretations made with caution. Models accounting for the eruption of the Northern Cordilleran volcanic province lavas have typically relied upon extension along north-trending faults that were generated by stresses along the continental margin. However, we consider a slab window model which better accounts for the initiation and distribution of northern Cordilleran Neogene volcanic activity.

Higgins, M. D., 2009. The Cascadia megathrust earthquake of 1700 may have rejuvenated an isolated basalt volcano in Western Canada; age and petrographic evidence; Journal of Volcanology and Geothermal Research, v. 179, no. 1-2, p. 149-156.

Abstract: The basaltic Tseax flow is the product of one of only two eruptions in western Canada during the last thousand years. Reinterpretations of ^{14}C and paleomagnetic data indicate that Tseax volcano last erupted between 1668 and 1714 CE. This date straddles that of the Cascadia megathrust earthquake of 26 January 1700, whose rupture lay 450 km to the south. Hence, the

largest recent earthquake in northwest North America may have rejuvenated an existing magmatic system and produced this isolated flow. Although the flow is chemically uniform there are significant textural differences between the early and late parts of the flow. It is proposed that both magmatic components were contained within a steep conduit. Gas produced by degassing of magma in the lower part of the conduit ascended, heated magma in the upper part, coarsening plagioclase, and then continued to the surface along fissures. This stable configuration was disrupted by the Cascadia earthquake: dilatation widened the conduit and enabled both magmas to rise to the surface along existing fissures.

Higgins, M.D. and Allen, J.M., 1985. A new locality for primary xenolith-bearing nephelinites in northwestern British Columbia; Canadian Journal of Earth Sciences, v. 22, no. 10, p. 1556-1559.

Abstract: High Ni abundances (420–500 ppm) and Mg* values (100 × Mg/(Mg + Fe^{2+}) = 69–71) and the presence of mantle-derived xenoliths indicate that a subvolcanic nephelinite intrusion in northwestern British Columbia represents an unmodified primary magma. A separate, closely associated nephelinite intrusion shows evidence of minor olivine fractionation from a similar composition. Only three other occurrences of primary nephelinite have been described. This new occurrence suggests that these magmas may not be so rare as previously supposed. The trace-element abundances closely resemble those of primary nephelinites of similar La content from Freemans Cove, Canada. Such compositions are usually taken as evidence of intraplate rifting and doming. Therefore, these rocks are further evidence of late Tertiary or Quaternary rifting in the Stikine volcanic belt.

Hungerford, J.D.G., Edwards, B.R., Skilling, I.P., and Cameron, B.I., 2014. Evolution of a subglacial basaltic lava flow field: Tennena volcanic center, Mount Edziza volcanic complex, British Columbia, Canada; Journal of Volcanology and Geothermal Research, v. 272, p. 39-58.

Abstract: Studies of terrestrial glaciovolcanic deposits have elucidated the utility of these deposits as tools to constrain ice conditions at the time of their emplacement. Very few studies, however, have documented the emplacement of effusion-dominated, basaltic glaciovolcanic eruptions. The Tennena volcanic center (TVC), located at 57° 40' 57.705″ N 130° 39' 43.138″ W on the western flank of Mount Edziza volcanic complex (MEVC) in northwestern British Columbia, Canada, preserves a detailed record of interactions between coherent basaltic lavas and a local/regional ice sheet inferred to be associated with the Last Glacial Maximum (LGM). Here we describe the field characteristics of five primary volcanic lithofacies and five associated glaciogenic lithofacies, and discuss their spatial distribution within the volcanic center. We find that 1) the distribution of primary hydrovolcanic clastic deposits (tuff breccias and lapilli tuffs) is confined to Tennena Cone, 2) pillow lavas are present throughout the extent of the surrounding lava field with morphologies that include distinctive structures comprising vertically-oriented, distended pillows, 3) multiple lobes of massive (non-pillowed) lavas that represent high initial magma discharge rates are confined to medial distances from the cone, and 4) associated glaciogenic facies that underlie or onlap the TVC lavas indicate a variable sediment/water ratio during subglacial meltwater drainage at the time of the eruption or shortly afterwards. Analyses of H_2O/CO_2 in pillow rim samples give broad constraints for emplacement pressures equivalent to 500-1400m of overlying ice. No subaerial lava morphologies are found on the cone or in the proximal, medial and distal lithofacies, and the sequence is interpreted as documenting an eruption of basaltic lava flows beneath either the LGM Cordilleran ice sheet or a Younger Dryas expansion of the still-extant Edziza ice cap. The TVC lavas, especially medial and distal ones, display excellent examples of textures and morphologies that can be used to: 1) help identify other terrestrial and Martian basaltic lava flows emplaced beneath ice and 2) further our understanding on how sub-ice lava flows are emplaced.

Huscroft, C. A., Ward, B.C., Barendregt, R.W., Jackson, L.E., Jr., and Opdyke, N.D., 2004. Pleistocene volcanic damming of Yukon River and the maximum age of the Reid Glaciation, west-central Yukon; Canadian Journal of Earth Sciences, v. 41, no. 2, p. 151-164.

Abstract: Stratigraphic, paleomagnetic, and radioisotope investigations of the Selkirk Volcanic Group have identified a new eruptive period and constrained the age of the Reid Glaciation, the most extensive middle Pleistocene cordilleran advance recognized in central Yukon. Downstream from Fort Selkirk, a complex of valley-filling compound pahoehoe basalt flows and pillow basalt is exposed for 10 km along the Yukon River and is overlain by outwash deposited during the Reid Glaciation. The flows have an $^{40}Ar/^{39}Ar$ age of 311 ± 32 ka. This age is consistent with the normal magnetization of the flows and their termination below the level of the contemporary Yukon River flood plain. Taken with the ca. 190 ka Sheep Creek tephra, which overlies Reid drift elsewhere in Yukon Territory, the Reid Glaciation is constrained to oxygen isotope stage 8, not stage 6 as previously thought. The presence of thick foreset-bedded pillow breccia units intercalated with the subaerial flows indicates that this eruption caused damming of the Yukon River. Reevaluation of the stratigraphy of early Pleistocene basalt flows and pillow lavas in the Fort Selkirk area indicates that volcanic damming of the Yukon River has occurred at least once previously.

Jackson, L. E., Jr., Barendregt, R.W., Baker, J., and Irving, I., 1996. Early Pleistocene volcanism and glaciation in central Yukon; a new chronology from field studies and paleomagnetism; Canadian Journal of Earth Sciences, v. 33, no. 6, p. 904-916.

Abstract: The paleomagnetism of the Selkirk Volcanics and nearby stratified Pleistocene sediments was investigated to resolve the chronology of Early Pleistocene glaciations in central Yukon. Radiometric dates on these low-K basalts have proven to be erroneously old. Most sampled sediments and all basalts accurately record the paleofield and true reversals. The valley-filling phase of the Selkirk Volcanics was in part coeval with the younger pre-Reid glaciation. It was erupted during the Matuyama Chron, either post-Cobb Mountain Subchron or post-Jaramillo Subchron, over a period too brief to average secular variation. The older pre-Reid glaciation occurred after ca. 1.60 Ma and prior to the eruption of the Fort Selkirk tephra (pre-Jaramillo or pre-Cobb Mountain). Sediments investigated at Revenue Creek and Braden's Canyon are normally magnetized. The assigned Brunhes age is compatible with their occurrence in valleys that were cut or deepened sometime after the pre-Reid glaciations.

Jackson, L.E., Jr., Nelson, F.E., Huscroft, C.A., Villeneuve, M., Barendregt, R.W., Storer, J.E., and Ward, B.C., 2012. Pliocene and Pleistocene volcanic interaction with Cordilleran ice sheets, damming of the Yukon River and vertebrate Palaeontology, Fort Selkirk Volcanic Group, west-central Yukon, Canada; Quaternary International, v. 260, p. 3-20.

Abstract: Neogene volcanism in the Fort Selkirk area began with eruptions in the Wolverine Creek basin ca. 4.3 Ma and persisted to ca. 3.0 Ma filling the ancestral Yukon River valley with at least 40 m of lava flows. Activity at the Ne Ch'e Ddhawa eruptive center overlapped with the last stages of the Wolverine Creek eruptive centers. Hyaloclastic tuff was erupted between ca. 3.21 and 3.05 Ma. This eruption caused or was coincident with damming of Yukon River. The first demonstrable incursion of a Cordilleran ice sheet into the Fort Selkirk area was coincident with a second eruption of the Ne Ch'e Ddhawa eruptive center ca. 2.1 Ma. The Ne Ch'e Ddhawa subglacial mound was erupted beneath at least 300m of glacial ice (Ne Ch'e Ddhawa Glaciation). The eruption of the Fort Selkirk center occurred between the last eruption of Ne Ch'e Ddhawa and Fort Selkirk Glaciation (ca. 2.1-1.5 Ma). Till and outwash from Fort Selkirk Glaciation are conformably overlain by nonglacial sediments that contain the Fort Selkirk tephra (fission track dated at ca. 1.5 Ma). These nonglacial sediments also preserve a short magnetic reversal (reversed to normal) identified as the Gilsa polarity excursion. Temporal control and sedimentology constrain Fort Selkirk Glaciation and the Fort Selkirk Local Fauna to marine

isotope stage 54. Rapid and extensive eruption of the Pelly eruptive center filled the Yukon River valley with 70 m of lava which buried these glacial and nonglacial sediments and dammed Yukon River. Local striations and erratic pebbles occur on the last of these lava flows. They document a subsequent incursion of glacial ice during the last 500 ka of the Matuyama Chron (Forks Glaciation). The last major eruption of mafic lava occurred in the middle Pleistocene west of (early Holocene) Volcano Mountain in basin of Black Creek: lava flowed down the valley presently occupied by Black Creek and dammed Yukon River in the area of the Black Creek confluence. This eruption predated the middle Pleistocene Reid Glaciation. Minor volcanism has continued in this area since the middle Pleistocene at Volcano Mountain.

Jercinovic, M. J., Keil, K., Smith, M.R., and Schmitt, R.A., 1990. Alteration of basaltic glasses from north-central British Columbia, Canada; Geochimica et Cosmochimica Acta, v. 54, no. 10, p. 2679-2696.

Abstract: Evidence of palagonitization (glass replacement by poorly crystallized, clay-like material) is seen on all glasses studied from three Pleistocene subglacial volcanoes in north-central British Columbia, Canada. Samples from foreset breccias of Tuya Butte are more highly palagonitized than those from the tephra cones of Ash Mountain and Southern Tuya. Extensive palagonitization is generally associated with authigenic mineralization (clays, zeolites). Palagonite composition varies widely relative to glass composition, and palagonite can be broadly categorized as either high-Al or low-Al, depending on whether Al was retained or lost to aqueous solutions during palagonitization. The lowest Al palagonites are those from the foreset breccias of Tuya Butte. Loss of Al during palagonitization is related to closed-system alteration, including precipitation of aluminosilicate authigenic cements. Low initial pH is suggested for Al depletion, consistent with the behavior of Ni, Co, and Cr, which are retained in high-Al and depleted in low-Al palagonite. Microenvironment appears to be more influential than macroenvironment in determining the composition of palagonite. Palagonite rinds are compositionally zoned, generally becoming progressively higher in Al and Ca, and lower in Fe and Mg, towards the innermost (later-formed) portions of the rinds. This apparently reflects changing solution composition (increasing pH) with time. Compositional zoning does not change the overall stoichiometry of palagonite which resembles smectite clay. Mineral paragenesis is related to the Ca content of the palagonite, with partial replacement of palagonite by smectite (Fe-saponite) occurring when Ca is retained in the rind. This replacement phenomenon occurs prior to zeolitization. No such replacement clay occurs with low-Ca palagonite, but a late-stage nontronite film overgrows zeolite. Phillipsite is the first zeolite formed, followed by chabazite. Analcime and calcite occur in the most highly palagonitized samples. Mass balance considerations indicate higher mass loss where palagonitization has not proceeded to the point where zeolite solubility limits were attained in the local solution. Zeolites occur in closed-system conditions (low flow rates), where little net system mass loss or gain has occurred. The colloidal nature of palagonite allows the effective adsorption of Rb, Cs, Sr, Ba, and REEs.

Jessop, A. M., Souther, J.G., Lewis, T.J., and Judge, A.S.., 1984. Geothermal measurements in northern British Columbia and southern Yukon Territory; Canadian Journal of Earth Sciences, v. 21, no. 5, p. 599-608.

Modified abstract: Measurements at seven sites in the intermontane region show heat flow of 63-100 mW/m^2 and heat generation, obtained from intrusive rocks at three of these sites, of 1.8-6.5 mu W/m^3. The plotted points lie between the lines of the stable crust of the eastern United States and of the Basin and Range Province. Conductive thermal models of the crust, assuming a basalt composition for the lower crust, predict at 35 km depth a heat flow of 30 mW/m^2 and temperatures between 645 and 775° C at most sites. At two sites conductive models based on reasonable properties do not yield temperatures. The site on the axis of the Stikine volcanic belt shows a probable component of convectively enhanced heat flow or the presence of a young intrusion at depth. The site in the Bowser Basin shows the probable effect of water movement in the sediments.

Kuehn, S.C., Froese, D.G., and Shane, P.A.R., 2011. The INTAV intercomparison of electron-beam microanalysis of glass by tephrochronology laboratories; results and recommendations; *in* Enhancing tephrochronology and its application (INTREPID Project), (ed.) D.J. Lowe, S.M. Davies, H. Moriwaki, N.J.G. Pearce, and T. Suzuki; Quaternary International, v. 246, no. 1-2, p. p. 19-47.
Modified abstract: The INternational focus group on Tephrochronology And Volcanism (INTAV) of the International Union for Quaternary Research (INQUA) has conducted an intercomparison of tephrochronology laboratories with electron-beam microanalytical data on volcanic glasses submitted from 27 instruments at 24 institutions in 9 countries, motivated by the desire to assess the quality of data currently being produced and to stimulate improvements in analytical protocols and data reporting that will increase the efficacy of tephra fingerprinting and correlation. Participating laboratories were each supplied with a mount containing three samples for analysis: (1) rhyolitic Lipari obsidian ID3506, (2) phonolitic Sheep Track tephra from Mt. Edziza, British Columbia, Canada, and (3) basaltic Laki 1783 A.D. tephra. A fourth sample, rhyolitic Old Crow tephra, was also distributed. Despite substantial variety in procedures and calibration standards, most mean concentrations compare favorably between laboratories and with other data, although obtaining accurate Na_2O concentrations for the phonolitic tephra proved to be a challenge for many laboratories. Only one-half of the data sets had means within ±1 standard deviation of the approximately 8.2 wt% Na_2O value obtained by other methods. Most submissions had relative precision better than 1-5% for the major elements. For low-abundance elements, the precision varied substantially with relative standard deviations as small as 10% and as large as 110%. The tephrochronology community now has a large comparative data set derived from common reference materials that will facilitate improvements in accuracy and precision and which can enable improved use of published data produced by the participating laboratories. Finally, recommendations are provided for improving accuracy, precision, and reporting of electron-beam microanalytical data from glasses.

Lakeman, T. R., Clague, J.J., Menounos, B., Osborn, G.D., Jensen, B.J.L., and Froese, D.G., 2008. Holocene tephras in lake cores from northern British Columbia, Canada; Canadian Journal of Earth Sciences, v. 45, no. 8, p. 935-947.
Abstract: Sediment cores recovered from alpine and subalpine lakes up to 250 km apart in northern British Columbia contain five previously unrecognized tephras. Two black phonolitic tephras, each 5–10 mm thick, occur within 2–4 cm of each other in basal sediments from seven lakes in the Finlay River – Dease Lake area. The upper and lower Finlay tephras are slightly older than 10,220 – 10,560 cal year B.P. and likely originate from two closely spaced eruptions of one or two large volcanoes in the northern Cordilleran volcanic province. The Finlay tephras occur at the transition between deglacial sediments and organic-rich postglacial mud in the lake cores and, therefore, closely delimit the termination of the Fraser Glaciation in northern British Columbia. Sediments in Bob Quinn Lake, which lies on the east edge of the northern Coast Mountains, contain two black tephras that differ in age and composition from the Finlay tephras. The lower Bob Quinn tephra is 3–4 mm thick, basaltic in composition, and is derived from an eruption in the Iskut River volcanic field about 9400 cal years ago. The upper Bob Quinn tephra is 12 mm thick, trachytic in composition, and probably 7000–8000 cal years old. A fifth tephra occurs as a cryptotephra near the top of two cores from the Finlay River area and is correlated to the east lobe of the White River tephra (ca. 1150 cal year B.P.). Although present throughout southern Yukon, the White River tephra has not previously been documented this far south in British Columbia. The tephras are valuable new isochrons for future paleoenvironmental studies in northern British Columbia.

Marshall, P., 1975. Ice-blocked tubes in the Aiyansh flow, British Columbia; Arctic and Alpine Research, v. 7, p. 399-400.
Abstract: The only known lava tubes in Canada are found in the Aiyansh lava flow, British Columbia, and have been dated at 250 ± 130 BP. Selected tubes in the cinder cone area are blocked by

massive ice deposits having similar petrographic characteristics to those in high altitude caves. The terms "fossil" and "glacial" used to describe ice formations in some high altitude caves must be reconsidered.

McCullagh, J.B., 1918. Ignis: a parable of the great lava plain in the valley of “eternal bloom”, Naas River, British Columbia; Aiyansh, British Columbia, 20 p.

Summary: This is a short booklet that recounts, in poem form, the Nisga’a people’s oral history about the volcanic eruption in the Nass Valley (herein spelled as “Naas”) several hundred years ago, during which approximately 2000 people died. This is the only eruption in Canada for which there exists an historical account.

Moore, J. G., Hickson, C.J., and Calk, L.C., 1995. Tholeiitic-alkalic transition at subglacial volcanoes, Tuya region, British Columbia, Canada; Journal of Geophysical Research, v. 100 B12, p. 24577-24592.

Abstract: Ash Mountain, South Tuya, and Tuya Butte are three small basaltic volcanoes in the Stikine volcanic belt of northern British Columbia. The volcanoes rise 700, 500, and 400 m above their bases and are about 3.2, 1.6, and 2.6 km^3 in volume, respectively. They began eruptive activity under several hundred meters of overlying glacial ice, or water in an ice-impounded lake, and undegassed pillow lava was erupted and forms the bases of all three. Later, as the vents grew into shallow water, explosive phreatomagmatic activity erupted partly degassed glassy tuffs. Finally, when the volcano emerged through the surface of the ice or water (or the water was drained), degassed subaerial lava flows were erupted and were converted to assemblages of foreset-bedded pillow breccia and pillow lava when subaerial flows crossed a shoreline and flowed into meltwater lakes. The undegassed subglacial pillow base of Ash Mountain is overlain by partly degassed pillows and hyaloclastite tuff cut by dikes; at South Tuya the pillow base is overlain by hyaloclastite tuffs and lenses of pillow lava; at Tuya Butte the pillow base is overlain by foreset-bedded pillow lava, pillow breccias, and hyaloclastite tuffs, which in turn are overlain by subaerial lava flows composing a small shield volcano. The undegassed basal subglacial pillow lava of the three volcanoes contain 0.10 ± 0.01 wt % sulfur and 0.5 wt % H_2O. The overlying partly degassed assemblages contain 0.06 ± 0.02% sulfur and 0.2% H_2O at Ash Mountain, 0.07 ± 0.01% sulfur at South Tuya, and 0.03 ± 0.01% sulfur at Tuya Butte. The differences in the degree of degassing can be related to the nature of eruption and quenching and the distance of flow of the subaerial lava. When the volcanoes switched from subglacial to shallow water or subaerial eruptions, as shown by change to more explosive activity and then to subaerial lava flows (and by a marked reduction of sulfur in volcanic glass), the magma shifted from tholeiitic to alkalic composition. This transition occurs at each of the three volcanoes. The tholeiitic and alkalic magmas cannot be related by shallow crystal fractionation and apparently originated by differing degrees of deep melting at a mantle source. Prior to eruption the tholeiitic melts overlay alkalic melts in shallow chambers underlying each of the volcanoes because of their lower density and were, therefore, the first to erupt under subglacial conditions. As the volcano grew through the ice (or ice-impounded water), the volcanic conduit vented to the atmosphere, producing a partial depressurization of the conduit and the subsurface chamber. This sudden reduction in confining pressure caused enhanced vesiculation of volatile saturated melts, particularly of the more volatile-rich alkalic melts, causing them to rise to the top of the chamber and erupt.

Nadeau, S., Pineau, F., Javoy, M., and Francis, D., 1990. Carbon concentrations and isotopic ratios in fluid-inclusion-bearing upper-mantle xenoliths along the northwestern margin of North America; Chemical Geology, v. 81, no. 4, p. 271-297.

Abstract: At least three and perhaps four carbon components have been identified by step-heating extraction of upper-mantle xenoliths from Nunivak Island and Prindle Volcano (Alaska), Fort Selkirk and Alligator Lake (Yukon), Jacques Lake and Castle Rock (British Columbia). One component, released mostly between 200° and 600°C, comprises 30–95% of the total carbon

extracted and has $\delta^{13}C$-values between −28 and −23‰. This carbon corresponds mostly to complex carbon compounds condensed on surface minerals and cracks and will be referred to as isotopically light carbon (ILC). CO_2 released between 600° and 800°C is derived from interstitial carbonates. It has variable $\delta^{13}C$ and concentrations that generally do not exeed 24 ppm C. The carbon extracted from 1000° to 1450°C is a mixture of CO_2 from fluid inclusions and the ILC fraction. The amount of ILC released in this temperature interval never exceeds 10 ppm. Because part of this ILC may have been introduced from the host lava, the $\delta^{13}C$ variations of this carbon extracted above 800°C is not only characteristic for the original carbon present in fluid inclusion-poor xenoliths. However, xenoliths enriched in CO_2 fluid inclusions show C isotopic variations at the highest temperature steps that fall in a relatively narrow range between −10 and −4‰. Depending upon the fluid-inclusion abundance, the concentration of high-temperature C derived from fluid inclusions varies from 0.1 to 66 ppm. Anhydrous spinel lherzolites and harzburgites generally contain <2 ppm C as fluid inclusions. Pyroxenite intruding anhydrous spinel lherzolites have $\delta^{13}C$-values lighter than their host rocks. Anhydrous pyroxenites and tectonized harzburgite xenoliths with numerous fluid inclusions contain between 18 and 66 ppm C as fluid inclusions and the heaviest $\delta^{13}C$-values (−5 to −4‰). Fluid-inclusion-rich amphibole-bearing clinopyroxenite, spinel lherzolite and harzburgite xenoliths contain 8–24 ppm C as fluid inclusions with $\delta^{13}C$ ranging from −10 to −6‰. The range of CO_2 isotopic compositions observed in fluid inclusions corresponds to those measured in other mantle carbon material such as diamonds, kimberlites, carbonatites and volcanic gases. The observed carbon isotopic variations reflect isotopic fractionation between fluids and carbon dissolved in melts present in the upper mantle.

Nelson, F. E., Barendregt, R.W., and Villeneuve, M., 2009. Stratigraphy of the Fort Selkirk volcanogenic complex in central Yukon and its paleoclimatic significance; Ar/Ar and paleomagnetic data; Canadian Journal of Earth Sciences, v. 46, no. 5, p. 381-401.

Abstract: Brunhes, Matuyama, Kaena, and Mammoth age basaltic lava flows (Tertiary-Quaternary Selkirk Volcanics) were sampled in west-central Yukon. The mean characteristic remanent magnetization (ChRM) direction of the flows sampled in this and previous studies has a declination of 348.7° and an inclination of 70.8° (n=42, k=99.6, $alpha_{95}$ =2.2°) (all on lower hemisphere). The time range represented in this study (ca. 3.25 to ca. 0.004 Ma) is great enough to have confidently averaged secular variation. Sediment associated with the basalt has a mean declination of 7.6° and inclination of 78.8° (n=5, k=5.6, $alpha_{95}$ =35.7°). A new ^{40}Ar- ^{39}Ar date on the reversely magnetized basal basalts at Ne Ch'e Ddhawa places the eruption in the Mammoth subchron of the Gauss Normal Chron. The newly dated basal basalt at Ne Ch'e Ddhawa precedes the initial continental glaciation in Yukon and is older than the Fort Selkirk vent (Lower Mushroom), which was previously thought to be the oldest eruption at Fort Selkirk Volcanic Complex (FSVC). This basal flow at Mushroom is dated at 1.82±0.03 Ma and the uppermost flow is reproducibly dated at 1.36±0.04 Ma. Till on the flanks of a subglacial volcanic mound called Ne Ch'e Ddhawa (informal) is older than previously thought; its reverse magnetization indicates an Early Pleistocene age rather than the Reid glaciation, which falls during the Brunhes Normal Chron. The paleomagnetism of Tertiary-Quaternary Selkirk Volcanics outcrops outside the FSVC was studied for the first time. The ChRM direction of basalt at the northern edge of the northern Cordillera volcanic province agrees with FSVC directions, suggesting that this flow reflects the same period of volcanism. This suggests that an Eocene K-Ar date, previously thought to be unreliable, may well be correct.

Nicholls, J., Stout, M.Z., and Fiesinger, D.W., 1982. Petrologic variations in Quaternary volcanic rocks, British Columbia, and the nature of the underlying upper mantle; Contributions to Mineralogy and Petrology, v. 79, p. 201-218.

Abstract: Volcanic activity has produced Late Tertiary and Quaternary cinder cones and flows between the Snake River Plain, U.S.A. and the Yukon Territory, Canada. The rock types include basanites, alkali olivine basalts, high-iron basalts, hawaiites, ankaramites, nephelinites, and olivine tholeiites. The alkali olivine basalts, basanites and hawaiites sampled are chemically

similar to rocks from the mid-Atlantic islands. Associated with the volcanic rocks are xenoliths of ultramafic rocks, gabbros, granites and granulites. Seismic data indicate that the Moho throughout the region dips eastward at a very shallow angle. The low velocity zone has been located beneath southern British Columbia and displays a topographic high trending northwest-southeast. The nephelinite was erupted from near the crest of this high with less undersaturated lavas erupted from along its flanks. The suite of ultramafic xenoliths spans a greater variety of rock types than can be generated by maximum amounts of partial melting of a uniform source material to produce the lavas in the region. Calculated residual olivine compositions in equilibrium with the magmas at low velocity zone depths and liquidii temperatures are more iron-rich than the typical lherzolite xenolith olivine. This suggests that the residua from the partial melting episodes which produced the volcanic rocks are different from the upper mantle lid above the low velocity zone as represented by the ultramafic xenoliths.

Oskin, B., 2013. A blast of a find: 12 new Alaskan volcanoes; LiveScience, May 31, 2013. http://www.livescience.com/

Summary: This is a short on-line nontechnical article about newly discovered volcanoes in southeastern Alaska. It briefly discusses the recently-identified Alaska volcanoes and their relationship to volcanoes of Canada's Northern Cordilleran volcanic province. Although the article is intended for a general audience and is not from a scientific journal, it is included here because of the scarcity of other publications that discuss volcanoes of southeastern Alaska (the "panhandle") and their relationship to Canadian volcanoes.

Roberts, M. C. and McCuaig, S.J., 2001. Geomorphic responses to the sudden blocking of a fluvial system; Aiyansh lava flow, northwest British Columbia; Canadian Geographer, v. 45, no. 2, p. 319-323.

Summary: Some 250 years ago, near the town of New Aiyansh in northwestern British Columbia, lava flowed down the narrow valley of the Tseax River and then spread out over the floodplain of the Nass River causing catastrophic changes to the geomorphology of the area. Two villages of the Nisga'a people, located on the Nass River floodplain, were destroyed by the flow. The event took place over a period that lasted probably no more than a few days or, at the most, a couple of weeks. This paper describes how the Aiyansh lava flow radically changed the fluvial geomorphology of the Tseax and part of the Nass River valleys. The lava blocked and partially infilled the Tseax valley and thereby created lakes, diverted channels, formed multi-channeled streams, covered the lower reaches of alluvial fans, and forced the Nass to abandon its floodplain and to flow in a confined bedrock channel. In places, there is no longer surface flow because the Tseax River flows entirely within the lava flow.

Rogers, G.C., 1976. A microearthquake survey in northwest British Columbia and southeast Alaska. Bulletin of the Seismological Society of America, v. 66, p. 1643-1655.

Abstract: In an 81-day period during the summer of 1969 four portable seismographs were operated in northwest British Columbia and southeast Alaska. One hundred and forty microearthquakes were detected. Epicenters were located near the Queen Charlotte-Fairweather fault and the Denali fault. The Chatham Strait fault showed no activity and only a few events were located in the Quaternary volcanic zone of British Columbia. A scattering of microearthquakes through the archipelago and the Coast Range and a concentration in the Glacier Bay region suggest that the seismicity may be more complex than the pattern indicated by the distribution of larger earthquakes. The most numerous seismic events recorded, numbering in the thousands, were low-frequency events emanating from a number of specific areas where large glaciers are located.

Russell, J. K. and Hauksdóttir, S., 2001. Estimates of crustal assimilation in Quaternary lavas from the northern Cordillera, British Columbia; *in* Phase

equilibria in basaltic systems; a tribute to Peter L. Roeder, (ed.) D. Canil, H. Jamieson, and R.F. Martin; Canadian Mineralogist, v. 39, Part 2, p. 275-297.
Abstract: The region between the Iskut and Unuk rivers and immediately south of Hoodoo Mountain in northwestern British Columbia is host to eight distinct occurrences of Quaternary volcanic rocks comprising alkali olivine basalt and minor hawaiite. The centers range in age from 70,000 to approximately 150 years B.P. This volcanic field, called herein the Iskut volcanic field, lies along the southern boundary of the Northern Cordilleran volcanic province (Northern Cordilleran Volcanic Province) and includes sites identified as: Iskut River, Tom MacKay Creek, Snippaker Creek, Cone Glacier, Cinder Mountain, King Creek, Second Canyon and Lava Fork. The lavas are olivine- and plagioclase-phyric, contain rare corroded grains of augite, and commonly entrain crustal xenoliths and xenocrysts. Many crustally derived xenoliths are partially fused. Petrological modeling shows that the major-element compositional variations of lavas within the individual centers cannot be accounted for by simple sorting of the olivine and plagioclase phenocrysts or even cryptic fractionation of higher-pressure pyroxene. Textural and mineralogical features combined with whole-rock chemical data suggest that assimilation of the underlying Cordilleran crust has affected the evolution of the relevant magmas. Mass-balance models are used to test the extent to which the within-center chemical variations are consistent with coupled crystallization and assimilation. On the basis of our analysis of four centers, the average ratio of assimilation to crystallization for the Iskut volcanic field is 1:2, suggesting that assimilation has played a greater role in the origins of Northern Cordilleran Volcanic Province lavas than recognized previously.

Scarfe, C. M. and Hamilton, T.S., 1980. Viscosity of lavas from the Level Mountain volcanic center, northern British Columbia; Year Book - Carnegie Institution of Washington, no. 79, p. 318-320.
Summary: As part of a study of the petrology of alkaline, volcanic rocks from Level Mountain, northern British Columbia, viscosity measurements have been made on three representative lava types – an alkali basalt, a hawaiite, and a comendite. The measurements were made at 1 atm between 1200°C and 1450°C. The data are significant to the ascent rate of the lavas and to the transport of mafic nodules included in them.

Sinclair, P. D., Tempelman-Kluit, D.J., and Medaris, L.G., Jr., 1978. Lherzolite nodules from a Pleistocene cinder cone in central Yukon; Canadian Journal of Earth Sciences, v. 15, no. 2, p. 220-226.
Abstract: Fresh spinel lherzolite nodules occur in basaltic tuff on the flank of a Pleistocene cinder cone built on Selkirk Lavas in central Yukon. The nodules are mineralogically and chemically similar to others from diverse localities. The texture and mineral chemistry are consistent with an upper mantle origin for the Selkirk nodules. Equilibration temperatures for the nodules have been determined to be about 1100°C.

Souther, J.G., 1970. Recent volcanism and its influence on early native cultures of northwestern British Columbia; *in* Early Man and Environments in Northwest America, (ed.) R.A. Smith and J.W. Smith; University of Calgary Archaeological Association, Calgary, Alberta, p. 53-64.
Introduction: Recent volcanism has played an important role in shaping the present landscape of northwestern British Columbia. From the Aiyansh cinder cone, near Prince Rupert, a broad belt containing more than sixty post-Pleistocene volcanic centres extends northward into the southern Yukon. Most of these are small, short-lived cinder cones that produced ore or two flows and then became extinct. Others erupted enormous volumes of fluid lava that spread in thin sheets to form shield volcanoes covering many hundreds of square miles. A few produced viscous lava that piled up around the conduit to form steep-sided domes while elsewhere activity was characterized by explosive eruption of pumice. Mt. Edziza, near the centre of the volcanic belt, is a composite of all these types and, throughout its four-million year period of activity has erupted

lavas ranging in composition from olivine basalt to rhyolite. Although none of these eruptions has been recorded, both Tahltan and Tsimshian Indian lore make reference to hot ash and melted rock; and, geological evidence confirms that several eruptions have occurred in northwestern British Columbia within the last 2,000 years. The ash deposits related to these young volcanoes are thus potential reference horizons of archaeological as well as geological interest. Moreover, several of the volcanoes, particularly in the Stikine region have influenced the development of early native cultures. The high, fertile lava plateau of Level Mountain, Heart Peaks and Mt. Edziza abound in game and have long been favoured hunting areas, and obsidian from Mt. Edziza has provided a ready source of material for the manufacture of high quality stone implements.

Souther, J.G., 1970. Volcanism and its relationship to recent crustal movements in the Canadian Cordillera; Canadian Journal of Earth Sciences, v. 7, p. 553-568.
Abstract: "Compressive" folding, thrusting, and transcurrent fault movement have occurred during late Tertiary and Recent times in parts of southeastern Alaska and southern Yukon west of a line joining the Denali, Queen Charlotte, and San Andreas fault systems. East of this line "compressive" deformation and transcurrent faulting ceased in the Canadian Cordillera by late Eocene time or earlier, and was followed by a period of crustal relaxation that has continued to the present. The onset of relaxation was accompanied by acid volcanism, block faulting, and high-level intrusion of granitic plutons and dike swarms. Explosive eruptions that characterized early Tertiary volcanism were followed in late Miocene and Pliocene times by quiet outpouring of plateau basalt in central British Columbia and later, during Pleistocene and Recent times, by construction of nearly 150 cinder cones and strata volcanoes. Most of these young volcanic centers are confined to two north-south trending belts and an east–west belt offsetting them. The two north–south belts parallel the direction of post Eocene dike swarms and normal faults, and are considered to have formed in response to east–west regional extension that has persisted in the western Canadian Cordillera since late Eocene time.

Souther, J.G., 1990. Edziza; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 124-126.
Summary: The volcanoes of the Mount Edziza volcanic complex in northern British Columbia are summarized briefly.

Souther, J.G., 1990. Hoodoo; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 127-128.
Summary: Hoodoo Mountain and related lava flows in northwestern British Columbia are summarized briefly.

Souther, J.G., 1990. Iskut-Unuk River cones; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 128-129.
Summary: The six small basaltic centres of the Iskut River cones, in northwestern British Columbia, are summarized briefly.

Souther, J.G., 1990. The Thumb; *in* Volcanoes of North America, (ed.) C.A. Wood and J. Kienle; Cambridge University Press, Cambridge, United Kingdom, p. 129-130.
Summary: The Thumb, largest of a group of at least seven Quaternary volcanic necks and associated dikes and flows, is described briefly.

Souther, J. G., Armstrong, R.L., and Harakal, J., 1984. Chronology of the peralkaline, late Cenozoic Mount Edziza volcanic complex, northern British

Columbia, Canada; Geological Society of America Bulletin, v. 95, no. 3, p. 337-349.

Abstract: The late Cenozoic Mount Edziza Volcanic Complex covers an area of about 1,000 km^2 in north-central British Columbia, 300 km east of the transcurrent boundary between the North American and Pacific plates. It is made up of a group of overlapping basaltic shields and intermediate to salic peralkaline composite domes, flows, and central volcanoes that are associated with extensional structures in the underlying basement. New K-Ar and fission-track dates (45) and Rb-Sr and Sr isotope analyses (12) from the Mount Edziza Volcanic Complex are reported. The age dates are for the most part consistent with the stratigraphy and indicate that frequent eruptive activity occurred during the past 8 m.y. Five major magmatic cycles each began with the eruption of basalt and culminated with the eruption of oversaturated peralkaline magma. Low $^{87}Sr/^{86}Sr$ initial ratios (0.7028 ± 0.0001) indicate a mantle source for the basalts. Low Sr contents and high $^{87}Sr/^{86}Sr$ ratios in the salic end members suggest that the oversaturated rocks were derived from the basaltic magma by crystal fractionation in crustal reservoirs. Rb-Sr isochrons suggest that residence times for the fractionating magma were about 0.7 to 1 m.y. Early removal of large amounts of plagioclase, followed by fractionation of potash feldspar, can account for most of the observed petrological and isotopic relationships. A few individual compositions and one suite of mainly intermediate samples contain anomalously large amounts of both ^{87}Sr and radiogenic argon. This indicates that contamination with crustal material and possibly mixing of parental basalt with partly fractionated magma from previous events may have produced the relatively small volume of intermediate rocks.

Souther, J. G. and Hickson, C.J., 1984. Crystal fractionation of the basalt comendite series of the Mount Edziza volcanic complex, British Columbia; major and trace elements; Journal of Volcanology and Geothermal Research, v. 21, no. 1-2, p. 79-106.

Abstract: The Mount Edziza Volcanic Complex in north-central British Columbia includes a group of overlapping basaltic shields, salic composite volcanoes, domes and small calderas that range in age from 7.5 Ma to less than 2000 years B.P. The volcanic assemblage is chemically bimodal, comprising voluminous alkali olivine basalt and hawaiite, a salic suite of mainly peralkaline trachyte and comendite, plus a relatively small volume of intermediate rocks (trachybasalt, tristanite, mugearite, benmoreite). The complex is the product of five cycles of magmatic activity, each of which began with alkali olivine basalt and culminated with the eruption of salic magma. The regular chemical variation shown by almost 100 major- and trace-element analyses suggests a genetic lineage between the basic and salic members of each cycle. Least-squares mathematical modelling, indicates that the salic rocks (trachyte and comendite) have formed by fractionation of observed phenocryst and cumulate nodule mineral phases from a common alkali olivine basalt parent magma. Hawaiite is thought to be a cumulate rock, formed by partial fractionation and feldspar accumulation within rising columns of primary alkali olivine basalt. Fractionation leading from alkali olivine basalt through trachybasalt and trachyte to comendite is believed to have taken place where primary basalt became trapped in large crustal reservoirs. The early removal of olivine, clinopyroxene and plagioclase, leading to a trachytic residuum, and subsequent fractionation of mainly alkali feldspar, leading to the peralkaline end members, is consistent with major- and trace-element variation and with isotopic and REE data. The chemical diversity of the complex is attributed to its location over a zone of crustal extension where mantle-derived basalt, trapped in large high-level reservoirs, underwent prolonged fractionation.

Spooner, I. S., Osborn, G.D., Barendregt, R.W., and Irving, E., 1995. A record of early Pleistocene glaciation on the Mount Edziza Plateau, northwestern British Columbia; Canadian Journal of Earth Sciences, v. 32, no. 12, p. 2046-2056.

Abstract: Mount Edziza is a Plio-Pleistocene volcanic complex that is located in the Stikine Terrane in northwestern British Columbia. A sequence of diamictites preserved between Ice Peak Formation basalts on the northwestern blank of Mount Edziza records an Early Pleistocene regional glaciation. The lowest Ice Peak Formation basalt flow (IP1; about 1 Ma) was probably extruded onto glacial ice because it is deformed and brecciated, it is pillowed at the base, it lies directly on hyaloclastite deposits, and there is a lack of fluvial and lacustrine sediments at the base. Fabric measurements from the underlying diamictites are consistent with lodgement processes and indicate northwest and southwest transport directions. These data, and an abundance of striated exotic cobbles, indicate that the sediment was deposited by Coast Mountain ice. Radiometric, paleomagnetic, and stratigraphic data all support the interpretation that diamictites at the section are the sedimentary record of an Early Pleistocene (about 1.1 Ma, isotope stage 32–34) regional glaciation(s). The normal paleomagnetic polarity of one of the Ice Peak Formation basalts (IP2) records extrusion during the Jaramillo normal polarity subchron (1.07–0.99 Ma) and further constrains the age of the underlying diamictites.

Spooner, I.S., Osborn, G.D., and Groot, A.,1996. Resident oral histories; a tool for the study of Recent environmental change on the Stikine Plateau of northwestern British Columbia; *in* Geomorphic Hazards, (ed.) O. Slaymaker; John Wiley and Sons, Chichester, United Kingdom, p. 9-28.

Abstract: Resident oral histories are potentially powerful tools for both the spatial and temporal resolution of past changes in the physical environment, particularly in remote, isolated areas. Although subsequent physical verification is desirable, oral histories may provide the initial evidence of past events. This methodology is most likely to be effective when researchers have some knowledge of the social structure and ethical code of the community. We have obtained information on Late-Holocene landslide and flood activity, volcanism and jokulhlaup drainage in northwestern British Columbia, in stories related by both the Tahltan natives and non-native settlers, some of whose ancestors have resided in the area for over 100 years. Landslide activity has occurred sporadically and most often has been associated with spring runoff during high snowpack years. A landslide along the Tuya River blocked the migratory route of salmon to Tuya lake, altering settlement patterns. A landslide along the Tahltan River (ca. 20 years ago) altered river hydraulics and overran a traditional gathering place. The potential exists for future landslide activity and possible blockage of the river at this site, the most important migratory route for sockeye salmon in the Stikine River drainage. A flood created by the failure of a rock avalanche-created dam once reversed the flow direction of the Stikine River. Both legends and resident histories indicate that volcanic activity on Mt. Edziza may have occurred within the last millennium indicating that the eruptive history of Mt. Edziza should be re-evaluated, especially in light of proposed economic development of the region. Recollections of jokulhlaup drainage on the lower Stikine River further document a major event that is not well understood or documented.

Sutherland Brown, A., 1969. Aiyansh lava flow, British Columbia; Canadian Journal of Earth Sciences, v. 6, no. 6, p. 1460-1468.

Abstract: The Aiyansh alkali basalt lava flow is one of the youngest volcanic features of British Columbia, about 220 years old. It issued from a vent area (55°7’N, 128°54’W) in a narrow tributary valley of the Tseax River, flowed 14 miles (22.5 km) to the Nass Valley, and there spread out in a lava plain 6 miles (9.7 km) long, forcing the river to the northern margin of the valley. The Aiyansh flow has an area of about 15 miles^2 (38.8 km^2) and a volume of about 0.1 mile^3 (0.455 km^3). The lava flow is a single cooling unit. Its surface consists of pahoehoe, slab, and block lava in a pattern related to slope, with low slopes favoring preservation of level pahoehoe. Piping and collapse were important about the margins of the lava plain. The eruption must have terminated with a series of lava fountains and explosions in the vent area which built one main and several small cones of bombs and cinders. The Aiyansh flow is entirely a fresh alkali basalt varying only slightly in crystallinity and texture. Holocrystalline specimens from the interior of the lava plain consist of about 50% plagioclase (An_{55+5}), 10% olivine (Fa_{35}), 30% pyroxene, and 10% opaques. A new chemical analysis confirms that it is a high-iron, low-magnesium, alkali basalt.

Symons, D. T. A., 1975. Age and flow direction from magnetic measurements on the historic Aiyansh flow, British Columbia; Journal of Geophysical Research, v. 80, no. 17, p. 2622-2626.

Abstract: Specimens (197) from 122 cores from 23 sites were collected from the 33-km length of the Z-shaped Aiyansh lava flow in the Nass valley of northwestern British Columbia, Canada. The specimen and core remanence directions are very consistent and give a mean of 14.0°, + 72.9° (α_{95} = 0.8°; k = 1372) after af demagnetization based on site mean directions. A field slump block test, thermomagnetic tests, and other data indicate that the flow has a very stable, uniform primary thermoremanent magnetization residing mainly in the matrix magnetite. The site mean maximum axes of the ellipsoids of anisotropy of magnetic susceptibility are not preferentially aligned along the flow direction of the lava. The flow was extruded in 1650 ± 40 A.D. based on the flow's remanence declination and extrapolation of observatory records. This refines the Indian legend and tree ring date of about 1770 A.D. and the ^{14}C date of 1700 ± 130 A.D. The virtual geomagnetic pole for the Aiyansh lava flow is 68.0°W, 81.7°N ($P_{0.05}$ δ_m = 1.4°; δ_p = 1.3°).

Thorkelson, D.J., Madsen, J.K., and Sluggett, C.L., 2011. Mantle flow through the northern Cordilleran slab window revealed by volcanic geochemistry; Geology, v. 39, no. 3, p. 267-270.

Abstract: The Northern Cordilleran slab window formed beneath western Canada concurrently with the opening of the Californian slab window beneath the southwestern United States, beginning in Late Oligocene-Miocene time. A database of 3530 analyses from Miocene-Holocene volcanoes along a 3500-km-long transect, from the northern Cascade Arc to the Aleutian Arc, was used to investigate mantle conditions in the Northern Cordilleran slab window. Using geochemical ratios sensitive to tectonic affinity, such as Nb/Zr, we show that typical volcanic arc compositions in the Cascade and Aleutian systems (derived from subduction-hydrated mantle) are separated by an extensive volcanic field with intraplate compositions (derived from relatively anhydrous mantle). This chemically defined region of intraplate volcanism is spatially coincident with a geophysical model of the Northern Cordilleran slab window. We suggest that opening of the slab window triggered upwelling of anhydrous mantle and displacement of the hydrous mantle wedge, which had developed during extensive early Cenozoic arc and backarc volcanism in western Canada. High heat flow throughout the western Canadian Cordillera is broadly coincident with the field of intraplate volcanism and is linked to slab window-induced mantle upwelling.

Trupia, S. and Nicholls, J., 1996. Petrology of Recent lava flows, Volcano Mountain, Yukon Territory, Canada; Lithos, v. 37, no. 1, p. 61-78.

Abstract: Volcano Mountain, Yukon Territory, a Quaternary edifice located near the junction of the Pelly and Yukon Rivers, erupted two Recent nephelinite lava flows between 3000 and 7300 years BP and a third Recent lava flow that is probably younger. The porphyritic nephelinites have olivine phenocrysts, Fo_{91} – Fo_{79}, and Ti-rich diopside microphenocrysts. The groundmass consists of olivine, Fo_{83} – Fo_{80}, Ti-rich diopside, ulvoespinel-magnetite solid solutions, nepheline, leucite, patches of residual glass and traces of calcite. The nephelinites also carry spinel-lherzolite xenoliths and xenocrystic olivine, Fo_{87} – Fo_{90}. The xenocrysts have lower CaO contents than the phenocrysts. Samples from the two older flows have similar Thompson space representations whereas the youngest flow has a distinctly different representation. The Thompson space representations of the Volcano Mountain nephelinites are different from the representations of nephelinites from other centers in the Cordillera. Thompson space representations and Pearce element-ratio diagrams suggest the two older flows are comagmatic whereas the youngest flow is from a separate magma batch. Thermodynamic modeling suggests the magmas that supplied the lava flows originated at pressures near 2.5 GPa, left behind a residue containing olivine, and rose along an isenthalpic path after separating from the source rocks.

Watson, K. and Mathews, W.H., 1948. Partly vitrified xenoliths in pillow basalt; American Journal of Science, v. 244, p. 601-614.

Abstract: Pillow basalt in the Tuya Range of northern British Columbia contains many xenoliths of granite and a few of quartzite. The feldspar and quartz of the granite inclusions are highly cracked and, together, have yielded abundant colourless glass with a refractive index of 1.495. Some of the partly vitrified feldspar grains are cut by glass veinlets that form extremely fine meshworks. A small proportion of the quartz contains tridymite in minute veinlets of glass. The mafic mierals have been converted almost completely to dark-brown glass. Quartzite inclusions show partial vitrification, development of basic pale-brown glass, and the formation of sanidine, cordierite, and hypersthene. A fragment of granite in basaltic agglomerate is also partly vitrified and contains the new minerals: augite and anorthoclase. The temperatures attained by the xenoliths did not exceed 1075° C, but were probably greater than 900° C.

Wuorinen, V., 1978. Age of Aiyansh Volcano, British Columbia; Canadian Journal of Earth Sciences, v. 15, no. 6, p. 1037-1038.

Abstract: Previous work on Aiyansh Volcano has suggested one period of volcanic activity, about 250 ± 130 years BP. A new radiocarbon dating of 625 ± 70 years BP suggests that two eruptions have occurred.

Yagi, K. and Souther, J.G., 1974. Aenigmatite From Mount Edziza, British Columbia, Canada; American Mineralogist, v. 59, no. 7-8, p. 820-829.

Abstract: Aenigmatite is a ubiquitous constituent of the highly fractionated, peralkaline end members of the Mt. Edziza volcanic complex in northern British Columbia. In comendite lavas and tephra it occurs as phenocrysts with aegirine, aegirine-augite, and arfvedsonite, whereas it is confined to the groundmass of trachytes. This is attributed to different fO_2's during the intratelluric and groundmass stages of crystallization of comendite and trachyte. Electron microprobe analyses indicate that both groundmass and phenocrystic aenigmatite have similar compositions that are close to those of aenigmatite from other localities. The absence of intermediate compositions between aenigmatite and rhonite suggests that solid solution between the two minerals is lacking or limited by a wide range of immiscibility.

Reports, Government Publications, and Theses

Abraham, A.-C., 2002. The nature of mantle sources for recent alkaline basalts across the northern Canadian Cordillera; Ph.D. thesis, McGill University, Montréal, Québec, 437 p.

Abstract: The Stikine Volcanic Belt is a lineament of Tertiary to Recent alkaline volcanic centres that cross disparate oceanic and continental terranes of the northern Canadian Cordillera, and extend onto the North America craton. This volcanic lineament thus offers an unique opportunity to probe the lithospheric mantle beneath these terranes and investigate the relative roles of lithospheric and asthenospheric mantle sources in the generation of alkaline lavas. Alkaline lavas in twelve volcanic centres of the Stikine Volcanic Belt were sampled and studied for major and trace elements and Sr-Nd-Pb isotopic compositions. The primitive lavas of each volcanic centre define binary arrays between two compositional end-members, olivine nephelinite (NEPH) and hypersthene-normative olivine basalt (Hy-NORM). The NEPH end-member is characterized by large enrichments in incompatible trace elements with respect to primitive mantle, but is depleted in term of its isotopic composition. The presence of amphibole in its source suggests that this end-member is derived from the lithospheric mantle. The Hy-NORM end-member has lower incompatible trace element contents, but is still relatively enriched in incompatible elements compared to primitive mantle. Although this end-member has always more radiogenic Sr and Pb, and less radiogenic Nd isotopic ratios than the NEPH end-member, its isotopic signature varies with the tectonic belt in which it erupted, indicating a significant role for the lithospheric mantle in

the derivation of the Hy-NORM basalts. The Canadian Cordilleran, and other continental Hy-NORM basalts, have low Ca and high Na contents compared to their equivalents at oceanic hot spots such as Hawaii or associated with mid-ocean ridges. A comparison with experimental melts of mantle peridotite indicates that these characteristics reflect smaller degrees of partial melting (<10%) in continental regime. The range of observed lava compositions is explained by the melting of two distinct lithospheric components, a NEPH end-member representing the melting of amphibole-rich veins, and a Hy-NORM end-member resulting from small degrees of partial melting of their host garnet lherzolite. The high heat flow values reported in the northern Canadian Cordillera are consistent with a model in which ongoing melting and thinning of the lithospheric mantle is responsible for generating the mafic alkaline magmas.

Aitken, J.D., 1959. Atlin map-area; Geological Survey of Canada, Memoir 307, 89 p.

Summary: This is a detailed description of the geology of the Atlin map-area, in northern British Columbia. A short portion of the text contains descriptions of Quaternary volcanic rocks, which include olivine basalt flows at Mount Llangorse, Cracker Creek, and Ruby Creek.

Boscov, S., 2004. Degassing study of subglacial volcanoes in the Tuya region of northern British Columbia using H_2O content and hydrogen isotope analyses; M.Sc. thesis, University of Wisconsin at Milwaukee, Milwaukee, Wisconsin, 222 p.

Summary: This study of degassing at subglacial volcanoes in northern British Columbia showed that B.C. tuyas typically have higher water contents than Icelandic tuyas. However, at B.C. tuyas, magmatic water content decreases with elevation, unlike at Icelandic tuyas. B.C. data support models where pillow basalts erupted under thicker ice or in deeper water than hyaloclastite deposits, and measured H_2O contents can be used to constrain overlying ice thicknesses. Hydrogen isotopes similarly support models that propose pillows erupted in deeper water than hyaloclastites: at Ash Mountain, δD values are less depleted (-87.2 to -102.0 per mil) than associated hyaloclastite deposits (-112.5 to -122.6 per mil).

Bostock, H.S., 1952. Geology of Northwest Shakwak Valley, Yukon Territory; Geological Survey of Canada Memoir 267, 54 p.

Summary: This is a detailed description of the geology of the Yukon Territory's Shakwak Valley, including portions of the widespread White River ash.

Casey, J.J., 1980. Geology of the Heart Peaks volcanic centre, northwestern British Columbia; M.Sc. thesis, University of Alberta, Edmonton, Alberta, 120 p.

Abstract: The Heart Peaks volcanics of northwestern British Columbia represent one of a series of late Cenozoic eruptive centres which form shields of alkali basalt and related volcanic rocks. The Level Mountain and Mt. Edziza Ranges are typical examples of this style of volcanism. The Heart Peaks plateau is a series of flat-lying, fine-grained and porphyritic flows and related pyroclastics belonging to the Level Mountain group. Associated with the plateau lavas are rhyolite and trachyte domes of the Heart Peaks Formation. The acid rocks appear to be closely related to the plateau series, having been erupted contemporaneously but likely from different vents than the basic rocks. Compositions in the Level Mountain group range from ankaramite to andesite and trachyte. Major and trace element variation in Level Mountain Group rocks give trends indicative of a fractional crystallization sequence. Basaltic rocks are transitional to mildly alkaline. Alkali basalt and hawaiite are the most voluminous compositions. Basic rocks contain abundant cognate inclusions containing olivine, clinopyroxene, kaersutite, titanomagnetite, plagioclase and alkali-feldspar which is indicative of the mineralogy of the fine-grained eruptives. Strontium and oxygen isotope compositions support a mantle origin for alkali basalt and high abundances of large-ion lithophile elements are compatible with models where small degrees of partial melting of peridote give rise to alkali basalt. The rocks of the Heart Peaks Formation differ from acid rocks of other northern B.C. centres in their lack of peralkaline compositions. There are no alkali-rich

ferromagnesian minerals which are typically found in acid rocks associated with the Level Mountain and Mt. Edziza Ranges. The close association in space and time of acid rocks to the basic rocks of the level Mountain Group suggests a mutual relationship, but lack of compositions in the intermediate range and the highly altered nature of the acid rocks makes this link obscure. The importance of alkali basalt as a significant regional magma type is supported by data from Heart Peaks. Evidence from the Heart Peaks area supports Souther's (1970, 1977a) model for the tectonic regime of late Cenozoic volcanism in the Stikine belt of northern British Columbia, where alkali basalt magma is generated in a tensional tectonic environment.

Casey, J.J. and Scarfe, C.M., 1978. Geology of the Heart Peaks volcanic centre, northwestern British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 78-1A, p. 87-89.

Abstract: The Heart Peaks Plateau, one of several late Cenozoic volcanic centres, is broadly subdivided into flat-lying basalts and trachybasalts of the Level Mountain Group and rhyolite domes of the Heart Peaks Formation. Preliminary field and petrographic observations are discussed in light of this bimodal distribution of rock types.

Casey, J. J. and Scarfe, C.M., 1980. Summary of the petrology of the Heart Peaks volcanic centre, northwestern British Columbia; Current Research, Part A; Geological Survey of Canada, Paper 80-1a, p. 356-356.

Abstract: The late Cenozoic Hearts Peak Plateau of northwestern British Columbia (Casey and Scarfe, 1978; Casey, 1979) is broadly subdivided into flat-lying basaltic to intermediate rocks of the Level Mountain Group and rhyolite and trachyte of the Hearts Peak Formation. The compositions of the Level Mountain Group lavas range from ankaramite to andesite and trachyte; alkali basalt and hawaiite are the dominant rock types. Major and trace element variations support the derivation of these lavas by a process of fractional crystallization from an alkali basalt parent. Textural and compositional similarities exist between Level Mountain Group lavas at Heart Peaks and at Level Mountain 16 km to the east (Hamilton and Scarfe, 1977; Hamilton, in preparation). The rhyolite and trachyte domes of the Heart Peaks Formation appear to be closely related to the plateau lavas and probably erupted contemporaneously from different vents. The lack of peralkaline compositions contrasts with the distinctively peralkaline nature of silicic rocks present at Level Mountain and Edziza (Souther, 1970). Strontium and oxygen isotope data support a mantle origin for alkali basalt (see also Hamilton et al., 1978) and high abundances of large-ion lithophile elements are compatible with models that have small degrees of partial melting of peridotite. The origin of the rhyolites is more obscure, however, and requires further work. Evidence from the Hearts Peak area supports Souther's (1970, 1977) model of a tensional tectonic environment for late Cenozoic volcanism in the Stikine belt of northern British Columbia.

Edwards, B.R., 1997. Field, kinetic, and thermodynamic studies of magmatic assimilation in the Northern Cordilleran volcanic province, northwestern British Columbia; Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 324 p.

Abstract: This thesis investigates the process of magmatic assimilation. Field observations, kinetic considerations, and thermodynamic calculations are used together to form a calculational model for assimilation processes in mafic magmas. Field and petrographic constraints derive from lavas within the newly defined Northern Cordilleran Volcanic Province (NCVP) of northwestern British Columbia and the Yukon Territories (Chapter One). Petrographic and geochemical evidence for assimilation is common throughout the NCVP and is especially important at the Hoodoo Mountain volcanic complex (HMVC), a pair of previously unstudied alkaline to peralkaline volcanoes within the Stikine subprovince of the NCVP, in northwestern British Columbia. Chapter Two presents the geology, stratigraphy, geochronology, petrography, and geochemistry of the HMVC and discusses its chemical and physical evolution. Subglacial volcanism and magmatic assimilation are shown to be important processes in the physical and chemical evolution of the HMVC.

Chapter Three reviews kinetic constraints on magma assimilation and the available experimental data for rates of mineral dissolution in mafic silicate melts. Published mineral dissolution experiments in basaltic melts are consistent with a time-independent dissolution mechanism. The most extensive experimental dataset (Donaldson 1985) is used to develop a model for predicting rates of mineral dissolution in basaltic silicate melts. It is shown that rates of dissolution can be simply predicted by calculating the thermodynamic driving force for the dissolution reactions (the Affinity), using the thermodynamic database of Ghiorso and Sack (1995). An existing model based solely on equilibrium thermodynamics (MELTS; Ghiorso and Sack 1995) demonstrates that crystal growth and compositional zoning are sensitive recorders of specific assimilation paths (Chapter Four). The thermodynamic database for the MELTS model is combined with the kinetic model for predicting mineral dissolution rates to produce a new model for magmatic assimilation (Chapter Five). The new model is different from preexisting models because it predicts cooling and crystallization rates implied by kinetically-controlled magmatic assimilation. Results from the new model demonstrate that magmatic assimilation processes that are controlled by kinetics operate on a time-scale of days to weeks. Given the time-scale of magma transport and volcanism, magmatic assimilation is shown to be a temporally, as well as geochemically, viable process during transport of mantle derived magmas and in the evolution of Hoodoo Mountain volcanic complex (~240 ka).

Edwards, B. R., Anderson, R.G., and Russell, J.K., 1997. Geology of the Quaternary Hoodoo Mountain volcanic complex and adjacent Mesozoic and Paleozoic basement rocks, parts of Hoodoo Mountain (NTS 104B/14) and Craig River (NTS 104B/11) map areas, northwestern British Columbia; Geological Survey of Canada, Open File 3321, scale 1:20 000.

Summary: This map shows the geologic and volcanic features of portions of the Hoodoo Mountain volcanic complex.

Edwards, B. R., Anderson, R.G., Russell, J.K., Hastings, N.L., and Guo, Y.T., 2000. Geology, the Quaternary Hoodoo Mountain volcanic complex and Paleozoic and Mesozoic basement rocks, parts of Hoodoo Mountain (NTS 104B/14) and Craig River (NTS 104B/11) map areas, northwestern British Columbia; Geological Survey of Canada, Open File 3721, scale 1:20 000.

Summary: This map shows the geologic and volcanic features of portions of the Hoodoo Mountain volcanic complex.

Edwards, B.R. and Bye, A., 2003. Preliminary results of field mapping, GIS spatial analysis and major element geochemistry, Ruby Mountain volcano, Atlin volcanic district, northwestern British Columbia; Geological Survey of Canada, Current Research, 2003-A10, 9 p.

Abstract: We present results from fieldwork, GIS spatial analysis, and major-element whole-rock geochemistry completed between July 2000 and May 2002 for the Ruby Mountain volcano, in the northwestern Atlin map area (NTS 104 N/11). The map of the distribution of lava flows, tephra, and volcanic breccia at the Ruby Mountain volcano enables the use of the Spatial Analyst tool in ArcView® 3.2 to calculate the surface areas of the lava flows and, subsequently, to estimate flow volumes. Preliminary analysis of whole-rock major-element results for 10 samples of olivine-porphyritic volcanic rocks, including samples from the Ruby Mountain volcano (8), the Ruby Creek lava flow (1), and the Cracker Creek cone (1), show that all are alkaline and vary in composition from basalt to hawaiite to basanite.

Edwards, B. R., Evenchick, C.A., McNicoll, V.J., Wetherell, K., and Nogier, M., 2006. Overview of the volcanology of the Bell-Irving volcanic district, northwestern Bowser Basin, British Columbia; new examples of mafic alpine glaciovolcanism from the northern Cordilleran volcanic province; Geological Survey of Canada, Current Research 2006-A3, 12 p.

Abstract: Fourteen previously undescribed volcanic occurrences were documented from the west-central Bowser Basin, in northern British Columbia, and have been assigned to the Bell-Irving volcanic district. Thirteen of the areas were briefly surveyed during aerial reconnaissance, while the fourteenth was mapped and described during three days of fieldwork in August of 2004. All fourteen areas contained deposits of pillow lavas and/or volcaniclastic rocks and were interpreted as products of Pleistocene, alpine glaciovolcanic eruptions. Samples from Craven Lake volcanic centre are basanites. A sample from the Bell-Irving River volcanic centre was dated by ^{40}Ar- ^{39}Ar to be 0.43±0.15 Ma, consistent with the interpretation that the deposits formed via interaction with Pleistocene ice. The Bell-Irving volcanic district is considered to be part of the northern Cordilleran volcanic province.

Edwards, B. R., Hamilton, T.S., Nicholls, J., Stout, M.Z., Russell, J.K., and Simpson, K., 1996. Late Tertiary to Quaternary volcanism in the Atlin area, northwestern British Columbia; *in* Current Research 1996-A, Geological Survey of Canada, p. 29-36.

Abstract: We extend the previous descriptions and report preliminary interpretations for age constraints based on field data for several occurrences of Late Tertiary to Quaternary volcanic deposits in the Atlin area: Ruby Mountain, Cracker Creek, Volcanic Creek, Llangorse Mountain, and Chikoida Mountain. The deposits include a collection of extensively eroded feeder pipes (Chikoida), a tall, columnar-jointed vent plug or a vent proximal lava flow (Llangorse), isolated cinder cones with associated lava flows (Cracker and Volcanic creeks), and a partly eroded stratovolcano (Ruby Mountain). The volcanic products at two localities, Ruby and Chikoida mountains, contain crustal xenoliths. Peridotite xenoliths are present at all five localities. Two of the deposits, Volcanic and Cracker creeks, appear to be postglacial, whereas Ruby and Llangorse mountains have undergone moderate glacial modification. An approximate age for the bodies exposed at Chikoida Mountain is indeterminate but they appear to have been extensively glaciated.

Edwards, B. R. and Russell, J.K., 1994. Preliminary stratigraphy of Hoodoo Mountain volcanic centre, northwestern British Columbia; *in* Current Research 1994-A; Geological Survey of Canada, p. 69-76.

Abstract: Hoodoo Mountain volcanic centre is a complex edifice consisting of multiple trachyte lava flows and domes interlayered with pyroclastic rocks and deposits. Aphanitic trachyte flows and hyaloclastite are the oldest volcanic units; they underlie sequences of welded and unwelded pyroclastic flows, and aphanitic domes and lavas. Porphyritic trachyte lavas with up to 20% anorthoclase phenocrysts cap the entire volcanic sequence. Little Bear mountain volcanic centre lies immediately north of Hoodoo Mountain and consists of basalt, basaltic breccia, hyaloclastite, and crystal lithic tuff. Stratigraphy and radiometric dates (Souther and Yorath, 1991) suggest volcanic activity was interspersed with glacial activity over at least the past 110 000 years. The youngest lava flows erupted after the last major glaciation in this region. Hyaloclastite deposits at Hoodoo Mountain and at Little Bear mountain are interpreted as products of subglacial eruptions.

Edwards, B. R. and Russell, J.K., 1995. Revised stratigraphy for the Hoodoo Mountain volcanic centre, northwestern British Columbia; *in* Current Research 1995-A; Geological Survey of Canada, p. 105-115.

Abstract: Detailed mapping during 1994 at Hoodoo Mountain volcanic centre indicates: 1) some hyaloclastite deposits on Hoodoo Mountain are genetically related to subglacial lava flows, 2) pillow lavas and pillow lava breccias occur on Little Bear mountain, and 3) tillites and glaciolacustrine sediments are an important part of the volcanic stratigraphy. The revised stratigraphy for the Hoodoo Mountain volcanic centre suggests: 1) at least five periods of subaerial and subglacial eruption at Hoodoo Mountain volcano, 2) the Little Bear mountain

volcano is older than the youngest subglacial lava flows of the Hoodoo Mountain volcano, and 3) grey phonolite dykes associated with subglacial eruptions from Hoodoo Mountain volcano postdate the two oldest lava series at that volcano.

Edwards, B.R. and Russell, J.K. 1996. An overview of the nature, distribution and tectonic significance of xenoliths from the Stikine Volcanic Belt, northern Cordiller; *in* Slave-NORthern Cordillera Lithospheric Evolution (SNORCLE) and Cordilleran tectonics workshop, University of British Columbia, Lithoprobe Secretariat for the Canadian Lithoprobe Program, Calgary, Alberta; Lithoprobe Report, v. 50, p. 96-107.

Summary: Ultramafic and feldspathic xenoliths are found throughout the northern Cordillera in magmatic centres of the Stikine Volcanic Belt (SVB), which is a broad zone of Neogene to Recent, extension/plume-related magmatism 1200 km in length. The xenoliths comprise samples from several different depths of the continental lithosphere and as such contain important information about the composition and evolution of the northern Cordillera lithosphere. The purpose of this paper is to briefly review the nature and distribution of the xenoliths and to outline their importance for constraining tectonic models for the evolution of the northern Cordillera.

Edwards, B. R., Russell, J.K., Anderson, R.G., and Harder, M., 2003. Overview of Neogene to Recent volcanism in the Atlin volcanic district, Northern Cordilleran volcanic province, northwestern British Columbia; Geological Survey of Canada, Current Research 2003-A8, 6 p.

Abstract: We present an overview and summary of recent field and geochemical studies on Neogene to Recent mafic alkaline volcanic rocks in the Atlin volcanic district, one of the major subdivisions within the Northern Cordilleran volcanic province. The volcanic deposits in this district are subdivided into two spatially separated volcanic fields, Surprise Lake and Llangorse. Both comprise mafic alkaline rocks, which range in composition from alkaline basalt to nephelinite, contain abundant populations of felsic and peridotitic xenoliths, and locally directly overlie deposits of late Tertiary-Quaternary gravels. In two locations, Ruby Creek and Volcanic Creek, the Au-bearing gravels are being actively mined (Ruby Creek) or explored (Volcanic Creek). Field relationships suggest that many volcanic features in the Atlin district formed during the Quaternary.

Eiché, G.E., 1986. Petrogenesis of the basalts of the Alligator Lake alkaline complex, Yukon Territory; M.Sc. thesis, University of Toronto, Toronto, Ontario, 100 p.

Abstract: Primitive and differentiated lava types of alkaline affinity comprise the five extrusive units of the Quaternary Alligator Lake volcanic complex of southwestern Yukon. The chemical distinctiveness of units 1, 4, and 5 (hypersthene-, quartz-, and nepheline-normative, respectively) suggests that these lavas had a complex history involving the differentiation of their magmas after leaving their mantle sources. Most lava flows comprising units 2 and 3, however, are alkali olivine basalts and basanites which have high Mg contents (13.5-19.5 cation %) and host spinel lherzolite xenoliths, indicating that their compositions reflect primary magmas derived directly from the mantle. However, although the lavas from both units 2 and 3 have erupted coevally from adjacent vents and are petrographically similar, they are chemically distinct. Unit 2 lavas have considerably higher abundances of LREE, LILE, and Fe; lower HREE, Y, Ca, Si, and Al; and similar ratios of highly incompatible elements and isotopes relative to unit 3. These features are most simply explained if unit 2 magmas segregated at greater depths than unit 3 magmas from a garnet-bearing mantle by smaller degrees of partial melting relative to unit 3. Thus, the lavas of units 2 and 3 reflect the coexistence of two contrasting primary magma types. The relatively low or similar abundances of incompatible trace elements in the differentiatied lavas of units 1, 4, and 5 relative to units 2 and 3 indicate that they could not have fractionated from the latter, and the large range in their normative composition suggests that they were derived from several parental

magma types. Thus, a spectrum of compositionally distinct primary magma types appear to have been associated with the eruption of less than 0.5 km^3 of lava at Alligator Lake, emphasizing the complex but small batch nature of magma genesis and evolution in this region of the northern Canadian Cordillera.

Elliott, R.L., Koch, R.D., and Robinson, S.W., 1981. Age of basalt flows in the Blue River valley, Bradfield Canal quadrangle; United States Geological Survey, Circular 823-B, p. B115-B116.

Summary: Holocene flows of alkali-olivine basalt in the valley of the Blue River, and its tributary Lava Fork, are probably the youngest eruptive rocks in the southern part of southeastern Alaska. A single radiocarbon date on wood from a partly charred conifer log on the surface of one of the flows yields an age of 360±60 yr B.P. (USGS-639) for that flow. The flows cover alluvial glacial (?) deposits in the glacially eroded valleys of Lava Fork, Blue River below Lava Fork, and Unuk River at is confluence with Blue River. The principal vent area is at or near the top of a 1,400-m-high ridge on the east side of Lava Fork, 5 km north of the international boundary in British Columbia. No well-formed cone is present at the vent area, and none is likely to have formed on the precipitous slopes above Lava Fork. Steep cascades of basalt follow two broad channels down the valley wall from the vent area to lava Fork where two lakes, 1 and 2 km long, were formed as the lava and debris fans at the base of the basalt cascades dammed the river. Lava flowed 12 km down Lava Fork and its confluence with Blue River where a broad lava fan spread across the 1-km-wide valley floor to dam the river and create Blue Lake. Basalt continued to flow southward down the Blue River valley for 9 km where it spilled out onto the broad alluvial flat of the Unuk River and forced the river against its southeastern valley wall. A broad, gently sloping lava field, extending nearly 1 km upstream and 3 to 4 km downstream from the mouth of the Blue River valley, represents the farthest extent of the Blue River flows. A single small sleep-walled cinder cone on the floor of the Blue River valley, 15 km downstream from the main vent area, is surrounded by flows. Two or more flows above the horizon of the radiocarbon sample may be significantly younger than 360±60 yr B.P.

Evenchick, C. A., Alldrick, D.J., Currie, L.D., Haggart, J.W., McCuaig, S., McNicoll, V., and Woodsworth, G.J., 1997. Status of research in the Nass River multidisciplinary geoscience project, British Columbia; *in* Current Research 1997-A/B; Geological Survey of Canada, p. 21-30.

Modified abstract: Progress of research in the Nass River map area includes completion of bedrock mapping in one quarter of the area and surficial mapping in the west half. Advance on related topics was integrated with bedrock mapping through structural and stratigraphic analysis, radiometric age determination sampling to constrain the timing of events, completion of sampling for a study of Tertiary uplift, and studies of young volcanic rocks, which include those of the Tseax volcanics.

Evenchick, C.A., Ferri, F., Mustard, P.S., McMechan, M.E., Ricey, D., McNicoll, V.J., Osadetz, K.G., O'Sullivan, P.B., Stasiuk, L.D., Wilson, N.S.F., Poulton, T.P., Lowe, C., Enkin, R.J., Waldron, J., Snyder, D.B., Turner, R.J.W., Nowlan, G., and Boddy, M., 2005. Highlights of recent research in the Bowser and Sustut basins project, British Columbia; Geological Survey of Canada, Current Research 2005-A1, 11 p.

Summary: This paper summarizes recent mapping and analysis of the Bowser and Sustut basins, with a focus on energy resource potential. However, there is also a brief introduction to the Quaternary volcanic rocks of the Bell-Irving volcanic district.

Evenchick, C. A. and Mustard, P.S., 1996. Bedrock geology of north-central and west-central Nass River map area, British Columbia; *in* Current Research 1996-A; Geological Survey of Canada, p. 45-55.
Abstract: Jurassic (and earliest Cretaceous(?)) Bowser Lake Group rocks underlie more than 90% of north-central and west-central Nass River map area. Tertiary, Quaternary(?), and Recent igneous rocks comprise 10% of bedrock. Bowser Lake Group is composed entirely of turbidites. They are commonly lithic to arkosic arenites; minor variations include thick mud-rich intervals, sandstone with detrital muscovite, and turbidites derived from a volcanic source. The structure is dominated by chevron-style parallel folds which accommodated significant horizontal shortening. In the northeast, folds are upright, trend northwest, and have gentle plunge. In the southwest, folds are gently inclined (varying to overturned), trend northeast, and verge southeast. Interference between the two orientations is apparent in the southwest. Hyder pluton is composed of massive biotite hornblende granite and quartz monzonite with peraluminous and K-feldspar megacrystic phases. Extrusive rocks are erosional remnants of upper Tertiary or Quaternary and Recent basaltic flows.

Evenchick, C.A. and Thorkelson, D.J., 2005. Geology of the Spatsizi River map area, north-central British Columbia; Geological Survey of Canada, Bulletin 577, 276 p.
Summary: This paper describes in detail the bedrock geology of the Spastizi River map area of north-central British Columbia. Although most of the volcanic rocks in the area are pre-Pleistocene, one ridge east-southeast of Tumeka Lake is capped by an erosional remnant of columnar-jointed basalt that may be Pleistocene in age; it includes numerous lherzolite nodules.

Fillipone, J. A. and Ross, J.V., 1989. Stratigraphy and structure in the Twin Glacier-Hoodoo Mountain area, northwestern British Columbia (104B/14); Geological Fieldwork 1988, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1989-1, p. 285-292.
Summary: This short paper describes the results of geologic mapping of a small area north of Hoodoo Mountain, British Columbia, which includes some young volcanic rocks.

Fladmark, K.R., 1985. Glass and ice: the archaeology of Mount Edziza; Department of Archaeology, Publication no. 14, Simon Fraser University, Burnaby, British Columbia, 217 p.
Abstract: Results of a first-stage archaeological reconnaissance of the Mt Edziza obsidian source area in northwestern British Columbia, Canada, are described. Mt Edziza obsidian has been utilized by native people for 9-10,000 years and widely distributed throughout surrounding regions. Archaeological investigations reveal primary concentrated obsidian outcrops and quarry sites at high elevation, as well as lower and more dispersed areal scatters of raw material. Preliminary excavation results and paleoenvironmental reconstructions suggest that the concentrated alpine obsidian sources were probably most intensively exploited prior to 3000 B.P. and the onset of cooler Neoglacial climates. Site 'trains', or series of functionally differentiated workshops and campsites are distributed around the primary obsidian sources at lower elevations near the tree-line. Many of these sites appear to have emphasized manufacture of ovate biface-preforms as the main form in which obsidian was redistributed beyond the mountain source.

Gabrielse, H., 1962. Geology, Cry Lake; Geological Survey of Canada, Map 29-1962, Sheet 1041, scale 1: 253 440.
Abstract: The map is a compilation of work done from 1957-1962, and includes a series of Pleistocene cinder cones in the vicinity of Dark Mountain and Dome Mountain, and some flat-lying lava flows and intercalated tuffs which may be remnants of a stratovolcano.

Gabrielse, H., 1970. Geology of Jennings River map-area, British Columbia (104-0); Geological Survey of Canada, Paper 68-55, 37 p.

Modified abstract: The Jennings River map-area lies mainly within the Cassiar Mts. and Stikine Plateau, from 59-60° N and 130-132° W. In the northeastern part of the map-area, stratified rocks range in age from Proterozoic to possibly Permian. Pre-Mississippian rocks are nonvolcanic, whereas the younger rocks include abundant volcanics. Southwest of Cassiar batholith the area is underlain by Carboniferous and Permian cherts, slates, quartzites, limestones, and volcanics, in part regionally metamorphosed, and locally overlain unconformably by Triassic volcanics and minor sedimentary rocks and by Lower Jurassic (?) greywacke and slate. Large bodies of granitic rocks of possible Jurassic to Early Tertiary age have intruded the stratified rocks. Regional deformation occurred during post-Permian and pre-LateTriassic time; later deformations involved Upper Triassic and Lower Jurassic (?) strata. Late Tertiary, Pleistocene, and Recent volcanic centres have produced numerous conical and flat-topped volcanoes and gently-dipping flows, including the volcanics of the Iverson Creek, Klinkit Lake, High Tuya Lake, and Rancheria regions.

Godfrey-Smith, D. I., 1985. X-ray fluorescence characterization of the obsidian flows from the Mount Edziza volcanic complex of British Columbia, Canada; M.Sc. thesis, Simon Fraser University, Burnaby, British Columbia, 147 p.

Abstract: The purpose of this work was to determine how many chemically distinct obsidian flows exist in the Mount Edziza Volcanic Complex; to characterize these obsidian flows chemically; and to apply this information towards the understanding of prehistoric obsidian exploitation within the Complex. The Complex, located in northwestern British Columbia, constitutes the largest obsidian source area in Canada; by virtue of its size, accessibility, and location, it is also the most significant prehistorically exploited obsidian quarry in the Northwest. This is attested to by the wide distribution of artifacts made from Mount Edziza obsidian, extending hundreds of kilometres away from the Complex. This thesis reports the results of x-ray fluorescence analyses of both native obsidian rocks and of artifacts collected within the study area. A set of 174 obsidian rocks from outcrop and gravel deposits was analyzed semi-quantitatively by energy-dispersion x-ray fluorescence, and the relative concentrations of a number off elements were determined. On the basis of these relative elemental concentrations, ten chemically distinct types of obsidian were identified. Each chemical type of obsidian was then correlated to a unique obsidian flow within the Complex. The absolute concentrations of 28 major and minor elements in each of the ten obsidian flows were determined using wavelength-dispersion x-ray fluorescence. On the basis of these quantitative data, eight of the Edziza obsidians were found to have a peralkaline chemical composition; five of these fall within the class of rocks known as pantellerites, while three were classified as comendites. The other two flows were interpreted as sub-alkaline. The semi-quantitative energy-dispersion x-ray fluorescence method was also applied to determine the sources of 169 obsidian artifacts from three archaeological sites situation within the Mount Edziza Volcanic Complex. The results indicate preferred exploitation of the high-elevation obsidian sources from one central location. The results also suggest that the people who exploited the Complex ignored all the poorer-quality low- elevation obsidian scatters, and that they may not have exploited the high plateau region north of Raspberry Pass. This raises the possibility that the obsidian sources north of Raspberry Pass were not accessible at that time, perhaps due to harsher environmental conditions than at present.

Haggart, J.W., Woodsworth, G.J., and Justason, A., 1998. Update on geological mapping, southeast Nass River map area, British Columbia; *in* Current Research 1998-A; Geological Survey of Canada, p. 69-77.

Abstract: Paleontological data indicate that Lower Jurassic strata are present in the Hazelton Mountains, southeastern Nass River map area. Upper Jurassic strata of the Bowser Lake Group underlie most pasts of Kiteen River map area, British Columbia, although (?) Eocene plutonic rocks and Pleistocene volcanic and sedimentary strata are noted locally. Within the Bowser Lake Group, a fossiliferous, massive, fine-grained facies and a poorly fossiliferous turbidite facies are

recognized; the former may predate the latter within the group. Bowser lake Group strata are deformed into east-verging fold and thrust structures, cut by undeformed (?) Tertiary dykes. Available evidence suggests that no gradational relationship exists between the Bowser Lake Group and the Lower Cretaceous Skeen Group.

Hamilton, T.S., 1981. Late Cenozoic alkaline volcanics of the Level Mountain range, northwestern British Columbia: geology, petrology and paleomagnetism; Ph.D. thesis, University of Alberta, Edmonton, Alberta, 490 p.

Modified abstract: Level Mountain is a Late Cenozoic shield volcano located near 13°120'W, 58°31'N in the Stikine Volcanic Belt of northern British Columbia. The volcanic plateau with an average elevation of 4500' (1372 m), is younger than Upper Miocene in age and comprises up to four sequences of alkali basalt and ankaramite flows and tuffs. The central region of peaks and ridges rises to a maximum elevation of 7200' (2195 m), and has a repetitive bimodal distribution of alkali basalt and peralkaline salic lavas and tuffs that spans the period from 4.5 million years b.p. to recent times. Feeble basaltic vents with spatter, bombs and scoria apparently postdate continental glaciation. A paleomagnetic study on two stratigraphic sections that span the entire range of volcanism samples the earth's major polarity reversals for the past 6 MY. Petrochemically the lavas belong to the sodic alkali basalt series and are of continental affinity. The presence of basic and salic, undersaturated and oversaturated, peralkaline and metaluminous rocks attests to the complexity of petrogenetic processes at Level Mountain. Although the two volumetrically important lava types appear to be primary and mantle derived, the presence of some rhyolites enriched in ^{18}O, granitic gneiss inclusions in basalts and tristanites and great variation in whole rock lead isotope rations are probably all indicative of some degree of interaction between magmas and crustal rocks. Major and trace element geochemical variations and mineralogy indicate an upper mantle origin at shallower than 15 kbar pressure from an undersaturated ultramafic source that possessed an abundance of alkalis and incompatible elements. The field relations of some comendite flows imply fluid behaviour and seems to indicate a viscosity two to three orders of magnitude lower than would be predicted on the basis of silica content and whole rock chemistry. This could be partially reconciled if the gas phase had been halogen rich and dry. Calculations of the volume and energetics of the volcanism of the Stikine Belt indicate that less than 15% of the modern heat flow is necessary to maintain the levels of volcanicity since Pliocene times.

Hamilton, T. S. and Scarfe, C.M., 1977. Preliminary report on the petrology of the Level Mountain volcanic centre, northwest British Columbia; Geological Survey of Canada, Paper 77-1A, p. 429-434.

Introduction: Level Mountain is a shield volcano which outcrops over an areas of about 700 square miles in northeastern British Columbia (131°20'W; 58°31'N). The volcanic plateau, with an average elevation of about 4500 feet, has a central region of peaks and ridges rising to a maximum elevation of 7200 feet at Meszah Peak. Reconnaissance mapping by Gabrielse and Souther (1962) indicates a sequence of lavas of Late Tertiary to Recent age. These lavas belong to the alkalic series and range in composition from ankaramite to comendite (Hamilton and Scarfe, 1976). Souther (1966) and Souther and Symons (1974) have described similar alkalic lavas on Mt. Edziza, a volcano about 60 miles southeast of Level Mountain. Late Cenozoic volcanism in this part of British Columbia may be associated with deep crustal rifting (Souther, 1970). This report covers work completed during the 1975 and 1976 field seasons, a total of 11 weeks, together with supporting petrographic and chemical analyses.

Harder, M., Russell, J.K., Anderson, R.G., and Edwards, B.R., 2003. Llangorse volcanic field, British Columbia; Geological Survey of Canada, Current Research 2003-A6, 10 p.

Abstract: The Llangorse volcanic field is located southeast of Atlin, British Columbia, and is part of the larger Atlin volcanic district of the Northern Cordilleran volcanic province. The Llangorse volcanic field comprises seven localities of Neogene to Quaternary volcanic rocks: Hirschfeld Creek-Line Lake, Mount Sanford, Llangorse Mountain (sites 1, 2, 3, and 4), and Chikoida Mountain. The compositions of lava from these centres include olivine nephelinite, basanite, and alkali olivine basalt; all of the Llangorse Mountain sites are basanite. During the summer of 2002, the Llangorse Mountain sites and Chikoida Mountain were mapped in detail as part of the Atlin Targeted Geoscience Initiative, and the results are described in this paper. These exposures of volcanic rocks represent erosional remnants of valley-filling lava flows. Furthermore, many of these volcanic rocks show features that suggest impoundment against or eruption under ice.

Hauksdóttir, S., 1992. Petrography, geochemistry and petrogenesis of the Iskut-Unuk Rivers volcanic centres, northwestern British Columbia; M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 253 p.

Abstract: The Iskut-Unuk Rivers centres consist of eight Recent volcanic centres located within the Stikine volcanic belt, northwestern British Columbia. The centres include: Iskut River, Tom MacKay Creek, Snippaker Creek, Cone Glacier, Cinder Mountain, King Creek, Second Canyon and Lava Fork and comprise lava flows, pillow lava, cinder and ash. The volcanic rocks range in age from 70,000±30,000 to -150 years B.P. and are dominantly alkali olivine basalts; hawaiite is observed only at Cinder Mountain volcanic centre. The basalts are olivine and plagioclase porphyritic and contain rare resorbed clinopyroxene. The groundmass includes olivine, plagioclase, titanaugite, magnetite and locally ilmenite. Large plagioclase crystals with extremely diverse crystal habits and textures are abundant in lavas from Iskut River, Snippaker Creek, Cone Glacier and King Creek volcanic centres. Crustal xenoliths are most abundant at Lava Fork but also occur within the lavas from Iskut River, Snippaker Creek, Cone Glacier and King Creek. Olivine compositions within the basalts range from Fo_{55} to Fo_{83}; Cinder Mountain hawaiites contain Fo_{33-54}. Clinopyroxene Mg#'s range from 46 to 76 and can contain up to 6 wt % TiO_2. The compositions of resorbed clinopyroxene phenocrysts indicate crystallization at slightly different magmatic conditions than the groundmass clinopyoxene. Based on textures and habits, plagioclase crystals are divided into 4 groups including: megacrysts, phenocrysts, sieved phenocrysts and groundmass. Megacrysts and phenocrysts range in composition from An_{50} to An_{70}. Groundmass laths of plagioclase range from An_{38} to An_{68} in composition. Sieved phenocrysts of plagioclase are either of magmatic origin (An_{50-70}) or they are xenocrysts as suggested by prominent dissolution surfaces (sieved), observed with Nomarski technique, and low An-content (An_{6-48}). Most crustal xenoliths derive from granitic basement rocks; partial melting of xenoliths gives rise to glasses with compositions close to alkali feldspar. The chemical diversity observed within the centres cannot be explained by closed system processes involving the observed magmatic mineral phases. Two different hypotheses can explain this variation: i) source region processes including heterogeneous mantle melt or many separate partial melts and/or ii)assimilation of crustal material. With mass balance calculations the chemical variations of samples within Iskut River, Snippaker Creek and Cone Glacier volcanic centres, can be explained by fractionation of olivine (3.2-5.7%) and plagioclase (1.2-11.22%) and assimilation of granitic melt (3.5-6.2%). Cinder Mountain intermediate rocks are not derived from a basalt collected from the area, but the variation within the hawaiite flows is possibly related through coupled fractionation and assimilation processes.

Hauksdóttir, S., Enegren, E.G., and Russell, J.K., 1994. Recent basaltic volcanism in the Iskut-Unuk rivers area, northwestern British Columbia; *in* Current Research 1994-A, Geological Survey of Canada, p. 57-67.

Abstract: The Iskut-Unuk rivers area contains eight Recent volcanic centres comprising alkali-basalt lava flows, pillow lava, hyaloclastite and cinder cones, including: the Iskut River, Tom MacKay Creek, Snippaker Creek, Cone Glacier, Cinder Mountain, King Creek, Second Canyon and Lava Fork centres. Lava flows range from 70 000 to 150 years. The oldest volcanic rocks underlie the Iskut River Lava Flats and the youngest occur at the Lava Fork centre. The lavas erupted from each centre are similar in mineralogy. Most contain plagioclase and olivine phenocrysts and clinopyroxene occurs as a groundmass phase. Plagioclase megacrysts characterize lavas from a

number of volcanic centres, but are particularly abundant in lavas from Snippaker Creek and Cone Glacier. Crustal xenoliths are abundant in Lava Fork and Cone Glacier lavas but less common elsewhere. Many of the volcanological features are attributable to volcanic eruptions occurring near and beneath glaciers.

Huscroft, C.A., 2002. Late Cenozoic history of the Yukon River valley, Fort Selkirk to the Stevenson Ridge map area (115 I/13,14 and J/13,14,15); M.Sc. thesis, Simon Fraser University, Burnaby, British Columbia, 153 p.

Abstract: The Plio-Pleistocene record of terrace formation, glacial incursion, and volcanic eruption was investigated to reconstruct the evolution of the Yukon River valley from Fort Selkirk to Stevenson Ridge map area. Regional surficial geology mapping was carried out in the unmapped portion of the study area (NTS map sheet 115 J/13,14,15). Surficial deposits range in age from latest Tertiary to Holocene. Mapping reveals a mature landscape in which colluvial blankets and veneers cover hillsides and ridge tops. Bedrock exposures are rare. Fluvial plains, glaciofluvial terraces, loess aprons, and organic fills have accumulated in most valley bottoms. The regional extent of glacial features, the distribution of surficial materials, and inventories of pebble lithologies in tributary drainages indicate that incursion of the Cordilleran Ice Sheet into tributary valleys did not extend beyond the confluence of Britannia Creek and Yukon River. However, local alpine areas above 4000 ft (1220 m) did support cirque glaciers. Stratigraphic, paleomagnetic and radioisotope investigations of the Selkirk Volcanic Group have identified a new eruptive period and constrained the age of the Reid Glaciation in central Yukon. Approximately 10 km downstream from Fort Selkirk, a succession of 311 ± 32 ka basalt flows, is overlain by outwash deposited during the Reid Glaciation. This relationship combined with a minimum age of 190 ka provided by the Sheep Creek tephra constrains the Reid Glaciation to Oxygen Isotope stage 8. The presence of thick, forset-bedded, pillow breccia units intercalated with middle and early Pleistocene subaerial flows indicates that lavas repeatedly caused damming of the Yukon River. A record of pre-Reid glaciation is chronicled by the presence of glaciofluvial terraces within the study area. Two populations of pre-Reid terraces were identified according to comparisons of their degree of soil development, terrace elevation, and regional glacial stratigraphy. Terraces 200-250 m above river level have preserved morphological and mineralogical features of the Wounded Moose paleosol (early Pleistocene). Soil development, characteristic of the Diversion Creek paleosol (middle Pleistocene), commonly occurs on pre-Reid terraces between 110 and 30 m above river level. These findings suggest that soils with characteristics of the Diversion Creek paleosol also developed prior to the Reid glaciation and that the soil chronosequence established for the central Yukon requires refinement.

Huscroft, C. A., Barendregt, R.W., and Jackson, L.E., Jr., 2001. Late Cenozoic geology, Ancient Pacific Margin NATMAP Project, Report 4, Paleomagnetic and geomorphic evidence for Brunhes-age volcanism, Fort Selkirk and Rosebud Creek area, Yukon Territory; Geological Survey of Canada, Current Research 2001-A4, 15 p.

Abstract: Normally magnetized, valley-filling basalt flows extend more than 10km down the Yukon River valley from the Fort Selkirk area. These flows are locally overlain by gravel and terminate at the level of the contemporary Yukon River flood plain, suggesting a middle to late Pleistocene age for this previously unrecognized eruptive event. Unlike other valley-filling phases of the Selkirk Volcanic Group, this eruption postdates the Pliocene to early Pleistocene pre-Reid glaciations. Normal magnetism was also determined for basalt flows underlying terraces in the area of the Rosebud Creek-Grand Valley Creek confluence, 60km to the northwest of the Fort Selkirk area. Based on their unique geomorphic and stratigraphic settings, the Rosebud basalt flows may represent yet another period of Pleistocene volcanism which predates one of the pre-Reid glaciations in the central Yukon Territory.

Jackson, L. E., Jr., 1989. Pleistocene subglacial volcanism near Fort Selkirk, Yukon Territory; *in* Current Research, Part E; Geological Survey of Canada, Paper 89-1E, p. 251-256.

Abstract: A volcanic edifice near Fort Selkirk, Yukon, is almost entirely composed of hyaloclastite tuffs, breccias, and pillow breccias. Pillow basalt is found near the summit of the mountain. All of these lithologies contain rounded and faceted exotic pebbles. These observations, plus the gentle slopes of the mountain, indicate that it erupted beneath an ice sheet. Since deposits of the Reid Glaciation only reach the base of the mountain, the eruption must have occurred during a pre-Reid glaciation. Faulting must have occurred beneath the north end of the mountain during the Pleistocene.

Jackson, L.E., Jr., 2000. Quaternary geology of the Carmacks map area, Yukon Territory; Geological Survey of Canada, Bulletin 539, 74 p.

Abstract: The Carmacks map area has been partly or extensively glaciated a minimum of four times during the past ca. 1.5 million years. The two oldest, named pre-Reid glaciations occurred prior to the last magnetic reversal (>0.78 Ma BP). The pre-Reid glaciations and subsequent Reid Glaciation were separated by at least two periods of interglacial climate. Interglacial climates were similar to those of today or radically warmer. The Wounded Moose paleosol developed early in this period. Auriferous placers were deposited in the Dawson Range. The glacial ice was less extensive during Reid Glaciation than during the pre-Reid glaciations. During the period between the Reid and McConnell glaciations, the climate warmed to one comparable to the present. The Diversion Creek paleosol developed during this mild interval. The glacial ice cover of the latest (McConnell) glaciation was less extensive than that of the Reid Glaciation. Following the end of the McConnell Glaciation, the Yukon River, and presumably other major streams, incised close to their contemporary levels by the early Holocene. Volcano Mountain erupted around the Pleistocene-Holocene boundary and may have been active during the mid-Holocene. Bedrock is characteristically competent in the study area with the exception of the Carmacks Group. The most significant occurrences of placer gold occur in the Dawson Range. They result from the weathering and transport of lode gold associated with intrusions of the felsic subvolcanic Mount Nansen Group. All existing placer operations either overlie or are topographically downslope from Mount Nansen Group intrusions.

Jackson, L. E., Jr., Barendregt, R., Irving, E., and Ward, B., 1990. Magnetostratigraphy of early to middle Pleistocene basalts and sediments, Fort Selkirk area, Yukon Territory; *in* Current Research, Part E; Geological Survey of Canada, Paper 90-1E, p. 277-286.

Abstract: Paleomagnetic study has shown that the Selkirk Volcanics and interstratified glacial and nonglacial sediments are excellent recorders of the paleofield. Comparison with the time scale of reversals of the paleofield shows that the Selkirk Volcanics in the vicinity of Fort Selkirk were laid down during the Matuyama Reversed Polarity Chron. The oldest pre-Reid Glaciation occurred prior to the start of the olduvai Normal Polarity Subchron (>1.87 Ma). The youngest pre-Reid Glaciation occurred in the post-Olduvai part of the Matuyama (0.79-1.67 Ma). The thick fill of glacial sediments in the adjacent Pelly River valley was deposited entirely within the Brunhes Normal Polarity Chron.

Jackson, L.E., Jr., Huscroft, C.A., Gotthardt, R., Storer, J.E., and Barendregt, R.W., 2001. Field guide: Quaternary volcanism, stratigraphy, vertebrate palaeontology, archaeology, and scenic Yukon River tour, Fort Selkirk area (NTS 115 I), Yukon Territory; Occasional Papers in Earth Sciences, v. 3, 36 p.

Summary: This is a field trip guide for an excursion that includes Ne Ch’e Ddhäwa, Volcano Mountain, and other Pleistocene and Holocene centres in the Fort Selkirk volcanic field.

Jackson, L. E., Jr. and Stevens, W., 1992. A Recent eruptive history of Volcano Mountain, Yukon Territory; *in* Current Research, Part A; Geological Survey of Canada, Paper 92-01A, p. 33-39.

Abstract: The most recent eruptions of Volcano Mountain are no younger than mid-Holocene and could be early Holocene or older. The latest events erupted lava flows and pyroclastic ejecta from a central crater and lava flows from breakouts low on the flanks of the mountain. These were accompanied by collapse of the crater rim on the east and west sides of the mountain.

Lakeman, T.R., 2006. Late-glacial alpine glacier advance and early Holocene tephras, northern British Columbia; M.Sc. thesis, Simon Fraser University, Burnaby, British Columbia, 115 p.

Abstract: Two related studies in northern British Columbia are presented. The first documents moraines in Finlay River area that record an advance of alpine glaciers. A minimum age of 9230 radiocarbon yr BP and the relation of moraines to ice-stagnation deposits suggest the advance is Younger Dryas in age. The advance demonstrates Younger Dryas glacier expansion differs in magnitude in western Canada, suggesting a complex glacier response to late-glacial climate change. The second study describes four early Holocene tephras. Two phonolitic tephras, older than 9180 radiocarbon yr BP, were found in sediments from Finlay River and Dease Lake areas. Their source may be a large volcano in northwest British Columbia. Two other tephras were recovered from Bob Quinn Lake. A lower basaltic tephra was produced by an eruption near Iskut River 8400 radiocarbon yr ago. The upper phonolitic tephra is 6000-7000 radiocarbon yr old.

LaMoreaux, K.A., 2008. Recognizing ice-contact trachyte-phonolite lavas at the Mount Edziza volcanic complex, British Columbia, Canada; M.Sc. thesis, University of Pittsburgh, Pittsburgh, Pennsylvania, 162 p.

Abstract: Mount Edziza Volcanic Complex (MEVC) lies within the Northern Cordilleran Volcanic Province (Northern Cordilleran Volcanic Province), in northwest British Columbia, Canada. The eruption products have been emplaced in a variety of subaerial, sub-ice and subaqueous environments from about 8 Ma to less than 2000 y.b.p. (Souther, 1992). Ice Peak Formation (IPF) trachyte lava flows of approximately 1 Ma age (Souther, 1992) are exposed at Ornostay Bluff (OB) and Koosick Bluff (KB). These flows comprise basal flow breccias overlain by massive conchoidally-fractured lava with large, poorly-developed columns, and local flow banding. Edziza Formation (EF) approximately 1 Ma (Souther, 1992) phonolite is exposed at Triangle Dome (TD). TD can broadly be divided into an upper and lower zone. The upper zone comprises poorly-developed columns in addition to prominent jointing. In the lower zone the columns are planar and 75cm-3m-wide in the interior of the complex grading into fan-like and curved subhorizontal columns <75cm-wide in the outer margins of the lower zone. The upper zone is interpreted as an "entablature" where slow cooling was overprinted by joints formed during abrupt cooling due to water ingress. Local areas with well-developed columnar jointing in the upper zone may reflect endogenous growth by late-stage intrusive emplacement, or areas where water ingress was less efficient. The lower zone is interpreted as a "lower colonnade" with slower cooling and less water ingress during cooling. The fan-like columns in the outer margins of the lower zone reflect cooling by direct contact with curved margins of the ice cavity. The estimated minimum thickness of the ice-contact zone is nearly equal 60m reflected by the thickness of the lower zone. Identifying ice-contact structures in trachytic-phonolitic lavas is difficult, especially in glacially eroded examples such as OB and KB, where marginal cooling-columns and structures caused by direct contact with ice have been eroded. Trachyte lavas display a wide range of viscosities, flow thicknesses, and aspect ratios therefore caution is required in interpreting "overthick" flows as having formed by confinement by former ice. Studies that focus on comparisons of estimated flow velocities and rates of ice melting are useful, though there are numerous unaccounted for variables in these models.

MacDonald, F.H., 2006. Quaternary geology of Hoodoo Mountain Volcano, northwestern British Columbia; M.Sc. thesis, University of Calgary, Calgary, Alberta, 138 p.
Abstract: Hoodoo Mountain Volcano in northwestern British Columbia is flanked and overlain by glacial ice, and bears an unusually good sedimentary record of glacial history because of the preservation of old deposits by lava flows. Five Pleistocene deposits and two Holocene glacial advances are observed. The five Pleistocene deposits are a gray tillite (Fraser Glaciation), a reddish-brown tillite (mid Wisconsinan), a green till (mid Wisconsinan), volcanic diamict (80-54 ka) and a debris flow (80-85 ka). During the Holocene, meltwater collected in two lake basins, one dammed by ice and the other dammed by lava. The result was distal and ice-contact lakes with varved sediments, dropstones, and coarse-grained delta foresets. A late Neoglacial advance may have been influenced by the Medieval Warm Period, resulting in glacier retreat and degradation. The LIA advance had begun by 1280-1420 AD with glaciers thickening by approximately 95 meters before retreating in the 16th to 18th century.

Muller, J.E., 1967. Kluane Lake map-area, Yukon Territory (115G, 115F, E 1/ 2); Geological Survey of Canada, Memoir 340, 137 p.
Summary: This is a summary of geological mapping in the Kluane Lake map-area of the Yukon Territory. It includes a discussion of the 1500 year-old White River ash and its possible source.

Nicholls, J., Page, T., Schmok, J., Russell, J.K., and Stasiuk, M.V., 1998. Global Positioning System survey of ground-penetrating radar traverses of the ice cap, Hoodoo Mountain, British Columbia; *in* Current Research 1998-1A; Geological Survey of Canada, p. 65-68.
Abstract: Three single-frequency GPS instruments were used to provide horizontal and vertical control for radar surveys of the ice cap on Hoodoo Mountain, British Columbia. Survey control was established by locating two survey control markers on a moraine at the edge of the ice cap. The survey control markers were located relative to a B.C. Government horizontal control point approximately 6 km from the new survey control markers on Hoodoo Mountain. Vertical adjustment to height above the ellipsoid was accomplished by comparing survey control-marker data on Hoodoo Mountain with GPS data collected by the British Columbia Active Control System (BC ACS) station at Dease Lake.

Nicholls, J. and Stout, M.Z. 1996. Basaltic lava flows and enclosed xenoliths as samples of the lithosphere and low velocity zone beneath northern British Columbia; a progress report; *in* Slave-NORthern Cordillera Lithospheric Evolution (SNORCLE) and Cordilleran tectonics workshop, University of British Columbia, Lithoprobe Secretariat for the Canadian Lithoprobe Program, Calgary, Alberta; Lithoprobe Report, v. 50, p. 109-115.
Summary: This is a short summary of Pleistocene and Holocene volcanic rocks and their enclosed xenoliths at The Thumb, Tseax, Llangorse Mountain, and Ruby Mountain, and a brief discussion of the source depth for these rocks, based on their whole rock and xenolith geochemistries.

Richards,T.A., 1976. Takla Project (Reports 10-16); McConnell Creek map-area (94 D, east half), British Columbia; Geological Survey of Canada, Paper 76-1a, p. 43-50.
Summary: This paper summarizes then-ongoing geologic mapping in the McConnell Creek map-area. Although most of the bedrock is pre-Pleistocene, there are a few younger basalt remnants, including the cinder cones and lava flows associated with The Thumb.

Roddick, J. A., 1996. Geology, Rivers Inlet (92M)-Queens Sound (102P) map areas, British Columbia; Geological Survey of Canada, Open File 3278, scale 1:250,000.

Summary: This geological map includes the Pleistocene Silverthrone volcanic complex. Because little has been published about Silverthrone, the map is included in this bibliography as one of the few available references.

Russell, J. K., Stasiuk, M.V., Hickson, C.J., Maxwell, M., and Edwards, B.E., 1998. The Hoodoo '97 Expedition; probing the ice cap of Hoodoo Mountain volcano, Iskut River region, British Columbia; *in* Current Research1998-01A/B; Geological Survey of Canada, p. 49-54.

Abstract: Hoodoo Mountain volcano is a Quaternary volcano located on the north side of the Iskut River, in the Coast Mountains of northwestern British Columbia. An ice cap, 3-4 km in diameter, covers the summit region of the volcano and obscures the youngest volcanic stratigraphy. In 1995, an Industrial Partners Program project involving the Geological Survey of Canada, Golder Associates Ltd., and several universities, was initiated. The aim of this field-based project was to map the thickness and shape of the ice cap with radar to produce an image of the sub-ice topography of the summit to the volcano. The survey comprised Global Positioning System-controlled traverses across the ice sheet using both ice radar and ground-penetrating radar. The radargrams give clues to the evolution of Hoodoo Mountain volcano and are critical for assessing the nature and magnitude of hazards that woulda rise from renewed volcanism.

Russell, J. K., Stasiuk, M.V., Schmok, J., Nicholls, J., Page, T., Rust, A., Cross, G., Edwards, B.R., Hickson, C.J., and Maxwell, M., 1998. The ice cap of Hoodoo Mountain volcano, northwestern British Columbia; estimates of shape and thickness from surface radar surveys; *in* Current Research 1998-01A/B; Geological Survey of Canada, p. 55-63.

Abstract: Preliminary results from a multiple-traverse radar survey across an ice cap situated on top of Hoodoo Mountain, a Quaternary subglacial stratovolcano in northwestern British Columbia are presented. The project defined the shape of the ice sheet and mapped the subglacial summit region of the volcano. Four traverses, using low-frequency ice radar and higher frequency ground-penetrating radar units, provided traces of the ice base as well as shallow, finer scale, internal reflectors. GPS was used to locate survey lines and individual radar traces were time tagged to position.

Ryane, C., Edwards, B.R., and Russell, J.K. 2011. The volcanic stratigraphy of Kima'Kho mountain; a Pleistocene tuya, northwestern British Columbia; Geological Survey of Canada, Current Research 2011-14, 16 p.

Abstract: The results of fieldwork completed during 2009 and 2010 at Kima'Kho Mountain, northwestern British Columbia, comprising a geological map and complementary stratigraphic and petrological data are presented herein. The geological map shows the distribution of three distinct basaltic lithofacies. The lithofacies are denoted as volcaniclastic, coherent intrusive dykes and sills, and extrusive massive and pillow lava and they record a transitional sequence from explosive subaqueous and subaerial to effusive subaerial volcanism. On the basis of these lithofacies and their stratigraphic relationships, the authors deduce that Kima'Kho is a volcanic edifice resulting from explosive and effusive eruption beneath and within a Pleistocene Cordilleran ice sheet.

Schroeter, T. G., 1985. Heart Peaks Prospect (104K/9E); Geological Fieldwork 1984, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1985-1, p. 358-364.

Introduction: The Heart Peaks precious metals prospect, consisting of 120 units, is located approximately 117 kilometres west of Dease Lake at latitude 58°36’ north and longitude 132°3’ north. A brightly coloured group of ‘domes’ on the western flank of Heart Peaks forms a prominent landmark that is visible for miles. Two local basalt domes underlie Heart Peaks to the east. During 1984, access to the property was by helicopter from either Dease Lake or Atlin. The writer visited the property on August 22 and 23. Kerr Addison Mines Ltd. conducted an eight-hole diamond-drill program under a joint venture agreement with Newmont in 1984. Work between 1980 and 1982 by the Newex Syndicate (Newmont, Lornex, and J.C. Stephen Ltd.) and during 1983 by Kerr Addison and Newmont discovered several precious metal anomalies in silicified and pyritized trachyte-rhyolite units and related breccias.

Shaw, J. M., Hamilton, T. S., and Dostal, J., 1996. An overview of xenolith-bearing Neogene to Recent volcanics in the northern Cordillera; *in* Current Research 1996-E; Geological Survey of Canada, p. 65-75.

Abstract: During August 1994 and July 1995 xenoliths were collected from 19 Neogene to Recent volcanic centres in the northern Cordillera including: Prindle (Alaska); 60 Mile, Clinton Creek, 40 Mile, Ne Che Dhawa, Alligator Lake (Yukon); Ruby Mountain, Cracker Creek, Volcano Creek, Chikoida Mountain, Llangorse, Ash Mountain, 3 Caribou Tuya, South Tuya, Matthews Tuya, Castle Rock, Maitland Creek, Aiyansh/Tseax River, and Summit Lake (British Columbia). This report presents the locations, xenolith types, and preliminary descriptions. Xenoliths types include: depleted and undepleted spinel lherzolite, clinopyroxene megacrysts, clinopyroxenite, gabbro, and granitic and metamorphic rocks (including granulite facies banded gneiss). Microprobe analyses for olivine, orthopyroxene, and clinopyroxene from peridotite xenoliths in three of the centres are consistent with a mantle paragenesis. The xenoliths are the foundation for ongoing petrological studies of the Cordilleran crust and upper mantle. They represent the only physical samples of the northern Cordilleran subsurface geology available to constrain the geophysics from the Lithoprobe SNORCLE transects.

Simpson, K. A., 1996. The geology, geochemistry, and geomorphology of Mathews Tuya: a subglacial volcano in northwestern British Columbia; B.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 97 p.

Abstract: Mathews Tuya is a Quaternary subglacial volcano in the Jennings River area of northwestern British Columbia. The volcano is part of the Stikine Volcanic Belt, a northerly-trending zone of Miocene to Recent volcanic centres. Crudely stratified rocks rest unconformably on Mesozoic granite and comprise a sequence of complexly interbedded basal basalt flows and/or sills, hyaloclastite tuffs and pillows. Overlying this sequence is a hyaloclastite tuff unit which is capped by a set of flat-lying basalt flows. The entire sequence is intruded by basalt dikes. Volcanic activity occurred during the last glaciation, beneath a valley glacier. Initial subaqueous volcanism was followed by subaerial eruptions resulting in a morphology and stratigraphy consistent with the classic “tuya” formation. Lava and glass samples from Mathews Tuya are alkali olivine basalts, with an olivine-plagioclase phenocryst assemblage. Pearce element ratio calculations suggest that olivine and plagioclase fractionation in a closed system is the dominant process responsible for chemical variations between the lavas. There is also evidence to suggest that an unquantified amount of crustal contamination may have affected the composition of basalts in the lower stratigraphic levels of the volcano. Phase saturation calculations place the magma chamber within the upper 10 km of the crust. Comparisons between Mathews Tuya and other Quaternary subglacial volcanoes in the area show compositional, morphological, and chronologic similarities; however, results of this study propose an alternate chemical evolution for Mathews Tuya, than that applied by previous workers to other volcanoes in the region.

Simpson, K., Edwards, B., and Wetherell, K., 2006. Documentation of a Holocene volcanic cone in the Tuya-Teslin volcanic field, northern British Columbia; Geological Survey of Canada, Current Research 2006-A1, 7 p.
Abstract: A previously unnamed Holocene volcanic cone is herein informally named Gabrielse cone. Gabrielse cone is a subaerial basaltic scoria cone that is one of the few subaerial volcanic features in the Tuya-Teslin area. The cone is approximately 400 m in diameter with a central crater approximately 30 m deep. It consists largely of unconsolidated basaltic scoria some of which show preserved fluidal shapes typical of subaerial bombs. To the northeast the scoria cone appears to be breached and remnants of a lava flow were observed. Mineral compositions as determined by scanning electron microscope-energy dispersive spectometer are consistent with other occurrences of alkali olivine basalts in the area.

Souther, J.G., 1967. Cordilleran volcanic study, 1966; Geological Survey of Canada, Paper 67-1, p. 89-92.
Summary: This is a brief summary of mapping at Mount Edziza, and a description of geothermal drilling at sites on the Cassiar-Stewart road near Dease Lake, on the Cassiar-Stewart road north of the Stikine River, and near Buckley Lake.

Souther, J.G., 1971. Geology and mineral deposits of Tulsequah map-area, British Columbia (104K); Geological Survey of Canada, Memoir 362, 84 p.
Summary: This is a summary of geologic mapping in the Tulsequah map-area, which includes the late Tertiary to Pleistocene volcanic complexes at Heart Peaks and Level Mountain.

Souther, J.G., 1972. Telegraph Creek map-area British Columbia; Geological Survey of Canada, Paper 71-44, p. 1-38.
Summary: This is a summary of geologic mapping in the Telegraph Creek map-area, which includes Tertiary, Pleistocene, and Recent lava flows and pyroclastic rocks ranging in composition from rhyolite to basalt.

Souther, J. G., 1973. Cordilleran volcanic project, Spectrum Range; Report of activities, Part A, Geological Survey of Canada, Paper 73-1, p. 46-48.
Summary: Detailed geologic mapping of the Mt. Edziza Volcanic Complex was extended south into the Spectrum Range 57°20'N, 130°45'W) where five distinct stages of late Tertiary and Quaternary volcanic activity are recognized.

Souther, J. G., 1981. Volcanic hazards in the Stikine region of northwestern British Columbia; Geological Survey of Canada, Open File 770, 3 p.
Summary: This is a brief description of the most probable volcanic hazards in the Stikine region of northwestern British Columbia. The most significant future eruptions are likely to occur in the Edziza-Spectrum Range, the Level Mountain volcanic complex, or the lower Iskut Valley.

Souther, J.G., 1992. The Late Cenozoic Mount Edziza volcanic complex, British Columbia, Canada; Geological Survey of Canada, Memoir 420, 329 p.
Abstract: The Mount Edziza Volcanic Complex lies about 100 km inland from the continental margin in north-central British Columbia. It includes a group of overlapping basaltic shields, felsic composite volcanoes, domes and small calderas which range in age from at least 7.5 Ma to less than 2000 B.P. During this long period of intermittent volcanic activity the ebb and flow of local and regional glaciations resulted in a complex assemblage of subaerial and subglacial volcanic landforms. The volcanic assemblage is chemically bimodal, comprising voluminous alkali olivine basalt and hawaiite, a felsic suite of mainly peralkaline trachyte and commendite, and a relatively small volume of intermediate rocks (trachyte, tristanite, mugearite, benmoreite). The complex is the product of five cycles of magmatic activity, each of which began with alkali basalt and

culminated with the eruption of felsic magma. Petrogenetic modelling suggests that the felsic rocks formed by fractionation of observed phenocryst and cumulate mineral phases from a common alkali olivine basalt. The chemical diversity and longevity of the Mount Edziza Volcanic Complex are attributed to its location over a zone of crustal extension where mantle-derived basalt, trapped in large high-level reservoirs, has undergone prolonged fractionation. Incipient rifting associated with the volcanic activity is probably related to dextral transcurrent movement between North America and the Pacific Plate, a tectonic regime that has persisted throughout the life of the complex.

Souther, J. G. and Symons, D.T.A., 1974. Stratigraphy and paleomagnetism of Mount Edziza Volcanic Complex, northwestern British Columbia; Geological Survey of Canada, Paper 73-32, 48 p.

Abstract: Mount Edziza is the largest and most complex in a group of Late Tertiary and Quaternary volcanoes that lie along a north-south zone of normal faults along the eastern side of the Coast Geanticline in northwestern British Columbia. It is a composite shield and dome in which flat-lying lavas and pyroclastic rocks rest unconformably on tilted lavas and clastic sediments of the Early Tertiary Sloko and Sustut groups. The products of Mount Edziza belong entirely to the alkali rock series and vary in composition from alkali olivine basalt through trachybasalt to peralkaline trachyte and sodic rhyolite. At least four principal magmatic cycles or stages are recognized. Each stage began with eruption of a primary basalt and culminated with eruption of a more acid phase. Rocks belonging to the earliest stages have been deeply dissected whereas the youngest flows and pyroclastic cones show little or no evidence of erosion. Detailed paleomagnetic polarity profiles of three stratigraphic sections indicate that six reversals in the earth's magnetic field occurred during the life of the volcano. Correlation of the polarity events with radiometric ages and glacial stratigraphy indicates that volcanic activity began about 6 m.y. B.P., during magnetozone 14, and continued intermittently throughout Pleistocene and into Recent time. During this long interval, successive centres of eruption were confined to a zone within a few miles of the present crater of Mount Edziza. Moreover, there is no evidence of progressive change in the character of the primary alkali olivine basalt, or its peralkaline fractionation products, that issued during the four successive stages of activity. Thus the volcanicity of Mount Edziza appears to reflect a consistent tectonic environment that has persisted throughout Late Tertiary and Quaternary time. The peralkaline nature of the Edziza lavas and their association with north-south normal faults suggests a zone of crustal rifting.

Stasiuk, M. V. and Russell, J.K., 1990. Quaternary volcanic rocks of the Iskut River region, northwestern British Columbia; *in* Current Research, Part E; Geological Survey of Canada, Paper 90-1E, p. 153-157.

Abstract: Along and south of the Iskut River, Quaternary volcanic rocks occur as scattered monogenetic cinder cones and lava flows. These volcanic centres comprise the Iskut River volcanic rocks and include localities at: Iskut Canyon, Cone Glacier, Cinder Mountain, King Creek, Second Canyon Creek, and Lava Fork Creek. All the Iskut River volcanic rocks are basaltic. Representative samples for petrographic and chemical analysis were collected from these six volcanic centres.

Trupia, S., 1992. Petrology of the nephelinites and associated ultramafic nodules of Volcano Mountain, Yukon Territory; M.Sc. thesis, University of Calgary, Calgary, Alberta, 123 p.

Abstract: Nephelinites from Volcano Mountain, Yukon Territory, contain olivine, Ti-rich diopside, ulvospinel, nepheline, leucite, traces of calcite, and residual glass with varying compositions. Mass balance calculations suggest that these compositional differences are due to different fractionation paths; a conclusion consistent with the observed mineral abundances near the glasses. Pearce Element Ratios show that at least one of the lava flows sampled is not comagmatic with the others. Thermodynnmic modeling of silicate melts and textural observations

indicate that the pressure-temperature path of fractionation was polybaric, and that the minimum depth of melt separation from the source rocks was 60 km. The volcanic rocks host dunite and lherzolite nodules consisting of diopside and hypersthene, olivine and chromian spinel. Deformation textures and mineral compositions are different from other occurrences in western North America. Geothermometry on the xenoliths provide temperature estimates between 930°C and 1350°C. The range of equlibrim pressures for the nodules is estimated from phase equilibria at 20 to 45 kilobars.

van der Heyden, P., Woodsworth, G.J., and Snyder, L.D., 2000. Reconnaissance geological mapping in Southwest Nass River map area, British Columbia; Geological Survey of Canada, Current Research 2000-A6, 9 p.

Abstract: The southwest Nass River (103 P/3, 103 P/4, and 103-O/1) map area is dominated by Upper (?)Jurassic marine sedimentary strata of the Bowser Lake Group and by Eocene granodiorite of the Coast Belt. A large stock of (?)Miocene miarolitic granite outcrops along Observatory Inlet. Remnants of Pleistocene volcanic rocks and the Recent Aiyansh lava flow occur in the eastern part of the area. Bowser Lake Group strata form a steep-sided, southwesterly tapering prong and were folded about northeast-trending axes. This deformation predates intrusion of the plutonic rocks and may be related to (?)Cretaceous deformation in the Skeena Fold Belt. Westernmost exposures of these strata may have been metamorphosed and deformed in a major, down-to-the-northeast, extensional, ductile shear zone immediately prior to its digestion by Eocene plutons. Granitoid rocks are cut by steeply dipping, northeast-trending faults and fractures and may record late Tertiary extension.

Watson, K. D. and Mathews, W.H., 1944. The Tuya-Teslin area, Northern British Columbia; British Columbia Department of Mines, Bulletin 19, p. 5-50.

Summary: The Tuya-Teslin Area, 1,600 square miles in extent, is situated in the Stikine and Atlin Mining Divisions of Northern British Columbia, partly within the western margin of the Cassiar-Omineca Mountains. The region includes the Kawdy Plateau, Tuya Range, and Atsutla Range. Rocks range widely in age from Paleozoic igneous, metamorphic, and sedimentary rocks to Pleistocene lava, tuff, and agglomerate of the Tuya Formation; many of these young volcanic rocks show evidence for eruption in contact with glacial ice.

Wetherell, K., Edwards, B.R., and Simpson, K., 2005. Preliminary results of field mapping, petrography, and GIS spatial analysis of the West Tuya lava field, northwestern British Columbia; Geological Survey of Canada, Current Research 2005-A2, 10 p.

Abstract: An overview and summary of fieldwork, GIS spatial analysis, and preliminary petrographic analysis conducted between July 2003 and August 2004 is presented for the West Tuya lava field, which is part of the northern Cordilleran volcanic province, in the south-central part of the Jennings River (NTS 104-O) map area, northwestern British Columbia. The most important preliminary results include the following: a) identification of three subaerial shield volcanoes, which, based on mineralogy, probably range in composition from alkaline basalt to nephelinite and/or mafic phonolite, b) confirmation that mantle-derived peridotite inclusions ranging from 1 to 4 cm in size are present at two of the volcanoes, and c) interpretation of the subaerial lava flows as predating the Holocene. Using the 3D Analyst extension of ArcGIS 8.3, the minimum and maximum volumes of material erupted can be constrained to 10.36 km^3 and 23.42 km^3, respectively.

Wheeler, J. O., 1961. Whitehorse map-area, Yukon Territory, 105D; Geological Survey of Canada, Memoir 312, 156 p.

Summary: This is a summary of the geology of the Whitehorse map-area, much of which is underlain by pre-Pleistocene rocks of various types. Several pages are devoted to a discussion of the Pleistocene Miles Canyon basalts.

Conference Proceedings, Abstracts, and Symposium Volumes

Bevier, M. L., 1992. A dominant asthenospheric mantle source for late Miocene-Quaternary volcanic rocks, Stikine volcanic belt, British Columbia and Yukon Territory, Canada; American Geophysical Union, EOS Transactions, v. 73, no. 14, p. 334.

Abstract: Major, trace, and Pb-Nd-Sr isotopic data for 25 alkaline volcanic rocks of the Stikine Volcanic Belt (lat. 55°-61° N, long. 130° W) that erupted in a continental rift setting through either Paleozoic accreted terranes or the edge of the North American craton indicate that asthenospheric mantle was the dominant source for the mafic rocks. Most volcanic centers are isolated cinder cones with one or more associated mafic, alkaline lava flows. Peralkaline rocks, erupted from large volume volcanic centers within the belt, formed from crystal fractionation of alkaline mafic magmas in long-lived magma chambers (e.g. Mt. Edziza). Mg# ranges from 50-63 in nephelinites and basanites to 36-59 in AOB. The most primitive rocks are nephelinites with 300 ppm Ni and 350 ppm Cr. Spidergrams normalized to primitive mantle reveal that the mafic rocks have patterns typical of alkaline magmas, whereas the peralkaline differentiates are depleted in Ba, Sr, and Ti, and relatively enriched in Nb, Nd, Zr, Y, and Yb. Pb-Nd-Sr isotopic compositions for SVB mafic rocks that erupted through accreted terranes lie within the mantle array for the northeast Pacific, and an asthenospheric mantle source is proposed. However, AOB and transitional basalts from the northern end of the belt that erupted through Cassiar or Yukon-Tanana terranes at or near the edge of the North American craton show elevated Pb, higher $^{87}Sr/^{86}Sr_i$, and lower ε_{Nd}. These isotopic signatures suggest a subcontinental lithospheric mantle source or contamination of asthenospheric mantle-derived magmas by Precambrian crust in the northern end of the SVB.

Cameron, B. I. and Boscov-Parfitt, S., 2003. Degassing at basaltic tuyas in northern British Columbia; insights from the hydrogen isotopic composition of glasses and whole rocks. American Geophysical Union, EOS Transactions, v. 84, no. 46, p. F1597.

Abstract: Interest in subglacial volcanism was rekindled by the spectacular 1996 Gjalp eruption in Iceland. Northern British Columbia, Canada, hosts numerous flat-topped subglacial volcanoes called tuyas. Ash Mountain, South Tuya, and Three Caribou Tuya are three examples of basaltic volcanoes that began eruptive activity under glacial ice during the Fraser glaciation (25 to 10 ka). Sections of the three superbly exposed tuyas reveal a consistent stratigraphic progression from pillow lavas to hyaloclastite deposits from the base upward. Locally the sections are capped by subaerial basaltic lava flows. Based on classic eruptive models, the glassy pillow basalts and overlying hyaloclastite deposits indicate eruption of basalt within melt water caverns of increasingly shallow depths. Capping subaerial flows record the emergence of lava above the ice sheet. Large thicknesses of ice and melt water overlying the basaltic volcanoes would significantly impede the release of volatiles from the ascending magma. Degassing and ascent rates of magma are thought to exert control on eruptive style. Despite hydrogen isotopes being sensitive measures of degassing, to our knowledge no hydrogen isotope data has been collected on glassy subglacial basaltic rocks. H_2O contents and hydrogen isotopic analyses of glasses from the pillow basalts and hyaloclastite deposits should improve our understanding of degassing processes at these classic tuyas and help refine current models of subglacial basaltic eruptions. Consequently, samples of glassy pillow basalts and hyaloclastites along with crystalline basalt flows were collected at Ash Mountain, South Tuya, and Three Caribou Tuya in northern British Columbia. XRF major and trace element analyses of glassy and crystalline basalts reveal relatively primitive compositions with MgO values ranging from 5.52-10.07 wt%. Whereas Ash Mountain samples are largely tholeiitic, South Tuya and Three Caribou Tuya basalts show more alkalic affinities. In order to definitively track degassing at these subglacial volcanoes, glasses and whole rock basalts were analyzed for their H_2O concentration and hydrogen isotopic composition. At Ash Mountain, glasses from pillow basalts have higher water contents (0.54-0.66 wt%) and less depleted δD values (-87.2 to -102.0 per mil) than associated hyaloclastite deposits (0.43-0.48 wt% H_2O and δD from -112.5 to -122.6 per mil). Hyaloclastite glasses from South Tuya have H_2O contents similar to the Ash Mountain pillow glasses, but δD values resembling Ash Mountain hyaloclastites. Bulk rock basalts have even lower H_2O contents than either the pillow glasses or hyaloclastite deposits and exhibit extreme depletions in δD (i.e., less than -140 per mil). These preliminary data support eruptive models that propose pillow basalts erupted in deeper water than hyaloclastite deposits. Moreover, the H_2O data can be used to constrain the thickness of ice overlying the basalts at the time of the eruption.

Cameron, B. I., Roggensack, K., Boscov, S., and Peterson, A.H., 2005. What's it Tuya; ice thickness determined from H_2O contents measured in glasses from subglacial volcanoes in British Columbia and Iceland; American Geophysical Union, EOS Transactions, v. 86, no. 52, v12b.

Abstract: Classic exposures of flat-topped subglacial volcanoes called tuyas exist in northern British Columbia and Iceland. In northern British Columbia, Ash Mountain, South Tuya, and Three Caribou Tuya are basaltic scoria cones that began eruptive activity under glacial ice during the Fraser glaciation (25 to 10 ka). In Iceland, Hlödufell, Raudafell, and Efstadalsfjall were erupted beneath ice caps in the western neovolcanic rift zone. In general, sections of the basaltic subglacial volcanoes reveal a stratigraphic progression from pillow lavas to hyaloclastite deposits from the base upward. Locally, the sections are capped by subaerial basaltic lava flows. Glass samples were extracted from pillow basalts, pillow breccias, and hyaloclastites in order to measure their H_2O content. Generally, British Columbia tuyas have higher magmatic H_2O contents (0.42-0.66 wt%) than the Icelandic tuyas (0.14-1.24 wt%). More interestingly, H_2O contents decrease with elevation at tuyas in British Columbia, whereas at Hlödufell and Efstadalsfjall in Iceland, H_2O contents increase with elevation. For example, at Ash Mountain in British Columbia, pillow basalts have higher H_2O contents (0.54-0.66 wt%) than associated hyaloclastite deposits (0.43-0.48 wt%). In contrast, at Hlödufell in Iceland basal pillow basalts have lower H_2O contents (0.14-0.22 wt%) than the overlying hyaloclastites (0.28-0.29 wt%). The preliminary data from British Columbia support eruptive models where pillow basalts erupted under thicker ice/deeper water than hyaloclastite deposits. Moreover, the measured H_2O contents can be used to constrain the thickness of ice overlying the scoria cones at the time of eruption. Assuming a basaltic composition of 49 wt% SiO_2 and an ice density of 0.9 g cm^{-3}, the ice at Ash Mountain was up to 453 m thick during extrusion of the pillows, but thinned to 215 m for the eruption of the hyaloclastites. At Efstadalsfjall in Iceland, overlying ice thickened from 79 m to 204 m during the course of the eruption.

Cameron, B.I., Wright, M., Skilling, I.P., Hungerford, J.D.G., and Edwards, B., 2008. Accurate ice thickness estimates from volatile contents of subglacial glasses from northern British Columbia, Canada; Geological Society of America, Abstracts with Programs, v. 40, no. 5, p. 25.

Abstract: Volatile concentrations (H_2O and CO_2) of glaciovolcanic pillow glasses can be used to estimate overlying ice thickness based on the pressure dependence of volatile solubility in magma. The few existing studies that have estimated ice thickness using volatile concentrations have suffered from errors associated with accurately measuring wafer thickness for FTIR measurements of H_2O and the lack of CO_2 data for the pillow glasses. In this study, we have attempted to overcome these two deficiencies to accurately estimate ice thicknesses in northern British Columbia. Basaltic pillow lavas erupted from Tennena Cone at the Mount Edziza Volcanic Complex (MEVC) in northern British Columbia occur as sinuous ridges with near vertical margins. Basaltic pillow lavas with steep margins suggest confinement by glacier ice. We have collected multiple samples of a pillow unit from Tennena Cone to attempt accurate ice thickness estimates using both H_2O and CO_2 concentrations of the glassy rims. Initial H_2O contents by manometry and hydrogen isotopic compositions for the 2006 samples from the Tennena Cone pillow rinds

range from 0.66 to 0.83 wt% and -94.5 to -127.1 per mil, respectively. H_2O content ranges from 0.719 to 0.988 wt% based on Fourier Transform Infrared (FTIR) measurements for 2006 and 2007 samples. Wafer thickness was accurately determined in the FTIR studies using interference fringes in reflected light. CO_2 concentrations of 25 ppm in the matrix glass were determined by manometry during the step heating analysis. To our knowledge, this is the first time that ice thickness estimates are based on the combination of measured FTIR H_2O and manometric CO_2 concentrations. Saturation pressures can be determined using the measured volatile data and a program called VolatileCalc. Assuming a basaltic composition with 49 wt% SiO_2, an eruption temperature of 1000 °C, and CO_2 concentrations of 0 ppm, the measured H_2O contents by FTIR yield eruption pressures that range from 48 to 94 bars. Assuming an ice density of 0.931 g cm^{-3}, these pressures correspond to ice thicknesses between 540 and 1057 m. For the samples that have measured CO_2 concentrations by manometry, ice thickness varies from 1336 to 1566 m.

Carignan, J., Ludden, J.N., and Francis, D., 1995. Asthenosphere-lithosphere interaction during the formation of continental alkaline basalts in the northern Canadian Cordillera; American Geophysical Union, EOS Transactions, v. 76, no. 46, p. 587-588.

Modified abstract: Quaternary alkaline magmatism ranging in composition from olivine nephelinite (OL-NEPH) to hypersthene-normative olivine basalt (HY-NORM AOB) erupted through various terranes accreted to ancestral North America. The volcanic centres are volumetrically small except for those of Mt. Edziza and Level Mountain, which represent more than 10 Ma of volcanism, and are interpreted as representing an asthenospheric mantle swell beneath northern British Columbia. Lavas from five centres (Edziza; Hirschfeld-Llangorse; Alligator Lake; Fort Selkirk; West Dawson) were analysed for their chemical and isotopic compositions. The presence of most of the lava types in all the studied centres and the fact that, as a whole, no gap in chemical or isotopic compositions is observed, are evidence for asthenosphere-lithosphere interaction during the formation of continental alkaline basalts in the Northern Canadian Cordillera.

Edwards, B., Osborn, J., Russell, J.K., Skilling, I.P., Evenchick, C., Spooner, I., Simpson, K., and Cameron, B., 2007. Physiographic controls on glaciovolcanism and the Cordilleran ice sheet in the Northern Cordilleran Volcanic Province, western Canada; 2nd Volcano-Ice Interaction on Earth and Mars Conference (VII2), Vancouver, British Columbia, p. 21-22.

Abstract: Glaciovolcanism in the Northern Cordilleran Volcanic Province of western Canada occurs in three different physiographic settings, each displaying unique relationships between topography, volcanism and glacial ice. The first is represented by the tuya type locality, Tuya Butte, located on the Tanzilla Plateau in northern British Columbia. This region comprises broad flatlands with comparatively low-lying hills, and may have been one of the centers of ice accumulation for the Cordilleran ice-sheet (CIS). Pleistocene volcanism in this area is dominated by basaltic glaciovolcanic eruptions. The most common glaciovolcanic landforms are individual tuyas, which seldom range in height more than a few hundreds of meters. Other edifice morphologies are also present, some of which are primary and others that are possibly the products of erosion. The subdued relief on the Tanzilla Plateau strongly influenced edifice morphologies, favoring broad-based tuyas. The hydrological conditions in these areas likely were controlled by relatively uniform ice thicknesses and gentle topography. Glaciovolcanic processes and landforms conform to Icelandic and Antarctic examples described in detail by many authors. The second type of interaction is found mainly to the east, south and southwest of the Tanzilla Plateau, in the Cassiar Mountains and the Skeena and Boundary Ranges. Volcanism in these areas is also predominantly mafic, but the greater local relief of these areas had a much more dramatic influence on glaciation and glaciovolcanism. Alpine-style glaciation dominated when the CIS was absent, and when overwhelmed by the CIS basal ice movement was strongly influenced by the deep, pre-glacial drainages. Accordingly, the erosional remnants of glaciovolcanic centers tend to be smaller and discontinuous. In the Skeena Ranges, the isolated outcrops of pillow lava and volcanic breccia are often located along the tops of arête-like ridges, with presumably temporally-associated volcaniclastic rocks having collected downslope. The third type of interaction is geographically limited to three volcanic structures: Level Mountain, Mount Edziza, and Hoodoo Mountain. All three are within the eastern part of the Boundary Ranges physiographic province and are large enough to support ice caps that probably influenced local ice flow, while still being influenced by the CIS at different times. Mount Edziza and Level Mountain have benches of older lava 1 km+ in elevations, and have been sites of volcanism long enough that their geothermal outputs may have had an influence on CIS dynamics much as the modern day Grímsvötn caldera is an important heat source beneath Vatnajökull in Iceland. At Mount Edziza most of the glaciovolcanic products are located on top of the main volcanic plateau, which is now elevated ~1000m above the surrounding stream valleys. Mount Edziza comprises a variety of interesting mafic glaciovolcanic products, but more uniquely, comprises some of the largest deposits of peralkaline felsic glaciovolcanic products known. At Mount Edziza and Level Mountain, glacier hydrology of the CIS probably was controlled by a complex interplay between drainage on the flat plateaus beneath relatively thinner ice and drainage within adjacent, steep valleys filled with much thicker ice.

Endress, C., Edwards, B., Skilling, I., Lloyd, A., LaMoreaux, K., and Hungerford, J., 2006. Preliminary interpretation of glacial and glaciofluvial deposits associated with 1 Ma glaciovolcanism of the Ice Peak Formation, Edziza volcanic complex, British Columbia, Canada; American Geophysical Union, EOS Transactions, v. 87, v53c.
Abstract: The Mount Edziza Volcanic Complex (MEVC) comprises ~775 km^3 of basalt, trachyte and rhyolite erupted in a variety of subaerial, sub-ice and subaqueous environments from about 8Ma to <2000 y.b.p. It forms a major component of the Stikine peralkaline subprovince of the central part of the northern Cordilleran volcanic province (NCVP), northwestern British Columbia, Canada. The Ice Peak Formation (IPF) is a widespread unit of the MEVC erupted about 1Ma (Souther, 1992) and includes basaltic and trachytic lava flows, trachytic domes, pyroclastic rocks, and a variety of glacial and glaciofluvial volcaniclastic rocks. Souther's (1992) interpretation of some of the trachytic effusive rocks as ice-contact has been confirmed by our recent study of flow morphologies and joint patterns (LaMoreaux et al., 2006). No evidence of mechanical interaction of the trachytic lava flows with the underlying glaciogenic deposits was observed, so they may be significantly older than 1Ma. However, these deposits may provide a critical record of local and/or regional paleoclimate conditions during a period of the Pleistocene that is poorly constrained in terrestrial settings. Massive and bedded, poorly sorted, pebble-cobble volcaniclastic sandstones exposed immediately beneath IPF trachytic lava flows were examined at 5 widely-spaced localities on the western and northern sides of the MEVC plateau. One of the locations, on the north-central edge of the Sezill Creek drainage, was described by Spooner et al. (1992) as meltout till and glaciolacustrine sediments. The other sequences have not previously been described and include three areas in the headwaters of Sezill Creek and one area at the northwestern end of the MEVC plateau. We interpret these sequences as deposits of meltout tills, debris flows, hyperconcentrated flood flows, with minor stream flows and subaqueous suspension in local areas. The widespread distribution of similar, stratigraphically equivalent glaciogenic deposits is perhaps more consistent with an "ice-sheet" environment, than valley glaciers. The presence of abundant grains of fresh volcanic glass in the glaciogenic deposits is consistent with deposition of the sediments penecontemporaneously with the eruption of IPF volcanics. Mineralogical, geochemical, geochronological and componentry studies are in progress to constrain possible relationships between IPF eruptions and the glaciogenic sediments, to document the palaeoenvironments in detail, and to understand the ice sheet conditions at Edziza at this time.

Evans, M. E. and Hamilton, T.S., 1980. Palaeomagnetic results from a late Tertiary-Quaternary volcano in northern British Columbia; American Geophysical Union, EOS Transactions, v. 61, no. 17, 218.

Abstract: Samples spanning a composite section of more than 1000 m have been collected from 50 separate cooling units from Level Mountain – an Upper Tertiary to Quaternary continental shield volcano in northwestern B.C. Most sites carry a stable remanence which can be determined with high precision (Fisher's precision parameter k generally exceeds 100). These site means record a series of at least 14 magnetic polarity zones, and include several low-latitude VGP's (N=5) and high internal scatter (N=7) leaves 38 site means, 24 of which have normal polarity and 14 of which are reversed. The average normal direction does not differ significantly from the inverted reversed direction, and the overall mean yields a paleopole at 256E, 85N (A_{95}=7°). The circle of confidence includes the spin axis but the mean itself is slightly near-sided, and thus lends no support to Wilson's eccentric dipole model. Instead near-sidedness seems to be a persistent characteristic of poles obtained from western North America, suggesting that a long-term non-zonal anomaly may be present.

Hickson, C.J., Spurgeon, T.C., Cocking, R.B., Russell, J.K., Woodsworth, G.J., Ulmi, M., and Rust, A.C., 2007. Tseax volcano: a deadly basaltic eruption in northwestern British Columbia's Stikine Volcanic Belt; Geological Society of America, Abstracts with Programs, v. 39, no. 4, p. 61-62.

Abstract: Tseax Volcano at the south end of the Stikine volcanic belt was the site of a deadly alkali olivine basaltic eruption in 1775. The eruption killed an estimated 2000 Nisga'a first nations people living in a village near the edge of the Nass River, approximately 20 km downstream from the vent area. Significant oral history documents the eruption and describes the death of some of the villagers from "poison smoke." Investigations are now underway to test various hypotheses as to how the villagers were killed. Field work during the summer of 2006 revealed several previously unknown details. Samples were collected from the proximal to the distal reaches of the flow (over 30 km). Analyses of volatiles in the samples will help constrain whether CO_2 was present in high enough concentrations to be a potential cause of death. Chemistry will also be used to estimate the viscosity of the flow. An orthophoto with a resolution of 1 m, and a DEM with a resolution of 5.6 m, were created of the flow surface. These will be used to evaluate flow dynamics along with detailed observations of surface morphology. The lower reaches of the flow interacted with water of some depth, possibly as much as 10 m. This left a pillowed, glassy surface close to where the flow debouches from the side valley and there is a change in slope. Proximal to the area displaying the pillows, and downstream, the lava surface is deeply crevassed and extremely irregular. Sections through the flow indicate large tubes, up to 10 m in diameter, with gas explosion vents marginal to the tubes. The lower sections of tubes rest on a pillowed sequence of unknown thickness. In rare cases, the flows are seen to rest on silt and fluvial gravels. One hypothesis is that as the flow debouched from the side valley it rapidly advanced into a lake-like widening of the river known to exist at this location at that time. People in the doomed village sought refuge on the opposite side of the broad river valley. They paddled across the river, possibly at the same time the flows were entering the water. We speculate that they may have been swept away in sudden waves and turbulence caused by the lava entering the river, but more work needs to be done to evaluate this hypothesis.

Hickson, C.J., Ulmi, M., Rust, A.C., Morvan, N., Slanina, C., Woodsworth, G.J., Weary, G., and Russell, J.K., 2006. The eruption of Tseax Volcano, British Columbia; Canada's most deadly geological disaster; International Volcanological Congress, Abstracts, v. 4, p. 173.

Modified abstract: Tseax Volcano, a small, alkali olivine basalt cinder cone in a remote area of northern British Columbia (B.C.) erupted sometime between 1750 and 1780 in a spectacular display of fire fountaining and far-travelled lava flows (25 km). The eruption was recorded in the oral history of the aboriginal Nisga'a and had a significant impact on them, destroying an abundant fishery and two major villages. Their history records that "poison smoke" killed more than 2000 people living in the villages, making this Canada's most deadly known disaster of geological origin. The accounts suggest that CO_2 may have been the cause of death, with a poosible SO_2 component. The lava flowed out from a tributary valley along side the Nass River for 10 – 12 km and may even have dammed the river and had much wider impact on downstream communities. The authors are embarking on a more rigorous review of the oral history of the Nisga'a, conducting chemical and physical analysis of the lava and pyroclastic material and updating volcanological aspects of this culturally important eruption. This work will also provide information on the potential for other cones in the region to erupt with significant quantities of CO_2; a previously underrated hazard in the area.

Hungerford, J. D., Skilling, I., Lloyd, A., and Edwards, B., 2006. Preliminary interpretation on the role of sub-ice topography on the emplacement of basaltic pillow lavas at Tennena Cone, Mount Edziza volcanic complex, British Columbia, Canada; American Geophysical Union, EOS Transactions, v. 87, v53c-1756.

Abstract: The Mount Edziza Volcanic Complex (MEVC) is a northeast trending, 75km long volcanic edifice in Northern British Columbia. Erupting cyclically over the last 7.5 ma, volcanic centers along the complex have erupted alkalic basalts to rhyolites and a range of intermediate alkalic lavas. Several episodes of sub-ice or ice- contact volcanism are recorded since 2Ma (Souther, 1992), including a basaltic volcaniclastic ridge and associated lava flows at Tennena Cone on the western side of the MEVC. Tennena Cone (TC) is a 200m high sequence, dominated by pillow-fragment breccias, that overlies trachytic lava flows of the approximately 1Ma-old Ice Peak Formation (IPF). The IPF flows vary from 3 to 7 meters in thickness and form a cliff-forming stepped topography. Underlying the IPF lavas are glaciogenic sediments, of dominantly glaciofluvial origin. A widespread area of pillow and subaqueous lobate lava flows that originated from TC were emplaced on its western margin. These lavas overlie both the steep topography of the IPF, and distally, the glaciogenic sediments. The geomorphology and structures of the TC lava flows suggest that were initially emplaced as sheet-like pillow lavas with local ponding on a dissected plateau of underlying IPF lavas, but as they approached the steep sub-ice cliffs of IPF lavas (and thicker ice), the growth of pillow mounds at the flow termini occurred. However, at one locality the pillow lavas spilled over a gap in the sub-ice cliffs, and were then focused downstream within sub-ice sinuous drainage tunnels. We intend to conduct volatile analyses on samples of glass rinds of pillow lavas in both pillow mounds and sheets to constrain the thickness of overlying ice. Knowing ice thickness and reconstructing the paleo- topography, we can begin to interpret how ice flow dynamics may control the emplacement of sub-ice basaltic lavas.

Huscroft, C. A., 2000. Volcanic and terrace stratigraphy along the Yukon River between Fort Selkirk and White River, Yukon Territory; Geological Society of America, Abstracts with Programs, v. 32, no. 6, p. 20.

Abstract: The drainage history of the Yukon River between Fort Selkirk and the confluence with the White River was investigated by magnetostratigraphic and paleo-pedological correlation of terraces and interstratified lava flows. The study area encompasses the limits of the pre-Reid (early Pleistocene) glaciations, which are the oldest and most extensive glaciations identified in Canada. Earlier magnetostratigraphic studies done upstream from the study sites by Jackson et al. (1996) identify a valley-filling sequence of reversely magnetized basalt flows which are attributed to be coeval with the youngest pre-Reid glaciation recorded in the area. Within the study area, this sequence dips below the current level of the river implying that, during emplacement of the lava, the Yukon River was flowing at, or near, its present level. Paleomagnetic sampling at the downstream tip of these basalt flows indicates that the sequence contains a magnetically normal component. Further downstream, at the mouth of Holbrook Creek, a single basalt flow lying 30 m above river level is interstratified with gravel and is magnetically reversed. The magnetic polarity of this flow suggests that Yukon River has incised only 30 meters in more than 780 Ka b.p. Therefore, the decrease in regional base levels that controlled the last cycle of fluvial incision and reworking of placer gold deposits in local tributary streams initiated before 780 Ka b.p. In contrast with paleomagnetic data, comparison of paleosol development in gravels capping the terraces and soil chronosequences developed for the region indicates that the terraces containing interstratified basalts are of Reid (late Pleistocene) age. Soil studies found pre-Reid age Wounded Moose paleosols developed only on high level terraces (120-250 m

above river level) and Reid age Diversion Creek paleosols have developed on intermediate and lower terraces (10-120 m above river level).

Jackson, L. E., Jr., Huscroft, C.A., Barendregt, R.W., Froese, D.G., and Villeneuve, M., 2003. A 2.5 Ma chronology of regional glaciation in west-central Yukon, Canada based on radiometric and paleomagnetic dating of volcanic rocks. Shaping the Earth; a Quaternary perspective; Congress of the International Union for Quaternary Research, v. 16, p. 175.

Abstract: Since the Late Pliocene, the Yukon Plateaus of west-central Yukon Territory, Canada, have experienced periodic fissure eruptions of valley-filling mafic lavas and eruption of small volcanoes (Selkirk Volcanics Group). Ar-Ar and fission track dating as well as paleomagnetic investigations of these volcanic rocks and interstratified sediments chronologically bracket at least three regional glaciations from the Late Pliocene through the Early Pleistocene. The ancestral valley of Rosebud Creek (63°15' N, 137°18' W) contains a magnetically normal basalt flow Ar-Ar dated at 2.69±0.04 Ma. The valley was buried by thick ice-terminus drift deposited during the most extensive and likely the oldest regional glaciation. Regional geomorphic evidence suggests that this glaciation reversed the ancestral Yukon River. The Yukon River assumed its present course by 1.83±0.3 Ma when a magnetically reversed basanite flow was erupted near Fort Selkirk (62°45' N, 137°25' W). The next Early Pleistocene regional glaciation (Fort Selkirk Glaciation (FSG)) is documented by a till near Fort Selkirk. The till is bracketed in time by Ar-Ar ages on overlying and underlying basalt flows and overlying fission-track-dated tephra. These limit FSG to one of the cold peaks that occurred between oxygen isotope stages (OIS) 64 and 50 inclusive (ca 1.8 to 1.5 Ma). A subsequent regional glaciation left striations and erratics on magnetically reversed alkaline olivine basalt flows dated at 1.47±0.05 Ma. This glaciation predated the eruption of a magnetically normal complex of valley-filling olivine basalt flows and pillow basalts that dammed the Yukon River near Fort Selkirk 311±30 ka. The complex is overlain in part by outwash from an ice sheet that formed during Reid Glaciation. Limiting ages determined on tephra overlying Reid drift along with the Ar-Ar age determined on the underlying volcanic rocks date Reid Glaciation to OIS 8. No deposits from OIS 6 ice sheets have been found in Yukon. The OIS 2 (McConnell Glaciation) ice sheet terminated east of Selkirk Volcanics.

Jackson, L. E., Jr., Huscroft, C.A., Ward, B.C., and Villeneuve, M., 2008. Age of volcanism of the Wolverine volcanic center, west-central Yukon Territory, Canada and its implications for the history of Yukon River; American Geophysical Union, EOS Transactions, v. 89, no. 53, V41D-2110.

Abstract: New Ar-Ar ages determined on the Wolverine Creek volcanic center (WC) establishes a middle Pliocene initiation of volcanism for the Fort Selkirk Volcanic Group (FSVG), Fort Selkirk area, west-central Yukon, Canada. WC was active between 4.34±0.06 and 2.98±0.05 Ma. Lava flows repeatedly descended Wolverine Creek valley and flowed into the Yukon River Valley (YRV) during the eruptive life of WC. The total thickness of WC lava flows in YRV decreases in a northward direction and the overall elevation of the surface of the highest flow at any point descends northward as well. Total thickness is up to 100 m in the canyon of Wolverine Creek with a surface elevation of approximately 550 m a.s.l. WC lava flows extend to the confluence of Yukon River with Pelly River 7 km north of the Wolverine Creek confluence with YRV. The lava fill has a total thickness of about 80 m at this northern limit with a surface elevation of 520 m a.s.l. The youngest flow there is dated at 3.05±0.07 Ma. The flows in this area show a general upward compositional change from basanite to alkali olivine basalt which is characteristic of WC. The thinning of the flows and decrease in elevation in a northward direction in YRV is consistent with the contemporary flow direction of Yukon River. Furthermore, the WC flows presumably extended farther down YRV (north and west) prior to erosional truncation. In contrast, lava flows are absent south (up contemporary flow of Yukon River) from the confluence of Wolverine Creek with YRV. This is consistent with the pattern of quenching that would be expected for any lava flow that enters YRV from Wolverine Creek and encounters a north-flowing Yukon River. This pattern is similar to those of lava flows from the younger Pelly and Black Creek FSVG eruptive centers

immediately downstream of the Yukon River-Pelly River confluence. Similar asymmetries in lava flows that entered river canyons have been reported by others in the western Grand Canyon and for the 200 year-old Tseax lava flow in the Nass River valley, north-western British Columbia, Canada. During the Tseax eruption, flows pressed less than 1 km upstream in the Nass River valley whereas they flowed a minimum of 11 km downstream. The gradient of the Nass River in that area is a small fraction of the 1m/km gradient that characterizes Yukon River in the area of FSVG. We conclude that Yukon River flowed in the same direction and along roughly the same course since at least 4.35 Ma in the Fort Selkirk area. This conclusion contradicts a widely accepted hypothesis that Pliocene regional glaciation reversed Yukon River from an ancestral southerly flow in the Fort Selkirk area. Regional glaciation initiated in west-central Yukon no earlier than ca. 2.9 Ma or about the time of the conclusion of WC eruptive activity. Although it is conceivable that Yukon River reversed prior to WC eruptions, such a reversal would have been the result of tectonism or stream piracy: not regional glaciation. Our conclusion applies to the YRV in the area of FSVG. We do not dispute the reversal of Yukon River into its present northward course between the confluence of White River and the Alaska border. There, southward-descending paleo-stream terraces and corroborating gravel fabrics provide incontrovertible evidence for flow reversal.

Jackson, L.E., Jr., Nelson, F.E., Huscroft, C.A., Villeneuve, M., Barendregt, R.W., and Ward, B.C., 2010. Volcanism and age constraints on Pliocene and early Quaternary Cordilleran ice sheet advances, Fort Selkirk area, west-central Yukon, Canada; Geological Society of America, Abstracts with Programs, v. 42, no. 5, p. 362.

Abstract: Fort Selkirk (FS) Yukon, Canada, is situated within (50 km east) of the all-time-limit of Cordilleran-ice-sheet glaciation (late Pliocene in age). Late Pliocene and early Pleistocene mafic volcanic rocks in the FS area are locally interstratified with glacial and non-glacial sediments and were erupted in part beneath late Pliocene and early Pleistocene Cordilleran ice sheets. Neogene volcanism began in the Wolverine Creek basin immediately south of FS ca. 4.3 Ma and persisted to ca. 3.0 Ma. The Yukon River valley was filled with at least 40 m of lava flows by these eruptions. Volcanic activity at the Ne Ch'e Ddhawa (NCD) eruptive center began with a subaqueous eruption of hyaloclastite tuff between ca. 3.0 and 3.1 Ma. It caused or was coincident with temporary volcanic damming of Yukon River. The first evidence of incursion of a Cordilleran ice sheet into the FS area was coincident with a second eruption of NCD eruptive center. It built the NCD volcanic edifice beneath 300 m of glacial ice. Radiometric dating of hyaloclastites and their reversed remanent magnetism refer this eruption to marine isotope stage (MIS) 82 or 78. The subsequent Fort Selkirk Glaciation (FSG) is documented by till and outwash. These overlie complexes of magnetically reversed lava flows (ca. 1.8 Ma) from the FS eruptive center and underlie ca. 1.3 Ma lava flows from the Pelly eruptive center (PC) north of FS. The glacial sediments also underlie non glacial sediments that preserve the short (magnetically normal) Gilsa Subchron. Consequently, FSG occurred during MIS 62 or 60 or 58. Eruption of PC dammed Yukon River with 70 m of lava at ca. 1.3 Ma. Striations and glacial erratics on these lava flows and reversely magnetized till document a glacial advance that reached FS during the last 500 kyr of the Matuyama Chron (MIS 40 to 20). "Forks Glaciation" (FG) is proposed for this event. The NCD and FS glaciations clearly occurred during MIS paced by the 41 kyr precession cycle whereas FG occurred during the transition between precession-paced and eccentricity-paced (100 kyr) glacial cycles. Glaciers never reached FS following FG. This pattern is in accord with the view that the progressive western expansion of North American continental ice sheets during eccentricity-paced glacial cycles resulted in progressively less moisture reaching the northern Cordillera.

Jansen, R.A., Edwards, B., and Ryane, C., 2011. Origins of polymictic diamict at Kima' Kho, northern British Columbia, Canada; Geological Society of America, Abstracts with Programs, v. 43, no. 1, p. 86.

Modified abstract: Kima' Kho is a partly eroded Pleistocene volcano that erupted on the Kawdy Plateau approximately 1.8 Ma. At the northern end of the volcano, a polymictic diamict is exposed in a stream valley, located at 0375930E, 6542126N (UTM zone 9N) at an elevation of 1509 m. We are testing the hypothesis that the diamict is a glacial till deposited by a regionally extensive Pleistocene icesheet. We have used a variety of field and laboratory techniques to characterize the diamict. The deposit was characterized in the field during July 2010. It extends roughly 200 m NE-SW and 20-25 meters vertically at its thickest point. Matrix and 50 clasts were sampled at random from the deposit, and trend and plunge measurements were taken for each clast (ave = 177 and 39 degrees W with Std Dev of 11.96 and 26.43); no imbrication of the clasts was obvious in the field and the deposit was massive. It appears to unconformably overlie palagonitized lapilli tuff from Kima' Kho. Clast dimensions were measured to document sphericity, and surface textures such as striations were documented. Twenty-one thin sections representing all internal textures were examined with a polarizing microscope, and 13 thin sections were analyzed by SEM-EDS. Six clasts of porphyritic volcanic rock were selected for geochemical analysis (analyses in progress), and XRD analysis was conducted to determine minerology of the diamict matrix (analysis in progress). All of our results are consistent with the interpretation that the diamict is of regional origin. Clast sphericities are consistent with mainly transport within ice, as are the striations on some clasts. Mafic volcanic rocks are dominated by olivine porphyritic basalt, some of which can be differentiated based on the presence in the groundmass of magnetite only or magnetite and ilmentite. Preservation of glass in some volcanic clasts indicates the presence of younger volcanic rocks, some of which are of possible local origin. We are presently working to identify possible bedrock sources for all of the clasts to constrain the direction and distance of glacial transport.

Karl, S., Baichtal, J., Calvert, A.T., and Layer, P., 2011. Pliocene to Recent alkalic volcanic centers in southeast Alaska: western component of the Northern Cordilleran Volcanic Province; American Geophysical Union, EOS Transactions, v. 2011, 1 p.

Abstract: More than 25 volcanic centers, including 11 newly identified flows, ranging in age from 6 Ma to 110 years old and scattered throughout southeast (SE) Alaska, constitute a previously unrecognized western component of the Northern Cordilleran Volcanic Province (NCVP). The volcanic rocks are dominantly mafic, locally bimodal, high-Na alkalic rocks that have "within plate" element ratios and primitive $^{87/86}$Sr ratios at 0.703. Mafic rocks have average MgO/SiO_2 ratios of 0.13, TiO_2/MnO ratios of 13.86, Nb/Zr ratios of 0.13, and La/Nb ratios of 0.93 (n=43). Trace element chemistry for obsidian from Suemez Island is indistinguishable from that of obsidian from Mount Edziza in British Columbia. These volcanic rocks have similar compositions, ages, isotopic signatures, and chemistry to rocks of the NCVP and are underlain by the same Northern Cordilleran (Pacific-Juan de Fuca) slab window. Some volcanic fields have associated warm springs. The volcanoes and warm springs are located along structures, commonly N-S and NW-SE striking faults, indicating that their plumbing systems are controlled by extension along the Pacific-North America transform margin in the vicinity of SE Alaska. Widely distributed thermal springs in SE Alaska reflect an elevated geothermal gradient under SE Alaska related to the slab window. Volcanic flows and tephra overlie and underlie glacial and marine deposits. Flows have subaerial, subaqueous, and ice contact features. Pollen, foraminifer, tree ring, C-14, and ^{40}Ar/^{39}Ar ages bracket the timing of volcanic flows, glacial advances and retreats, and subsidence and uplift of marine terraces. Basalts in Behm Canal yielded K-Ar ages of 6.1±0.18 Ma and 5.0±2 Ma. On Suemez Island, 2 rhyolite domes that yielded ^{40}Ar/^{39}Ar ages of 842±11 ka and 851±17 ka lie between glacial deposits and have ice contact features. A basalt flow that yielded a ^{40}Ar/^{39}Ar age of 367.7±8.7 ka fills a deeply incised pre-existing fiord in Rudyerd Bay and has been carved by subsequent glaciations. Near Duncan Canal, basalt flows that have ice marginal features yielded ^{40}Ar/^{39}Ar ages of 200.8±4.5 ka and 90.1±3.6 ka; fault-controlled flows east of Ketchikan yielded ^{40}Ar/^{39}Ar ages of 101.5±2.7 ka, 106±3.5 ka, and 65.7±2 ka. Shells and wood in a glaciomarine deposit that overlies glacially striated gneiss and lies beneath a basalt flow have C-14 ages of 42-44 ka; the flow is overlain by marine deposits that contain palagonite and shells that have C-14 ages of 13 ka. Nearby, a 430 m-thick deposit of hyaloclastite is bounded laterally by till. A

postglacial flow in Behm Canal is 8.1±1.8 ka. Basalt that overlies till near Suemez Island is 21.5±3.8 ka and an unglaciated pahoehoe flow at modern sea level is 6.7±ka. In Duncan Canal a basalt flow overlies glaciomarine deposits that contain left-coiling cold-water planktonic foraminifers of Holocene age. Historic flows on the Blue River are dated by tree rings and charcoal at 370 and 110 years. Discrete marine terraces in southern SE Alaska are dated by C14 shell and wood ages at about 9.6, 5.0, and 2.0 ka, indicating Holocene postglacial isostatic adjustments have been augmented by episodes of tectonic uplift.

Lloyd, A., Edwards, B., Edwards, C., Skilling, I., and LaMoreaux, K., 2006. Preliminary interpretation of processes and products at two basaltic glaciovolcanic ridges; Tsekone and Pillow Ridges, Mount Edziza volcanic complex (MEVC), Northern Cordilleran Volcanic Province, British Columbia, Canada; American Geophysical Union, EOS Transactions, v. 87, V53C-1754.

Abstract: We present detailed descriptions and preliminary interpretations of two basaltic, glaciovolcanic ridges, Tsekone Ridge and Pillow Ridge, that were erupted onto the northwestern side of a basaltic subaerial lava plateau at the MEVC, in northwestern British Columbia. Souther (1992) provided basic descriptions of both ridges and interpreted them as glaciovolcanic in origin. Our interpretation suggests that the two ridges formed under differing ice and meltwater drainage conditions and had very different eruptive histories, even though they are adjacent and stratigraphically related. Tsekone Ridge (TR) is a N-S elongate ridge with outcrops of pillow lava and interbedded vitric, vesicular, unpalagonitized, volcanic tuff-breccia. Our preliminary interpretation of the sequence at TR is that the ridge formed by an initially sub-ice fissure eruption that eventually became focused at four points along the fissure. During this phase of eruption, the confining pressure was sufficient to prevent magmatic fragmentation. At the central point of the ridge, the eruption continued during a period of rapid depressurization, allowing the eruption style to change from effusive to explosive. The products of this explosive eruption are dominantly vitric, highly vesicular lapilli that are not palagonitized. Pillow Ridge (PR) is a NW-S oriented, sinuous, ridge comprising alternating sequences of pillow lava and palagonitized volcanic tuff-breccia. PR preserves a much more complex stratigraphy than TR, with evidence for at least four periods of pillow lava emplacement. Visual reconnaissance combined with descriptions from Souther (1992) show the volcaniclastic rocks as opposed to pillow lavas dominate the sequence in the central part of the ridge. The clastic rocks display dominantly planar bedding, are moderately well sorted, and are cut by numerous dykes. The more complex stratigraphy of PR is consistent with its formation in a hydrologically- variable eruption environment and perhaps over a more prolonged period than TR. Visual inspections of the east side suggest the presence of Surtseyan cone on the ridge, indicating that the eruption switched from dominantly effusive to phreatomagmatic and emergent at this point. This cone is considered to be the source for much of the clastic sequence in the central part of the ridge.

Ludden, J.N., Francis, D.M., and Zindler, A.,1989. Geochemical evidence for asthenosphere-lithosphere interaction in the genesis of Quaternary alkaline magmas in the northern Canadian Cordillera; General Assembly of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI); New Mexico Bureau of Mines and Mineral Resources, Bulletin 131, p. 169

Abstract: The Quaternary alkaline volcanic centres of the Stikine Volcanic Belt of the northern Canadian Cordillera extend from north-central British Columbia to central Yukon. Mt. Edziza, the southernmost and largest of these centres, comprises four volcanic formations of Miocene to Recent age, ranging in composition from transitional alkaline basalt to hawaiite and pantellerite. Sr- and Nd-isotope compositions of the most primitive lavas in this centre are comparable to those of MORB. The Mt. Edziza lavas are considered to be related to upwelling of asthenosphere in central BC as a result of overriding of the Kula rise by the North American plate in the Miocene. The more northerly centres of the Stikine Belt display a range in composition from olivine

nephelinite to transitional alkaline basalt. Both field and petrographic evidence indicate an intimate spatial and temporal relationship between these two magma types. In the Fort Selkirk centre the olivine nephelinite magmas display isotope characteristics comparable to MORB, whilst the alkaline basalts of this centre and the Alligator Lake centre define more radiogenic isotope compositions. The olivine nephelinite end-member of the magma spectrum represents small volumes of non-radiogenic, strongly Si-undersaturated melts, which have infiltrated the more radiogenic and sub-Cordilleran lithosphere. Francis and Ludden (this volume) suggest that those melts are represented by amphibole-pyroxenite veins in an anhydrous lherzolite lithosphere. This model differs from other models of nephelinite genesis in that the nephelinitic melts are the precursor to more extensive melting of the lithosphere to produce more Si-saturated mafic lavas.

Nicholls, J. and Stout, M.Z., 1998. Volcanic studies in northern British Columbia; *in* Slave-NORthern Cordillera Lithospheric Evolution (SNORCLE) Transect and Cordilleran tectonics workshop meeting, Burnaby, British Columbia; Lithoprobe Report, v. 64, p. 289-304.

Introduction: A large number of volcanic centres scatter across northern British Columbia and the Yukon Territory. Wide variations in rock type exist between and within volcanic complexes. Four centres or complexes were selected for study because they contain nearly all the varied rock types in the region. These centres are the Nisga'a lava flows, The Thumb, Mount Edziza, and Llangorse Mountain in the Atlin Area. The rock types range between basanite-nephelinite and peralkaline rhyolite. The only rock types in the area that are not included in the study are phonolites which are found in the Hoodoo Mountain complex.

Nogier, M., Edwards, B.R., and Wetherell, K., 2005. Integrating laser-range finding, electronic compass measurements and GPS to rapidly map vertical changes in volcanic stratigraphy and constrain unit thicknesses and volumes; two examples from the northern Cordilleran volcanic province; American Geophysical Union, EOS Transactions, v. 86, no. 52, V53B-1568.

Modified abstract: We present preliminary results of laser-range finding-GPS surveys from two separate locations in northern British Columbia, in the south-central northern Cordilleran volcanic province: Hoodoo Mountain volcano and Craven Lake cone. This technique, described in detail below, is appropriate for rapidly measuring changes in vertical thicknesses of units that either would be difficult or impossible to measure by most other techniques. The ability to accurately measure thicknesses of geologic units in otherwise difficult-to-access locations will aid in generating better quantitative estimates of deposit geometries and eruption volumes. Such data is particularly important for constraining quantitative models of magma production and eruption dynamics. The deposits of interest in this study comprised at least partly inaccessible, largely pyroclastic units, although the technique could be used to map any vertical surfaces. The laser-range finding-GPS setup used in these studies comprises an IMPULSE LR laser-range finder, a MapStar Module II electronic compass, and a Trimble ProXL global positioning (GPS) unit attached to a tripod specially designed to hold all three pieces of equipment. The maximum distance over which the laser can used is 500m (this distance varies for different lasers); the tripod was set at a relatively short distance from the exposure of interest at Craven Lake (95-115m), but further away at Hoodoo Mountain (up to 450m). The range finder was used to 'shoot' bottom and top contacts of each unit within the vertical faces. The distance and relative bearing were automatically transferred into compass and then to the GPS unit, producing in a map of the vertical face with horizontal and vertical coordinates. Analysis of the data provides detailed estimates of unit thicknesses across the vertical faces. The data collected can be imported into ArcGIS as a SHAPE file and overlain on DEM models for the areas of interest. ArcGIS extensions such as Spatial Analyst and 3D Analyst can be used to estimate surface areas and volumes for units mapped within the laser-GPS setup.

Roggensack, K. and Cameron, B.I., 2004. Melt inclusions from a basaltic tuya in British Columbia; contrasts in early- and late-stage degassing processes; American Geophysical Union, EOS Transactions, v. 85, no. 47, V33A-1458.

Abstract: Volcanic tuyas are of interest because their formation beneath glaciers preserves information on ice-magma interaction and magma degassing processes. In northern British Columbia (58-60°N latitude) there exists a small volcanic field of Quaternary basaltic tuyas. Ash Mountain is one example that is 700m in height, 4-5 km in basal diameter and has a lower section of pillow lavas and an upper section of unconsolidated hyaloclastite. This distinctive morphological change, common to many of the tuyas, has been interpreted as corresponding to a shift from initial subglacial eruption to later subaqueous to subaerial eruption. Ash Mountain also displays the common shift in composition from early tholeiitic lavas to later alkalic lavas. Melt inclusions from the upper ash unit have been analyzed to investigate the later stages of volcano formation. Olivine crystals (Fo_{76-80}) separated from bulk ash from the upper flank of the volcano contain abundant melt inclusions and large glass-filled re-entrants. The melt inclusions are alkalic in character and closely match the groundmass glass composition indicating that the crystals and melt inclusions are representative of late-stage crystallization. FTIR analysis shows that the average water content of melt inclusions is 0.9 wt.% with variable CO_2 (0 to 1200 ppm). The variation in H_2O and CO_2 resembles an open-system degassing trend consistent with magma crystallization during transport within the shallow crust. Previously determined water abundance (0.5 to 0.7 wt.%) and hydrogen isotopic composition (δD -87.2 to -- 102.0 per mil) for Ash Mountain pillow lavas are consistent with shallow level degassing during early volcano formation. The melt inclusion data indicates the later alkalic magma,which erupted with greater energy, was derived from greater depth.

Skilling, I. P., Edwards, B., Hungerford, J., LaMoreaux, K., Endress, C., and Lloyd, A., 2006. Using glaciovolcanic processes and products at the Mount Edziza volcanic complex (MEVC), British Columbia, Canada to constrain paleo-ice conditions; initial results; American Geophysical Union, EOS Transactions, v. 87, v53c-1755.

Abstract: The Mount Edziza Volcanic Complex (MEVC) of the Northern Cordilleran Volcanic Province (NCVP) erupted basaltic, trachytic and rhyolitic effusive and explosive products in a wide variety of subaerial and subaqueous environments from about 8 Ma to about 2000 yrs BP. Souther (1992) suggested that several eruptive products were emplaced in a sub-ice or ice-contact environment; an interpretation confirmed by our investigations in 2006. Glaciovolcanic rocks at the MEVC are significant because they record evidence of ice presence and thickness in a region for which there is very little data on ice conditions prior to the most recent glaciation Several areas of likely basaltic and trachytic glaciovolcanic products were examined in detail on the western side of MEVC, in order to confirm their glaciovolcanic nature, and to ultimately better constrain paleo-ice presence and thickness. Our initial results presented here are focused on documenting the processes and products in detail. For example, a sequence of basaltic subaqueous lavas erupted from Tennana Cone, displayed spectacular evidence for the role of sub-ice bedrock topography on the geomorphology and structure of such lava flows. Proximal flows were emplaced in a sheet-like form as both pillow and lobate flows with mounding of pillow lavas at the crest of sub-ice cliffs (ie at contact with thicker ice). Pillow lavas were emplaced in sinuous drainage tunnels at the base of the cliffs. Trachytic lava flows and domes form an important part of the MEVC sequence and many also display evidence of ice-contact or sub-ice emplacement. In particular, Triangle Dome on the northwestern side of the MEVC displays a pattern of columnar cooling joints that indicates that it was emplaced as several very steep-sided domes in a sub-ice environment. Geochronology, geochemistry and volatile analysis of basaltic and trachytic glass from these and several other localities are currently ongoing, and with detailed study of the products, will help us constrain the paleo-ice thicknesses during the Pleistocene at the MEVC. We hope that the methods we develop for constraining paleo-ice conditions can be used at other glaciovolcanic centers and perhaps become part of a standard palaeoclimatological

toolbox for terrestrial environments.

Skilling, I.P., LaMoreaux, K., and Edwards, B., 2007. Using cooling-contraction joints in a trachyte lava dome to infer ice contact and water ingress: Mount Edziza Volcanic Complex, British Columbia, Canada; 2nd Volcano-Ice Interaction on Earth and Mars Conference (VII2), Vancouver, British Columbia, p. 63-64.

Modified abstract: The pattern and dimensions of cooling-contraction joints in lavas at glaciovolcanic centers can often provide important evidence for former ice contact and minimum ice thickness. In particular, narrow columns perpendicular to subvertical flow margins are commonly interpreted as evidence for contact with steep ice. Interpretation of joint patterns in such lavas can be complex and several factors need to be considered, including the topography of the contacted ice, water levels, ingress of water and steam along earlier joints, bedrock (including earlier flows) topography, lava effusion rates and rheology, lava intrusion (endogenous growth), ice unloading, recent freeze-thaw processes, etc. This presentation focuses on the influence of water ingress and the shape of the ice cavity on jointing patterns preserved at a trachytic lava dome at the Mount Edziza Volcanic Complex (MEVC), British Columbia, Canada, and also briefly discusses the possible role of ice unloading and endogenous dome growth on joint patterns at this dome.

Souther, J.G., and Lambert, M.B., 1972. Volcanic rocks of the northern Canadian Cordillera; International Geological Congress Guidebook, v. 24, Part A12, 54 p.

Summary: This guidebook summarizes an eleven day field trip in the northern Canadian Cordillera, looking at volcanic rocks of various ages, beginning in Edmonton, Alberta, and concluding at Prince Rupert, British Columbia, with descriptions of numerous features, including Mount Edziza.

Wrangell Volcanic Belt

Scientific Books and Articles

Donaldson, J. A., Guerstein, P.G., and Mueller, W., 1996. Facies analysis of a pumiceous terrace beside Klutlan Glacier, Yukon Territory; Canadian Journal of Earth Sciences, v. 33, no. 9, p. 1233-1242.

Abstract: Dacitic pumice forms discontinuous terraces along both sides of Klutlan Glacier, which emanates from Mount Churchill, Alaska. Mount Churchill is the eruptive source of the White River Ash, an extensive tephra deposit accumulated ~1200 and 1900 BP during two plinian eruptions. Composition, texture, primary structures, and lack of induration suggest that, apart from a locally preserved cover of air-fall tephra, the Klutlan pumice deposits are resedimented proximal equivalents of the White River Ash. The pumice terraces display large-scale crossbedding, normal and inverse graded bedding, channels, and both linguoid and climbing ripples, all sedimentary structures characteristic of subaqueous deposition. In addition, many of the pyroclasts are subround and show a wide variation in sorting from bed to bed, in contrast to the uniformly angular to subangular texture of well-sorted pyroclasts in an air-fall ash layer that caps the terraces. This uppermost tephra unit, up to 1 m thick, is attributed to the last major eruption of Mount Churchill. The underlying resedimented pumice deposits are attributed to deposition by meltwater produced as a result of substantial melting of the snow and ice fields below Mount Churchill, the headward region of Klutlan Glacier, in response to increased heat flow immediately before the last eruption. The terraces stand more than 100 m above the present surface of Klutlan Glacier, indicating that substantial melting has occurred since the time of terrace deposition. In comparison to present-day conditions, this implies a prolonged cold climate before accumulation of the pumice terraces in glacier-margin channels. An alternative explanation is that Klutlan Glacier may have been catastrophically thickened as a result of glacial surging in response to elevated heat flow during eruptions of Mount Churchill. Meltwater backed up behind one or more ice dams could have created temporary lakes in which detached segments of Klutlan Glacier locally abutted against and (or) scoured the shorelines, thus explaining the discontinuous nature of the pumice terraces. Rapid deposition of the pumice terraces, perhaps during a single winter, is inferred from an almost complete lack in the terraces of lithoclasts derived from the steep talus-covered slopes of Klutlan's U-shaped valley.

Downes, H., 1985. Evidence for magma heterogeneity in the White River Ash (Yukon Territory); Canadian Journal of Earth Sciences, v. 22, no. 6, p. 929-934.

Abstract: Two Recent Plinian eruptions in the Wrangell Mountains (southeast Alaska) gave rise to two distinct ash-fall deposits that are collectively known as the White River Ash and cover much of the Yukon Territory, northwest Canada. Analysis of the pumiceous glass indicates that the magma chamber was compositionally inhomogeneous prior to each eruption. No compositional stratigraphy has been detected in the deposits, indicating either thorough mixing in the eruption cloud or thorough reworking after deposition. Thus each individual sample of ash represents a large part of the magma chamber, whereas larger pumice fragments are more homogeneous. Variations in temperature, 950–990 and 995–1030°C, respectively, for the older and younger eruptions, and $-\log fo_2$ values, 9.3–8.3 and 8.3–7.7, derived from the Fe–Ti oxides, support the conclusion that the magma chamber was inhomogeneous.

Lerbekmo, J. F., 2008. The White River Ash; largest Holocene plinian tephra; Canadian Journal of Earth Sciences, v. 45, no. 6, p. 693-700.

Abstract: The White River Ash is a bi-lobate tephra in eastern Alaska, Yukon Territory, and western Northwest Territories. Plinian-type eruptions produced the north lobe ~1900 years BP and the larger east lobe ~1250 years BP (^{14}C years). Present evidence favors the vent for the east lobe to be beneath the Klutlan Glacier. East lobe pumice is not present atop Mt. Churchill, so the pumice there must belong to the north lobe and is also likely to have come from a vent beneath the Klutlan Glacier. Isopachs of the east lobe, now known to stretch as far east as Great Bear Lake, indicate an east lobe volume of ~47 km^3. Thickness and grain size of the east lobe decay in exponential fashion, producing straight line plots when the thickness half-distance and clast half-distance are plotted against the square root of the isopach area, the proximal slope being steeper than the distal. The east lobe eruption is indicated to have been into a wind of about 10 m/s and to have produced an eruptive cloud height of ~45 km. The eruption rate was at least 2.8×10^8 kg/s.

Lerbekmo, J. F. and Campbell, F.A., 1969. Distribution, composition, and source of the White River Ash, Yukon Territory; Canadian Journal of Earth Sciences, v. 6, no. 1, p. 109-116.

Abstract: The White River Ash is a bi-lobate 1500 year old deposit occupying at least 6 cubic miles and covering some 125 000 square miles of southern Yukon and eastern Alaska. Sixty-six samples were collected at 5-mile intervals, principally along two traverses 120 miles apart across the main lobe, and subjected to X-ray fluorescence and petrographic analysis.The ash is a rhyodacite composed of glass (n = 1.502), andesine, hornblende, hypersthene, and magnetite. The average chemical composition is SiO_2 = 67.4, Al_2O_3 = 15.1, TiO_2 = 0.5, MgO = 2.0, FeO = 2.0, Fe_2O_3 = 2.2, Na_2O = 4.1, K_2O = 2.5 and CaO = 4.1, but there is a significant difference between the two traverses owing to the increase in glass relative to crystal components downwind. A synthesis of the distribution of the ash permitted the drawing of a 5 by 12 miles 'target' source rectangle in the St. Elias Range between Mts. Natazhat and Bona in Alaska. Aerial photographs revealed a suspect mound 0.4 miles in diameter beside the Klutlan Glacier. Access by helicopter showed the mound to be a flat cone of large White River pumice fragments. It is believed that the vent lies beneath the glacier next to the cone.

Lerbekmo, J. F., Westgate, J.A., Smith, D.G.W., and Denton, G.H., 1975. New data on the character and history of the White River volcanic eruption, Alask; *in* Quaternary studies; selected papers from IX INQUA congress, (ed.) R.P. Suggate and M.M. Cresswell; Royal Society of New Zealand, Bulletin 13, p. 203-209.

Abstract: The White River Ash is a Recent bi-lobate tephra which covered more than 300,000 km^2, largely in the Yukon Territory, Canada. A northern lobe and an eastern lobe have axis lengths in excess of 500 and 1000 km, respectively. The vent lies on the northeastern flank of Mount Bona in the northern St. Elias Range, Alaska. Pyroclastics pf the two lobes have essentially identical mineralogy, but electron microprobe analysis of 35 Fe-Ti oxide samples shows the two lobes can be readily distinguished by the compositon of their ilmenites: the Fe, Ti, and Mg contents are the most discriminatory. By this means the northern lobe has been identified beneath the eastern, demonstrating considerable overlap. Using extrapolated experimental data of buddington and Lindsley, the T-fO_2 conditions of crystallization of co-existing ilmenite and magnetite are shown to be mutually exclusive for the two lobes, the ranges being:

T °C = 830 to 1005 (northern lobe) and 1035 to 1125 (eastern lobe)

$-\log_{10}fO_2$ = 11.5 to 8 (northern lobe) and 7.5 to 6.5 (eastern lobe)

Fifteen new radiocarbon ages are given, along with seven taken from previous publications. Eleven determinations on each lobe give means of 1887 and 1250 yr BP for the northern and eastern lobes, respectively.

Moodie, D. W., Catchpole, A. J. W., and Abel, K., 1992. Northern Athapaskan oral traditions and the White River volcano; Ethnohistory, v. 39, n. 2, p. 148-171.

Abstract: This article presents Athapaskan oral traditions that tell of volcanic eruptions at the beginning of time. It concludes that these stories recall a volcanic eruption in the upper White River basin circa A.D. 720. It also suggests that the ash fall from this eruption, which covered most of the southwestern Yukon Territory, triggered population displacements that led to Athapaskan migrations eastward into the Mackenzie valley.

Preece, S.J. and Hart, W.K., 2004. Geochemical variations in the <5 Ma Wrangell volcanic field, Alaska; implications for the magmatic and tectonic development of a complex continental arc system; *in* Continental margins of the Pacific Rim, (ed.) Y. Dilek and R. Harris; Tectonophysics, v. 392, no. 1-4, p. 165-191.

Summary: This paper presents geochemical data for nearly 400 new volcanic samples from the <5 Ma Wrangell Volcanic Field (a name which is commonly used as a synonym or near-synonym for the “Wrangell Volcanic Belt”) of southeastern Alaska. It includes a discussion of the tectonic affinity of the Wrangell Volcanic Field, which continues into Canada’s Yukon Territory, so although it does not specifically discuss the volcanoes of the Canadian portion of the belt, it is relevant to this bibliography (particularly since the number of publications focusing on volcanoes of Canada’s Wrangell Volcanic Belt) is small.

Preece, S.J., McGimsey, R.G., Westgate, J.A., Peearce, N.J.G., Hart, W.K., and Perkins, W.T., 2014. Chemical complexity and source of the White River Ash, Alaska and Yukon; Geosphere, v. 10, no. 5, p. 1020-1042.

Abstract: The White River Ash, a prominent stratigraphic marker bed in Alaska (USA) and Yukon (Canada), consists of multiple compositional units belonging to two geochemical groups. The compositional units are characterized using multiple criteria, with combined glass and ilmenite compositions being the best discriminators. Two compositional units compose the northern group (WRA-Na and WRA-Nb), and two units are present in the eastern group (WRA-Ea and the younger, WRA-Eb). In the proximal area, the ca. 1900 yr B.P. (Lerbekmo et al., 1975) WRA-Na displays reverse zoning in the glass phase and systematic changes in ilmenite composition and estimated oxygen fugacity from the base to the top of the unit. The eruption probably tapped

different magma batches or bodies within the magma reservoir with limited mixing or mingling between them. The 1147 cal yr B.P. (calibrated years, approximately equivalent to calendric years) (Clague et al., 1995) WRA-Ea eruption is only weakly zoned, but pumices with different glass compositions are present, along with gray and white intermingled glass in individual pumice clasts, indicating the presence of multiple magmatic bodies or layers. All White River Ash products are high-silica adakites and are sourced from the Mount Churchill magmatic system.

Preece, S.J., Westgate, J.A., Alloway, B.V., and Milner, M.W., 2000. Characterization, identity, distribution, and source of late Cenozoic tephra beds in the Klondike District of the Yukon, Canada; Canadian Journal of Earth Sciences, v. 37, no. 7, p. 983-996.

Abstract: A large number of distal, silicic tephra beds have been preserved in the late Cenozoic deposits of the Klondike region, Yukon Territory. Forty-one tephra samples, representing twelve distinctive beds, are detailed in this study. They range in composition from basaltic andesite to high-silica rhyolite, and were deposited during the late Pliocene to Late Wisconsinan time interval. Seven tephra beds are derived from volcanoes in the Wrangell volcanic field, and four come from the more distant eastern Aleutian arc-Alaska Peninsula region, but the source of the single andesitic tephra is unknown. The widespread and well known Old Crow and Sheep Creek tephra beds have been identified in the Klondike district, but all the other tephra units are characterized in detail for the first time. The ages of most tephra beds are poorly constrained, but will undoubtedly become better known with the application of recently developed glass fission-track methods. Hence, prospects are favourable for the eventual development of a comprehensive and reliable time-stratigraphic framework that will support on-going studies on the late Cenozoic geology, geomorphology, paleontology, and paleoenvironments of the Klondike area.

Preece, S.J., Westgate, J.A., Froese, D.G., Pearce, N.J.G., and Perkins, W.T., 2011. A catalogue of late Cenozoic tephra beds in the Klondike goldfields and adjacent areas, Yukon Territory; Canadian Journal of Earth Sciences, v. 48, no. 10, p. 1386-1418.

Abstract: Many distal tephra beds exist in the late Cenozoic sediments of the Klondike goldfields and nearby areas. They come from volcanoes in the Wrangell volcanic field and the eastern Aleutian arc and represent large-magnitude eruptions. During the course of our tephrochronological studies in this region over the last 40 years, we have discovered 196 tephra occurrences and 50 distinctive tephra beds. The location of these sites and the distinguishing features of each of these tephra beds are presented in the form of a catalog, which we hope will provide a stimulus for present and future tephrochronological studies in the Yukon Territory. These data are presented as a series of tables, as follows: location, stratigraphic context, petrography, geochemical characteristics, including major- and trace-element composition of glass shards, major-element composition of Fe-Ti oxides, classification, and age determinations. A new classification scheme is presented in which the rhyolitic and dacitic tephra beds are grouped into three classes: adakite, transitional, and typical arc.

Pyne-O'Donnell, S.D.F., Hughes, P.D.M., Froese, D.G., Jensen, B.J.L., Kuehn, S.C., Mallon, G., Amesbury, M.J., Charman, D.J., Daley, T.J., Loader, N.J., Mauquoy, D., Street-Perrott, F., and Woodman-Ralph, J., 2012. High-precision ultra-distal Holocene tephrochronology in North America; Quaternary Science Reviews, v. 52, p. 6-11.

Abstract: Far-travelled volcanic ashes (tephras) from Holocene eruptions in Alaska and the Pacific northwest have been traced to the easternmost extent of North America, providing the basis for a new high-precision geochronological framework throughout the continent through tephrochronology (the dating and correlation of tephra isochrons in sedimentary records). The reported isochrons are geochemically distinct, with seven correlated to documented sources in Alaska and the Cascades, including the Mazama ash from Oregon (~7600 years old) and the

eastern lobe of the White River Ash from Alaska (~1150 years old). These findings mark the beginning of a tephrochronological framework of enhanced precision across North America, with applications in palaeoclimate, surface process and archaeological studies. The particle travel distances involved (up to ~7000 km) also demonstrate the potential for continent-wide or trans-Atlantic socio-economic disruption from similar future eruptions.

Richter, D. H., Smith, J.G., Lanphere, M.A., Dalrymple, G.B., Reed, B.L., and Shew, N., 1990. Age and progression of volcanism, Wrangell volcanic field, Alaska; Bulletin of Volcanology, v. 53, no. 1, p. 29-44.
Abstract: The Wrangell volcanic field covers more than 10 000 km^2 in southern Alaska and extends uninterrupted into northwest Yukon Territory. Lavas in the field exhibit medium-K, calc-alkaline affinities, typical of continental volcanic arcs along convergent plate margins. Eleven major eruptive centers are recognized in the Alaskan part of the field. More than 90 K-Ar age determinations in the field show a northwesterly progression of eruptive activity from 26 Ma, near the Alaska-Yukon border, to about 0.2 Ma at the northwest end of the field. A few age determinations in the southeast extension of the field in Yukon Territory, Canada, range from 11 to 25 Ma. The ages indicate that the progression of volcanism in the Alaska part of the field increased from about 0.8 km/Ma, at 25 Ma, to more than 20 km/Ma during the past 2 Ma. The progression of volcanic activity and its increased rate of migration with time is attributed to changes in the rate and angle of Pacific plate convergence and the progressive decoupling of the Yakutat terrane from North America. Subduction of Yakutat terrane-Pacific plate and Wrangell volcanic activity ceased about 200 000 years ago when Pacific plate motion was taken up by strike-slip faulting and thrusting.

Robinson, S. D., 2001. Extending the late Holocene White River ash distribution, northwestern Canada; Arctic, v. 54, no. 2, p. 157-161.
Abstract: Peatlands are a particularly good medium for trapping and preserving tephra, as their surfaces are wet and well vegetated. The extent of tephra-depositing events can often be greatly expanded through the observation of ash in peatlands. This paper uses the presence of the White River tephra layer (1200 B.P.) in peatlands to extend the known distribution of this late Holocene tephra into the Mackenzie Valley, northwestern Canada. The ash has been noted almost to the western shore of Great Slave Lake, over 1300 km from the source in southeastern Alaska. This new distribution covers approximately 540 000 km^2 with a tephra volume of 27 km^3. The short time span and constrained timing of volcanic ash deposition, combined with unique physical and chemical parameters, make tephra layers ideal for use as chronostratigraphic markers.

Skulski, T., Francis, D., and Ludden, J., 1991. Arc-transform magmatism in the Wrangell volcanic belt; Geology, v. 19, p. 11-14.
Abstract: The Late Cenozoic Wrangell volcanic belt records a transition in magma supply and geochemistry from a subduction to transform margin between the northeastern Pacific and North American plates. The northwestern volcanic belt comprises calc-alkaline lavas that are above the Wrangell-Wadati Benioff zone, whereas the southeastern belt comprises transitional lavas with minor alkaline and calc-alkaline lavas that overlie a leaky transform fault. The subduction-transform transition is marked by an increase in Fe/Mg and Nb/La ratios and a decrease in Ba/La ratios. Thus, the lavas of the transform regime display a geochemical signature that is intermediate to that of calc-alkaline and intraplate alkaline lavas. Whereas the effects of crustal contamination can be recognized in the evolved lavas of all suites, all primitive lavas in the transform regime are mantle derived and reflect the variable melting and mixing of depleted (mid-ocean ridge basalt) upper mantle, enriched mantle (ocean island basalt), and slab-derived components.

Skulski, T., Francis, D., and Ludden, J., 1991. Volcanism in an arc-transform transition zone: the stratigraphy of the St. Clare Creek volcanic field, Wrangell volcanic belt, Yukon, Canada; Canadian Journal of Earth Sciences, v. 29, no. 3, p. 446-461.

Modified abstract: The St. Clare Creek volcanic field in the southwestern Yukon overlies a tectonic transition in the Wrangell volcanic belt between subduction to the northwest in Alaska and transform faulting along the Duke River fault in the southeast. Two large polygenetic volcanic centres dominated the Miocene landscape of the St. Clare Creek field: the 18–16 Ma Wolverine centre and the 16–10 Ma Klutlan centre. The volcanic stratigraphy of the St. Clare Creek field and $^{40}Ar/^{39}Ar$ geochronological data provide the basis for understanding the origin of St. Clare magmas in a regional tectonic context. Early Wolverine alkaline volcanism largely reflects leaky transform faulting, whereas subsequent transitional and calc-alkaline lavas record the onset of subduction-related volcanism at the margins of the then active Wrangell arc. The opposite eruption sequence at the Klutlan centre records the demise of subduction-related volcanism between 16 and 13 Ma, due to northwestward migration of the subducted plate. Upwelling of asthenospheric mantle in place of the subducted slab led to the generation of transitional basalts between 13 and 11 Ma, which resulted in more evolved lavas between 11 and 10 Ma. Although the St. Clare Creek field is older than Pleistocene, this reference is included herein because it discusses the tectonic and petrologic evolution of the Wrangell volcanic belt, which is useful for understanding the still-active Alaskan portion of the belt.

Stuiver, M., Borns, H.W., and Denton, G.H., 1964. Age of a widespread layer of volcanic ash in the southwestern Yukon Territory; Arctic, v. 17, no. 4, p. 259-261.

Abstract: Radiocarbon dates pertaining to a widespread layer of volcanic ash in the southwestern Yukon Territory are here reported. The volcanic ash generally occurs in lacustrine sediments and in peat and loess deposited during the Little Ice Age and thus affords a valuable marker horizon for correlating these deposits. Bostock constructed an isopach map showing two coalescing fans of ash with a combined area of about 129,000 sq. mi. and a maximum thickness of about 300 ft. near the international boundary about 10 mi. south of the White River. Both Bostock and Capps suggested that there was probably the source of the ash. Moffit and Knopf reported that a sample of this ash collected in the White River Basin, Alaska was an andesitic pumice. Berger described ash from the Tepee Lake area, southern Yukon Territory, and concluded that it was of dacitic composition. A microscopic analysis of an ash sample collected near the southeast shore of Kluane Lake, southwestern Yukon Territory, in 1963 showed it to be composed of whole and broken euhedral crystals of plagioclase (An 35 to An 50), hornblende, biotite, and a trace of magnetite. The glass sherds have a refractive index of approximately 1.510, suggesting a dacitic composition. Knopf reported a composition slightly more calcic than Ab 1, An 1, or essentially labradorite, whereas the two analyses from the Yukon Territory show the plagioclase to be andesine. The ash layer, 1 inch thick, was found in a peat bog on the timbered rocky knob separating the Slims and Kaskawulsh rivers, southwestern Yukon Territory, approximately 100 yd. north of and about 40 ft. above the Little Ice Age terminal moraine of the Kaskawulsh Glacier. In an excavation the top of the l-in. thick ash layer in this locality was 13 in. below the surface of the bog. Samples of peat, 0.5 in. thick, were collected from positions immediately above and below the ash for radiocarbon dating. The sample Y-1363 from just above the ash yielded an age of 1460 ±70 years B.P. and the sample Y-1364 from just below the ash was dated 1390 ±70 years B.P., indicating that the time of the ash fall was around 1425 ±50 years ago. Although the lower sample provides a younger date, the difference is not significant in view of the statistical error of ±70 years. Near the southeast shore of Kluane Lake, Yukon Territory, the ash occurs near the base of a deposit of loess 4 ft. thick. The centre part of a tree buried there in the growth position immediately above the ash was dated at 870 ±100 years B.P. (sample Y-1365) and gives a minimum age for the ash.

Trop, J.M., Hart, W.K., Snyder, D., and Idleman, B., 2012. Miocene basin development and volcanism along a strike-slip to flat-slab subduction transition; stratigraphy, geochemistry, and geochronology of the central Wrangell volcanic belt, Yakutat-North America collision zone; Geosphere, v. 8, no. 4, p. 805-834.

Abstract: New geochronologic, geochemical, sedimentologic, and compositional data from the central Wrangell volcanic belt (WVB) document basin development and volcanism linked to subduction of overthickened oceanic crust to the northern Pacific plate margin. The Frederika Formation and overlying Wrangell Lavas comprise >3 km of sedimentary and volcanic strata exposed in the Wrangell Mountains of south-central Alaska (United States). Measured stratigraphic sections and lithofacies analyses document lithofacies associations that reflect deposition in alluvial-fluvial-lacustrine environments routinely influenced by volcanic eruptions. Expansion of intrabasinal volcanic centers prompted progradation of vent-proximal volcanic aprons across basinal environments. Coal deposits, lacustrine strata, and vertical juxtaposition of basinal to proximal lithofacies indicate active basin subsidence that is attributable to heat flow associated with intrabasinal volcanic centers and extension along intrabasinal normal faults. The orientation of intrabasinal normal faults is consistent with transtensional deformation along the Totschunda-Fairweather fault system. Paleocurrents, compositional provenance, and detrital geochronologic ages link sediment accumulation to erosion of active intrabasinal volcanoes and to a lesser extent Mesozoic igneous sources. Geochemical compositions of interbedded lavas are dominantly calc-alkaline, range from basaltic andesite to rhyolite in composition, and share geochemical characteristics with Pliocene-Quaternary phases of the western WVB linked to subduction-related magmatism. The U/Pb ages of tuffs and $^{40}Ar/^{39}Ar$ ages of lavas indicate that basin development and volcanism commenced by 12.5-11.0 Ma and persisted until at least ca. 5.3 Ma. Eastern sections yield older ages (12.5-9.3 Ma) than western sections (9.6-8.3 Ma). Samples from two western sections yield even younger ages of 5.3 Ma. Integration of new and published stratigraphic, geochronologic, and geochemical data from the entire WVB permits a comprehensive interpretation of basin development and volcanism within a regional tectonic context. We propose a model in which diachronous volcanism and transtensional basin development reflect progressive insertion of a thickened oceanic crustal slab of the Yakutat microplate into the arcuate continental margin of southern Alaska coeval with reported changes in plate motions. Oblique northwestward subduction of a thickened oceanic crustal slab during Oligocene to Middle Miocene time produced transtensional basins and volcanism along the eastern edge of the slab along the Duke River fault in Canada and subduction-related volcanism along the northern edge of the slab near the Yukon-Alaska border. Volcanism and basin development migrated progressively northwestward into eastern Alaska during Middle Miocene through Holocene time, concomitant with a northwestward shift in plate convergence direction and subduction collision of progressively thicker crust against the syntaxial plate margin.

Reports, Government Publications, and Theses

Berger, A.R., 1958. Recent volcanic ash deposit, Yukon Territory, Canada; M.Sc. thesis, Dalhousie University, Halifax, Nova Scotia, pages unknown.

Summary: This thesis describes the distribution of the Holocene White River Ash in the Yukon Territory. It was not possible to obtain a copy of the thesis or abstract but it is included here as it is a significant early study of the White River Ash, and is frequently cited.

Bunbury, J. and Gajewski, K., 2009. Variations in the depth and thickness of the White River Ash in lakes of the southwest Yukon; *in* Yukon Exploration and Geology 2008, (ed.) L.H. Weston, L.R. Blackburn, and L.L. Lewis; Yukon Geological Survey, p. 77-84.

Abstract: The purpose of this study is to document the depth and thickness of the White River Ash in lakes across the southwest Yukon for use in paleoenvironmental impact studies. Sediment cores were sampled from seven lakes located within the plume of the eastern lobe of the White River Ash (1147 cal. years BP). Site locations are between 92 and 254 km from Mount Churchill, Alaska, the probable source for the White River Ash. Based on magnetic susceptibility measurements, the depth of the sediment above the ash layer in the lakes ranges between 38 and 98 cm; these differences are due to factors associated with sedimentation rates. The

thickness of the ash ranges between 0.1 and 32 cm and typically increases with proximity to the source vent. These results can be used in paleoenvironmental studies to assist in the interpretation of the impact of volcanic ash events.

Downes, H., 1979. The White River Ash, Yukon Territory; a petrologic study; M.Sc. thesis, University of Calgary, Calgary, Alberta, 137 p.

Abstract: Two Holocene Plinian eruptions in the Wrangell Mountains (S. E. Alaska) gave rise to two distinct ash-fall deposits, collectively known as the White River Ash. Explosion magnitues are estimated as 9.5 and 9.6 (Hedervari's scale) respectively, for the two events, and eruption cloud heights were between 30 and 35 km. Multivariate statistical analysis of the pumic glass indicates that the magma chamber was compositionally zoned prior to each eruption. The force of the explosion caused the vesiculated magma to be thoroughly mixed in the eruption cloud, resulting in a total lack of compositional stratigraphy in the deposit, contrary to earlier work. Thus, each individual sample of the ash represents a large part of the magma chamber. Variations in temperature (930-990°C and 985-1040°C) respectively for the older and younger eruptions, and -log fO_2 values (9.3-8.3 and 8.3-7.7) derived from the iron-titanium oxides, support the conclusion that the magma chamber was zoned. The two deposits cannot be distinguised by their glass composition (indicating their common origin) but they differ widely in their ilmenite compositions. Samples from a locaility in which both ashes were present were easily assigned to the appropriate event. Chemical zonation patterns in plagioclase crystals were examined and variations were attributed to changing conditions of pressure, temperature, water saturation and melt composition before eruption. Estimates of P_{H2O} were derived from plagioclase-glass equilibria and were found to range from very low to 1.2kb. An approximate value of P_{total} (4-5kb) was calculated by using the hb-mt-plag assemblage and by comparing the results to those obtained from a better-established method (Qtz-Mt-Pyx assemblage).

Hanson, L.W., 1965. Size distribution of the White River Ash, Yukon Territory; M.Sc. thesis, University of Alberta, Edmonton, Alberta, 118 p.

Abstract: The White River Ash is a recent tephra-fall covering a major portion of the southern Yukon Territory. The deposit has a bi-lobate form with the axis of the major lobe trending east and the axis of the secondary lobe trending north from an origin somewhat west of the International Boundary near 61º 30' latitude. Samples from 66 locations and thickness observations from 132 locations were taken along the Alaska Highway and along the roads between Whitehorse, Mayo, Dawson City and Tetlin Junction. The isopach map of the deposit published by Bostock (1952) was modified to fit the new thickness observations. The grain size distribution was determined from the main lobe of the White River Ash by sieving and pipette analysis. The distribution is different from that expected from a theoretical modal in that the modes of equal phi values are distributed about the axis so as to form V-shaped isopleths pointing away from the origin. By using the method of Knox and Short (1963) the location of the volcanic vent was calculated to be near Mount Bona, at least 20 miles west of Mt. Natazhat, which previous authors had proposed to be the source; the energy of the explosion was equivalent to 33.7 Kilotons of TNT; and the mean and maximum heights of the cloud were 16.8 and 22.6 kms. It is concluded that the results of the study are encouraging enough to warrant further study of tephra-falls in a similar manner.

McGimsey, R. G., Richter, D.H., DuBois, G.D., and Miller, T.P.,1992. A postulated new source for the White River Ash, Alaska; United States Geological Survey Bulletin, p. 212-218.

Summary: The White River Ash is the product of two of the most voluminous pyroclastic eruptions in North America in the past 2000 years, blanketing much of Canada's Yukon Territory, portions of the Northwest Territories, and a small part of eastern Alaska. The two lobes of this plinian fallout deposit cover more than 340,000 km^2 and contain an estimated 25-50 km^3 of tephra. Radiocarbon ages indicate that the northern lobe was deposited about 1887 BP, while the larger eastern lobe was deposited about 1250 BP. The authors herein postulate a vent for these deposits near the summit of Mount Churchill, Alaska.

Souther, J.G. and Stanciu, C., 1975. Operation Saint Elias, Yukon Territory: Tertiary volcanic rocks; Geological Survey of Canada, Paper 75-1A, p. 63-70.

Introduction: Scattered remnants of Tertiary sub-aerial lavas and pyroclastic rocks are preserved along the entire eastern fringe of the Saint Elias Mountains. Over large areas extrusive rocks lie in flat undisturbed piles on a Tertiary surface of moderate relief. Elsewhere, strata of the same age have been deformed during a late pulse of Saint Elias tectonism and faulted, contorted into tight symmetrical folds or overridden by pre-Tertiary basement rocks along southwesterly dipping thrust faults. Profound recent uplift, accompanied by rapid erosion has reduced once vast areas of Tertiary volcanic rocks to small isolated remnants. In place, the eruptive rocks have been stripped away completely, leaving only sub-volcanic plutons, necks, dyke swarms and zones of hydrothermal alteration. Tertiary volcanic rocks are extensively developed in eastern Alaska, where they are collectively referred to as the Wrangell Lavas (Mendenhall, 1905). In McCarthy Quadrangle, which lies east of the project areas, MacKevett (1970), described the Wrangell Lavas as “sub-aerial lava flows, less commonly pyroclastic rocks, vitrophyre and conglomerate more than 5,000 feet thick”. Equivalent rocks in western Yukon have been described by Wheeler (1963) in Kaskawulsh map-area, by Kindle (1953) in Dezadeash map-area, and by Muller (1967), who referred to them as the St. Clare Group in Kluane Lake map-area. In this report the name Wrangell Lava is adopted for all the Tertiary extrusive products and Wrangell Intrusions for the felsic, subvolcanic plutons that cut parts of the Wrangell Lava succession. Within the project area, three sub-provinces of the Wrangell terrain are recognized, each having distinctive stratigraphic and structural characteristics: (1) The Canyone Mountain Province (2) The St. Clare Province (3) The Alsek Province. (This paper provides a good introduction to volcanic rocks of the Wrangell volcanic belt, even though it focuses on pre-Pleistocene deposits.)

West, K.D., 2007. Resedimentation of the late Holocene White River Ash, Yukon Territory, Canada and Alaska, United States; Ph.D. thesis, Carleton University, Ottawa, Ontario, 269 p.

Abstract: The White River ash is one of the most distinct and widely dispersed pyroclastic deposits in Yukon-Alaska. It was produced from volcanic eruptions ca. 1887 (north lobe; Lerbekmo et al., 1975) and 1147 years B.P. (east lobe; Clague et al., 1995). The source of the deposit, Mount Churchill, is an ice-covered stratovolcano located 25 km west of the Yukon-Alaska border (61°25’N, 141°70’W). Distal deposits of ash occur as primary airfall over much of Alaska, Yukon, and Northwest Territories. Locally resedimented deposits of ash are common closer to the volcanic source and occur in highly glaciated regions. Distal deposits of White River ash provide important chronostratigraphic control and are used herein to interpret the cultural and environmental impact of ancient large-magnitude eruptions. Sedimentological observations of distal deposits of ash (preserved in fluvially deposited beds) indicates that emplacement of the east lobe of ash occurred during the late fall or early winter. Knowledge of the timing of the east lobe ash is significant to archeological studies since deposition is associated with the massive migration and expansion of Athapaskan peoples.

West, K.D. and Donaldson, J.A., 2002. Resedimentation of the late Holocene White River tephra, Yukon Territory and Alaska; *in* Yukon Exploration and Geology 2002, (ed.) D.S. Emond, L.H. Weston, and L.L. Lewis; Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 239-247.

Abstract: The Wrangell region of eastern Alaska represents a zone of extensive volcanism marked by intermittent pyroclastic activity during the late Holocene. The most recent and widely dispersed pyroclastic deposit in this area is the White River tephra, a distinct tephra-fall deposit covering 540 000 km^2 in Alaska, Yukon, and the Northwest Territories. This deposit is the product of two Plinian eruptions from Mount Churchill, preserved in two distinct lobes, created ca. 1887 years B.P. (northern lobe) and 1147 years B.P. (eastern lobe). The tephra consists of distal primary air

fall deposits and proximal, locally resedimented volcaniclastic deposits. Distinctive layers such as the White River tephra provide important chronostratigraphic control and can be used to interpret the cultural and environmental impact of ancient large magnitude eruptions. The resedimentation of White River tephra has resulted in large-scale terraces, which fl ank the margins of Klutlan Glacier. Preliminary analysis of resedimented deposits demonstrates that the volcanic stratigraphy within individual terraces is complex and unique.

Conference Proceedings, Abstracts, and Symposium Volumes

Berger, A.R., 1958. A recent volcanic ash deposit, Yukon Territory; Proceedings of the Nova Scotia Institute of Science, 1 p.

Abstract: Recent volcanic ash is found over a widespread area covering most of the southern part of the Yukon and extending into both Alaska and the Northwest Territories. It forms a conspicuous white layer close to the present ground surface with a maximum thickness of ten feet in the Upper White River basin. From the accompanying isopach map the ash is calculated to cover an area of 129,000 square miles comprising a total volume of 6 cubic miles which is equivalent to 1 ¾ cubic miles of solid rock. This deposit is due to a volcanic eruption from a centre somewhere south of the upper White River basin approximately 1700 years ago. A petrographic examination of the pumice shows that it consists of zoned and unzoned plagioclase, soda-hornblende, and magnetite, in a matrix of glass. Optical determinations of the composition of the plagioclase indicate that this volcanic ash is andesitic. Some speculations on the mode of origin and petrogenesis of the ash are made with consideration of previous theories.

Mashiotta, T.A., Thompson, L.G., and Davis, M.E., 2004. The White River Ash; new evidence from the Bona-Churchill ice core record; American Geophysical Union, EOS Transactions, v. 85, no. 47, PP21A-1369.

Abstract: The White River Ash (WRA) is a well-documented bi-lobate Plinian deposit covering as much as 540,000 square km of the Yukon Territory, Canada and adjoining eastern Alaska. Recent studies have identified the source of the ash as Mount Churchill in the St. Elias Mountains of southeastern Alaska by comparing pumice deposits from the summit area of Mount Churchill with more distal pumice deposits of the WRA (e.g. McGimsey et al., 1990; Richter et al., 1995). In spring 2002 a team from The Ohio State University's (OSU) Byrd Polar Research Center recovered a 460-m long ice core drilled to bedrock in the col (elevation 4420 masl) between Mount Churchill and Mount Bona (4 km southwest) to reconstruct a proxy climate history for the region. This core is also ideal to assess whether Mount Churchill is the source of the WRA. No evidence of a visible ash layer was encountered during drilling. Borehole temperatures of -24°C at 10m depth and -19.8°C at the ice-bedrock interface indicate the glacier is frozen to its bed. After being returned frozen to OSU the core was cut into 12,162 samples that were analyzed for stable isotopic ratios, insoluble particles and soluble chemistry. A preliminary time scale was developed using annual variations in oxygen isotopes, dust and calcium concentrations, beta-radioactivity (bomb horizons) and well-documented historic volcanic eruptions. The 1500 year long record shows elevated sulfate values at 803 AD possibly associated with the second of two eruptions in the past 2000 years that produced the eastern lobe of the WRA deposit. The paleoclimate records appear to be stratigraphically continuous and show no evidence of a depositional hiatus. The absence of an ash layer in the core suggests that the WRA deposit requires further investigation, and the source and age of the WRA will be addressed.

West, K.D. and Donaldson, J.A., 2000. Evidence for winter eruption of the White River Ash (eastern lobe), Yukon Territory, Canada; *in* GeoCanada 2000; the millenium geoscience summit; Geological Association of Canada, Program with Abstracts, v. 25, unpaginated.

Modified abstract: Rhyodacitic tephra of the bilobate White River Ash deposit covers more than 340,000 km^2 of the Yukon and Northwest Territories, Canada, and extends into the adjacent eastern region of Alaska, U.S.A. The White River Ash was deposited during two volcanic eruptions, the first of which produced the northern ash lobe ca.1887 years B.P.; the eastern ash lobe formed ca.1140 years B.P. The source of the two eruptions has been identified as Mount Churchill in the Wrangell Mountains, Alaska. The bilobate nature of the White River Ash deposit indicates that both lobes were deposited from high eruption columns under the influence of strong unidirectional winds. However, the eastern lobe contains a greater volume of tephra (up to 30 km^3) than the northern lobe (< 20 km^3), indicating a greater intensity for the latest eruption. Based on patterns of seasonal wind distribution, Workman (1979) suggested that the eastern lobe eruption occurred during the winter, and the northern lobe during the summer. Other workers have also speculated on winter emplacement for the eastern lobe (Hanson, 1965; Donaldson et al., 1995). This paper provides new evidence for winter emplacement of the eastern lobe of White River Ash, based on sedimentological observations of stratigraphic sections in the banks of Bock's Creek and Donjek River, at sites adjacent to the Alaska Highway. Hanson (1965) based his model for winter eruption on observations of uneroded ash beds on slopes as steep as 40°. To account for such stability, Hanson suggested that the ash may have been deposited while it was snowing, with the ash providing nucleation centres for condensing water vapor, thus enhancing compaction followed by freezing. This would allow preservation under the subsequently accumulated snow load, whereas if unfrozen, much of the ash would be washed off steep slopes by rain, and/or redistributed by wind. Hanson (1965) also suggested that preservation of these deposits is best explained by eruption during the early winter, which would allow accumulation of a substantial protective snowfall cover, thus leading to maximum preservation during the spring thaw. New evidence indicating that the eastern lobe of White River Ash was emplaced during the winter is provided by two stratigraphic sections of ash along the Alaska Highway. Additional evidence of winter emplacement for the eastern-lobe ash is provided by the Donjek River section, 200 m west of the Alaska Highway, and 130 km southeast of Mount Churchill.

West, K.D. and Donaldson, J.A., 2002. Transportation of ice-cemented pumice clasts: inferences from White River tephra examples in Holocene terraces, Yukon Territory; Geological Association of Canada – Mineralogical Association of Canada, Program with Abstracts, v. 27, p. 122.

Abstract: The White River tephra is a distinct unconsolidated layer of Holocene airfall ash distributed across parts of Alaska, Yukon, and the Northwest Territories. It is the product of two volcanic eruptions, preserved in two distinct lobes ca. 1887 years B.P. (northern lobe) and 1147 years B.P. (eastern lobe). The source of the tephra is Mount Churchill, located in the Wrangell Mountains of south-central Alaska. The combined area of the deposit is 540,000 km^2, with the eastern-lobe ash containing the greater volume of tephra. Although pumice is a widespread product of many pyroclastic eruptions, its behaviour during post-eruptive processes has rarely been studied in detail. Recent sedimentological studies on the proximal and distal deposits of White River tephra have helped to fill this gap. Recent evidence from a frozen layer of airfall tephra near Bock's Brook, Yukon Territory indicates that the eastern-lobe eruption of White River tephra occurred during the late fall or early winter. Similar evidence for winter emplacement is provided by ice-cemented pumice clasts discovered near Donjek River, Yukon Territory. Ice-cemented pumice clasts of the Donjek River section are located within a layer of fluvial silt 200 m west of the Donjek River bridge on the Alaska Highway. Internally the pumice clasts display faint horizontal lamination and are elongated subparallel to bedding. These clasts were originally deposited as a layer of airfall ash during the late fall or early winter. Subsequent fragmentation of the layer and rounding of pumice clasts occurred during spring flooding when the layer was still ice-cemented. Field study in 2001 of previously unexamined proximal sections of White River tephra terraces has revealed the occurrence of still-frozen ice-cemented pumice clasts, providing direct evidence for the transport of clasts reworked from previously deposited pumice accumulations, as postulated above. These observations hold significance for studies of ancient deposits in which the origin for such clasts might readily go unrecognized, especially where the

original ice cement has been replaced by diagenetically introduced cement. A key to recognition of clasts formed in this fashion is the lack of truncation of grains at the margins of the clasts. Although evidence of peripheral abrasion is readily apparent for clasts in which the component grains are of lapilli size, truncated grains could be easily overlooked in clasts composed of fine-grained volcanic ash.

Appendix 1. List of Canadian volcanoes active in the last 1.8 million years.

volcano	latitude (degrees)	longitude (degrees)	age of most recent activity	type of volcano
Abbot Creek cone	52.61	121.16	Pleistocene	cinder cone or other small volcano
Adzich	56.74	129.74	Pleistocene	cinder cone or other small volcano
Alice Arm A	55.42	129.48	Pleistocene	cinder cone or other small volcano
Alice Arm B	55.46	129.34	Pleistocene	cinder cone or other small volcano
Alixton Creek	51.80	122.14	Pleistocene	lava flow(s)
Alkali Lake	51.73	122.31	Pleistocene	lava flow(s)
Alligator Lake north cone	60.41	135.42	Holocene	cinder cone or other small volcano
Alligator Lake south cone	60.40	135.43	Holocene	cinder cone or other small volcano
Arctic Lake 2	57.37	130.73	Holocene	cinder cone or other small volcano
Ash Mountain	59.27	130.51	Pleistocene	cinder cone or other small volcano
Badman Point	59.03	131.10	Pleistocene	cinder cone or other small volcano
Bell Irving Northeast	56.94	129.49	Pleistocene	cinder cone or other small volcano
Bell-Irving River	56.90	129.62	Pleistocene	cinder cone or other small volcano
Bell-Irving River East	56.89	129.55	Pleistocene	cinder cone or other small volcano
Bell-Irving River East	56.89	129.55	Pleistocene	cinder cone or other small volcano
Big Creek	60.16	129.71	Pleistocene	cinder cone or other small volcano
Big Timothy	52.10	120.93	Pleistocene	lava flow(s)
Black Creek flow	62.81	137.56	Pleistocene	lava flow(s)
Black Tusk	49.98	123.04	Pleistocene	stratovolcano, caldera, or silicic dome(s)
Blackfly Tuya	59.11	130.86	Pleistocene	cinder cone or other small volcano
Boss Mountain	52.17	120.57	Pleistocene	cinder cone or other small volcano
Browns Lake	51.42	122.24	Pleistocene	lava flow(s)
Buck Hill Mountain/ Buck Hill cone	51.80	119.98	Pleistocene	cinder cone or other small volcano
Cache Hill	57.54	130.55	Holocene	cinder cone or other small volcano
Camp Hill	57.59	130.78	Holocene	cinder cone or other small volcano
Canyon Creek cones	56.36	130.72	Holocene	volcanic field
Caribou Tuya	59.24	130.57	Pleistocene	cinder cone or other small volcano
Castle Rock	57.84	130.21	Pleistocene	cinder cone or other small volcano
Cauldron Dome	50.16	123.32	Pleistocene	cinder cone or other small volcano
Chakatah Creek Peak	59.25	131.03	Pleistocene	cinder cone or other small volcano
Charnaud Creek	51.34	126.14	Holocene	cinder cone or other small volcano
Cheakamus Valley flows	50.23	123.17	Pleistocene	lava flow(s)

Cinder Cliff	57.75	130.55	Holocene	cinder cone or other small volcano
Cinder Cone	49.97	123.01	Pleistocene	cinder cone or other small volcano
Cinder Mountain	56.57	130.65	Holocene	cinder cone or other small volcano
Cocoa Crater	57.66	130.71	Holocene	cinder cone or other small volcano
Coffee Crater	57.64	130.67	Holocene	cinder cone or other small volcano
Cone Glacier	56.56	130.67	Holocene	cinder cone or other small volcano
Cottonwood Peak	59.38	130.23	Pleistocene	cinder cone or other small volcano
Cracker Creek	59.70	133.32	Holocene	cinder cone or other small volcano
Craven Lake	56.91	129.37	Pleistocene	cinder cone or other small volcano
Crow Lagoon source	54.70	130.23	Holocene	cinder cone or other small volcano
Crows Bar	52.01	123.67	Pleistocene	lava flow(s)
Dark Mountain	58.64	129.44	Pleistocene	cinder cone or other small volcano
Dark Mountain North	58.51	129.63	Pleistocene	cinder cone or other small volcano
Dark Mountain South	58.57	129.49	Pleistocene	cinder cone or other small volcano
Dark Mountain West	58.63	129.49	Pleistocene	cinder cone or other small volcano
Dog Creek	51.59	122.26	Pleistocene	lava flow(s)
Dome Mountain	58.46	129.64	Pleistocene	cinder cone or other small volcano
Dragon Cone/ Dragon	52.26	120.02	Holocene	cinder cone or other small volcano
Dufferin Island	52.20	128.33	Holocene	cinder cone or other small volcano
Eanastick Meadow	49.80	122.93	Pleistocene	cinder cone or other small volcano
Elaho Alpine volcanics	50.42	123.46	Pleistocene	cinder cone or other small volcano
Elaho side valley	50.49	123.51	Pleistocene	cinder cone or other small volcano
Elaho Valley 1	50.35	123.59	Pleistocene	cinder cone or other small volcano
Elaho Valley 2	50.41	123.58	Pleistocene	cinder cone or other small volcano
Elaho Valley 3	50.43	123.57	Pleistocene	cinder cone or other small volcano
Elaho Valley 4	50.46	123.57	Pleistocene	cinder cone or other small volcano
Elaho-Meager East	50.55	123.53	Pleistocene	cinder cone or other small volcano
Elaho-Meager West	50.55	123.56	Pleistocene	cinder cone or other small volcano
Ember Ridge North	50.08	123.24	Holocene	cinder cone or other small volcano
Ember Ridge Northeast	50.07	123.22	Holocene	cinder cone or other small volcano
Ember Ridge Northwest	50.08	123.26	Holocene	cinder cone or other small volcano
Ember Ridge Southeast	50.05	123.22	Holocene	cinder cone or other small volcano
Ember Ridge Southwest	50.05	123.25	Holocene	cinder cone or other small volcano
Ember Ridge West	50.07	123.26	Holocene	cinder cone or other small volcano
Enid Creek Cone	58.38	129.52	Pleistocene	cinder cone or other small volcano
Eve Cone	57.81	130.68	Holocene	cinder cone or other small volcano
Fiftytwo Ridge	51.92	119.89	Pleistocene	cinder cone or other small volcano

Fingal Island	52.10	128.45	Holocene	cinder cone or other small volcano
Flatiron	51.88	120.05	Pleistocene	lava flow(s)
Flourmill cones	52.06	120.32	Holocene	cinder cone or other small volcano
Fort Selkirk Vent	62.77	137.42	Pleistocene	lava flow(s)
Gabrielse Cone	59.44	130.38	Holocene	cinder cone or other small volcano
Gage Hill	52.07	120.02	Pleistocene	cinder cone or other small volcano
Glacier Dome	57.73	130.62	Pleistocene	cinder cone or other small volcano
Glacier Pikes	49.88	122.98	Pleistocene	cinder cone or other small volcano
Grain Creek Cone	52.62	121.15	Pleistocene	cinder cone or other small volcano
Grizzly Butte Vent	59.08	130.92	Pleistocene	cinder cone or other small volcano
Hanceville	51.95	123.14	Pleistocene	lava flow(s)
Heart Peaks 1	58.62	131.98	Pleistocene	cinder cone or other small volcano
Heart Peaks 10	58.57	131.95	Pleistocene	cinder cone or other small volcano
Heart Peaks 11	58.58	131.92	Pleistocene	cinder cone or other small volcano
Heart Peaks 12	58.60	131.95	Pleistocene	cinder cone or other small volcano
Heart Peaks 2	58.61	132.00	Pleistocene	cinder cone or other small volcano
Heart Peaks 3	58.61	132.01	Pleistocene	cinder cone or other small volcano
Heart Peaks 4	58.61	132.06	Pleistocene	cinder cone or other small volcano
Heart Peaks 5	58.58	132.01	Pleistocene	cinder cone or other small volcano
Heart Peaks 6	58.59	132.00	Pleistocene	cinder cone or other small volcano
Heart Peaks 7	58.55	132.03	Pleistocene	cinder cone or other small volcano
Heart Peaks 8	58.55	132.00	Pleistocene	cinder cone or other small volcano
Heart Peaks 9	58.56	131.96	Pleistocene	cinder cone or other small volcano
Helmet Peak	52.36	128.37	Holocene	cinder cone or other small volcano
Hoan Creek	55.35	129.30	Pleistocene	cinder cone or other small volcano
Holbrook Creek	62.81	138.11	Pleistocene	lava flow(s)
Hoodoo Mountain	56.77	131.30	Holocene	stratovolcano, caldera, or silicic dome(s)
Hyalo Ridge	52.12	120.36	Pleistocene	cinder cone or other small volcano
Ibex Mountain	60.55	135.53	Pleistocene	cinder cone or other small volcano
Ice Peak	57.72	130.64	Pleistocene	cinder cone or other small volcano
Icefall Cone	57.72	130.60	Pleistocene	cinder cone or other small volcano
Icefield Ridge	57.20	129.38	Pleistocene	cinder cone or other small volcano
Ida Ridge	51.80	119.94	Pleistocene	cinder cone or other small volcano
Ishkloo Cone	52.67	121.18	Pleistocene	cinder cone or other small volcano
Iskut River Cone	56.71	130.61	Holocene	cinder cone or other small volcano
Isspah Butte/Metah	59.10	131.32	Pleistocene	cinder cone or other small volcano
Itcha 1	52.54	124.80	Pleistocene	cinder cone or other small volcano

Itcha 10	52.53	124.72	Holocene	cinder cone or other small volcano
Itcha 11	52.54	124.78	Pleistocene	cinder cone or other small volcano
Itcha 12	52.64	124.69	Holocene	cinder cone or other small volcano
Itcha 13	52.60	124.81	Holocene	cinder cone or other small volcano
Itcha 14	52.58	124.49	Holocene	cinder cone or other small volcano
Itcha 15	52.73	124.56	Holocene	cinder cone or other small volcano
Itcha 16	52.58	124.86	Holocene	cinder cone or other small volcano
Itcha 17	52.74	124.98	Holocene	cinder cone or other small volcano
Itcha 18	52.70	124.96	Holocene	cinder cone or other small volcano
Itcha 19	52.51	124.70	Holocene	cinder cone or other small volcano
Itcha 2	52.79	124.42	Pleistocene	cinder cone or other small volcano
Itcha 4	52.82	124.56	Pleistocene	cinder cone or other small volcano
Itcha 5	52.82	124.75	Pleistocene	cinder cone or other small volcano
Itcha 6	52.80	124.84	Pleistocene	cinder cone or other small volcano
Itcha 7	52.64	124.44	Holocene	cinder cone or other small volcano
Itcha 8	52.61	124.58	Pleistocene	cinder cone or other small volcano
Itcha 9	52.49	124.83	Pleistocene	cinder cone or other small volcano
Itcha Mountain	52.72	124.83	Pleistocene	shield volcano
Iverson Creek	59.50	130.29	Pleistocene	cinder cone or other small volcano
Iverson Creek West	59.57	130.10	Pleistocene	cinder cone or other small volcano
Jack's Jump	52.12	120.06	Pleistocene	cinder cone or other small volcano
Jacques Lake	52.47	121.16	Pleistocene	cinder cone or other small volcano
Kana Cone	57.90	130.63	Holocene	cinder cone or other small volcano
Kawdy Mountain	58.88	131.23	Pleistocene	cinder cone or other small volcano
Kawdy Mountain South	58.86	131.15	Pleistocene	cinder cone or other small volcano
Keda Cone	57.61	130.69	Holocene	cinder cone or other small volcano
Kelowna	49.95	119.65	Pleistocene	lava flow(s)
King Creek	56.49	130.66	Pleistocene	cinder cone or other small volcano
Kitasu Hill	52.50	128.72	Holocene	cinder cone or other small volcano
Klastline - Buckley Lake	57.86	130.76	Pleistocene	cinder cone or other small volcano
Klastline cone	57.79	130.52	Pleistocene	cinder cone or other small volcano
Klastline Middle	57.87	130.60	Pleistocene	cinder cone or other small volcano
Klinkit Creek Peak	59.47	131.21	Pleistocene	cinder cone or other small volcano
Klinkit Lake Peak	59.48	131.00	Pleistocene	cinder cone or other small volcano
Kostal Cone	52.19	119.94	Holocene	cinder cone or other small volcano
Lambly Creek	49.94	119.53	Pleistocene	lava flow(s)
Lava Fork	56.42	130.77	Holocene	cinder cone or other small volcano

Leon Creek	50.97	121.93	Pleistocene	lava flow(s)
Level Mountain North	58.46	131.45	Pleistocene	cinder cone or other small volcano
Level Mountain Southeast	58.39	131.30	Pleistocene	cinder cone or other small volcano
Level Mountain Southwest	58.37	131.47	Pleistocene	cinder cone or other small volcano
Little Bear Mountain	56.80	131.30	Pleistocene	cinder cone or other small volcano
Little Eagle Peak	58.52	129.71	Pleistocene	cinder cone or other small volcano
Little Ring Mountain	50.28	123.32	Pleistocene	cinder cone or other small volcano
Llangorse Mountain #1	59.37	132.78	Pleistocene	cinder cone or other small volcano
Logan Ridge volcanic	50.81	123.41	Pleistocene	cinder cone or other small volcano
Logger's Lake volcano	50.06	123.04	Pleistocene	cinder cone or other small volcano
Machmel River	51.54	126.33	Holocene	cinder cone or other small volcano
Mathews Tuya	59.20	130.44	Pleistocene	cinder cone or other small volcano
McLeod Hill	52.02	120.01	Pleistocene	cinder cone or other small volcano
Meehaz Mountain	59.00	131.45	Pleistocene	cinder cone or other small volcano
Mess Lake # 2	57.46	130.76	Holocene	cinder cone or other small volcano
Mess Lake # 3	57.45	130.80	Holocene	cinder cone or other small volcano
Mess Lake #1	57.49	130.73	Holocene	cinder cone or other small volcano
Meszah Peak	58.48	131.44	Pleistocene	cinder cone or other small volcano
Metahag Creek Northeast	58.92	131.10	Pleistocene	cinder cone or other small volcano
Metahag Creek Northwest	58.98	131.14	Pleistocene	cinder cone or other small volcano
Miles Canyon	60.40	135.00	Pleistocene	lava flow(s)
Missezula Lake	49.81	120.54	Pleistocene	lava flow(s)
Monmouth Creek	49.69	123.19	Pleistocene	cinder cone or other small volcano
Moraine Cone	57.77	130.61	Holocene	cinder cone or other small volcano
Mosquito Mound	52.02	120.18	Pleistocene	cinder cone or other small volcano
Mount Boucherie	49.86	119.57	Pleistocene	lava flow(s)
Mount Brew East	50.04	123.18	Pleistocene	cinder cone or other small volcano
Mount Brew West	50.04	123.21	Pleistocene	cinder cone or other small volcano
Mount Cayley	50.12	123.29	Pleistocene	stratovolcano, caldera, or silicic dome(s)
Mount Downton	52.71	124.85	Pleistocene	cinder cone or other small volcano
Mount Edziza	57.72	130.63	Holocene	stratovolcano, caldera, or silicic dome(s)
Mount Fee	50.08	123.24	Pleistocene	stratovolcano, caldera, or silicic dome(s)
Mount Garibaldi	49.85	123.00	Pleistocene	stratovolcano, caldera, or silicic dome(s)
Mount Hoadley	55.33	128.78	Pleistocene	cinder cone or other small volcano
Mount Josephine	59.07	130.70	Pleistocene	cinder cone or other small volcano
Mount Meager	50.63	123.50	Pleistocene	stratovolcano, caldera, or silicic dome(s)
Mount Price/Clinker Peak	49.92	123.04	Holocene	cinder cone or other small volcano

Mud Lake Flow	50.80	123.38	Pleistocene	cinder cone or other small volcano
Nahta Cone	57.31	130.82	Holocene	cinder cone or other small volcano
Nanook Dome	57.72	130.62	Pleistocene	cinder cone or other small volcano
Nazko Cone	52.93	123.73	Holocene	cinder cone or other small volcano
Ne Ch'e Ddhawa	62.74	137.28	Pleistocene	cinder cone or other small volcano
Nichols Valley flows	50.95	123.38	Pleistocene	lava flow(s)
Nicola (Chester)	50.51	120.70	Pleistocene	lava flow(s)
Nome Lake South	59.54	130.88	Pleistocene	cinder cone or other small volcano
Northwest Volcanic	50.81	123.45	Pleistocene	cinder cone or other small volcano
Nuthinaw Mountain	58.79	131.06	Pleistocene	cinder cone or other small volcano
Ochre Mountain flow	50.80	123.37	Holocene	cinder cone or other small volcano
Opal Cone	49.82	122.98	Holocene	cinder cone or other small volcano
Outcast Hill	57.39	130.77	Pleistocene	cinder cone or other small volcano
Owl Creek North	56.88	129.70	Pleistocene	cinder cone or other small volcano
Owl Creek South	56.85	129.69	Pleistocene	cinder cone or other small volcano
Pali Dome East	50.14	123.27	Pleistocene	cinder cone or other small volcano
Pali Dome West	50.14	123.31	Pleistocene	cinder cone or other small volcano
Peak 1924	59.03	130.37	Pleistocene	cinder cone or other small volcano
Peak 2050	59.40	130.19	Pleistocene	cinder cone or other small volcano
Pharaoh Dome	57.65	130.60	Pleistocene	cinder cone or other small volcano
Pillow Creek	52.02	119.84	Pleistocene	cinder cone or other small volcano
Pillow Ridge	57.76	130.65	Pleistocene	cinder cone or other small volcano
Pointed Stick Cone	52.24	120.08	Holocene	cinder cone or other small volcano
Prentice Gulch	51.63	122.35	Pleistocene	lava flow(s)
Price Island	52.44	128.68	Holocene	cinder cone or other small volcano
Pyramid Mountain	51.99	120.11	Pleistocene	cinder cone or other small volcano
Quesnel Lake cone	52.65	120.99	Pleistocene	cinder cone or other small volcano
Quilchena Creek	50.12	120.51	Pleistocene	lava flow(s)
Rancheria River flows	60.09	130.64	Pleistocene	lava flow(s)
Rancheria River North	59.72	130.38	Pleistocene	cinder cone or other small volcano
Rancheria River South	59.72	130.18	Pleistocene	cinder cone or other small volcano
Ray Mountain	52.25	120.12	Pleistocene	cinder cone or other small volcano
Ridge Cone	57.68	130.63	Holocene	cinder cone or other small volcano
Ring Mountain	50.22	123.30	Pleistocene	cinder cone or other small volcano
Rochester Creek Northeast-North	56.88	129.51	Pleistocene	cinder cone or other small volcano

Rochester Creek Northeast-South	56.86	129.50	Pleistocene	cinder cone or other small volcano
Rochester Creek	56.82	129.55	Pleistocene	cinder cone or other small volcano
Rochester Creek	56.82	129.54	Pleistocene	cinder cone or other small volcano
Round Mountain	49.77	123.00	Pleistocene	cinder cone or other small volcano
Ruby Creek	59.65	133.35	Pleistocene	cinder cone or other small volcano
Ruby Mountain	59.69	133.37	Pleistocene	cinder cone or other small volcano
Salal Glacier volcanic	50.78	123.38	Holocene	cinder cone or other small volcano
Satah 1	52.48	124.70	Pleistocene	cinder cone or other small volcano
Satah 2	52.48	124.69	Pleistocene	cinder cone or other small volcano
Satah 3	52.47	124.68	Pleistocene	cinder cone or other small volcano
Satah 4	52.44	124.71	Pleistocene	cinder cone or other small volcano
Second Canyon Cone	56.41	130.72	Holocene	cinder cone or other small volcano
Sham Hill	50.91	123.51	Pleistocene	cinder cone or other small volcano
Sheep Track Bench	51.78	119.97	Pleistocene	cinder cone or other small volcano
Sheep Track Pumice	57.65	130.67	Holocene	cinder cone or other small volcano
Sidas Cone	57.86	130.63	Holocene	cinder cone or other small volcano
Silverthrone Caldera	51.46	126.08	Pleistocene	stratovolcano, caldera, or silicic dome(s)
Slag Hill	50.19	123.31	Pleistocene	cinder cone or other small volcano
Slag Hill Tuya	50.20	123.28	Pleistocene	cinder cone or other small volcano
Sleet Cone	57.78	130.55	Pleistocene	cinder cone or other small volcano
Snippaker Creek	56.63	130.87	Holocene	cinder cone or other small volcano
Snowshoe Lava Field 11	57.62	130.66	Holocene	cinder cone or other small volcano
Snowshoe Lava Field 2	57.69	130.66	Holocene	cinder cone or other small volcano
Snowshoe Lava Field 3	57.64	130.66	Holocene	cinder cone or other small volcano
Snowshoe Lava Field 4	57.66	130.69	Holocene	cinder cone or other small volcano
Snowshoe Lava Field 5	57.65	130.69	Holocene	cinder cone or other small volcano
Snowshoe Lava Field 6	57.64	130.70	Holocene	cinder cone or other small volcano
Snowshoe Lava Field 8	57.63	130.63	Holocene	cinder cone or other small volcano
Source Hill	57.29	130.81	Pleistocene	cinder cone or other small volcano
Southern Tuya	59.21	130.66	Pleistocene	cinder cone or other small volcano
Spanish Bonk	52.14	120.37	Pleistocene	cinder cone or other small volcano
Spanish Lake Centre	52.07	120.31	Holocene	cinder cone or other small volcano
Spanish Mump	52.17	120.34	Pleistocene	cinder cone or other small volcano
Sphinx Dome	57.75	130.57	Pleistocene	cinder cone or other small volcano
Sphinx Moraine	49.93	122.98	Pleistocene	cinder cone or other small volcano
Squamish Headwaters	50.36	123.39	Pleistocene	cinder cone or other small volcano

Storm Cone	57.77	130.64	Pleistocene	cinder cone or other small volcano
Swinton Creek	58.52	129.81	Pleistocene	cinder cone or other small volcano
Tadekho Hill	57.35	130.78	Pleistocene	cinder cone or other small volcano
Tanzilla Butte	58.39	129.86	Pleistocene	cinder cone or other small volcano
Tennena Cone	57.68	130.66	Holocene	cinder cone or other small volcano
Thaddeus Lake	51.93	122.82	Pleistocene	lava flow(s)
Thaw Hill	57.28	130.71	Pleistocene	cinder cone or other small volcano
The Big End Table	49.88	123.00	Pleistocene	cinder cone or other small volcano
The Black Hole	50.40	123.40	Pleistocene	cinder cone or other small volcano
The Gargoyles	49.81	123.00	Pleistocene	cinder cone or other small volcano
The Little End Table	49.89	123.01	Pleistocene	cinder cone or other small volcano
The Neck	57.66	130.59	Pleistocene	cinder cone or other small volcano
The Pyramid	57.75	130.56	Pleistocene	cinder cone or other small volcano
The Saucer	57.63	130.63	Holocene	cinder cone or other small volcano
The Table	49.90	123.01	Pleistocene	cinder cone or other small volcano
The Thumb	56.16	126.74	Pleistocene	cinder cone or other small volcano
The Thumb # 1	56.11	126.61	Pleistocene	cinder cone or other small volcano
The Thumb # 2	56.18	126.72	Pleistocene	cinder cone or other small volcano
The Thumb # 3	56.30	126.65	Pleistocene	cinder cone or other small volcano
The Thumb # 4	56.30	126.62	Pleistocene	cinder cone or other small volcano
The Thumb # 5	56.30	126.61	Pleistocene	cinder cone or other small volcano
The Thumb # 6	56.29	126.63	Pleistocene	cinder cone or other small volcano
Tom Mackay Creek	56.71	130.57	Pleistocene	cinder cone or other small volcano
Toozaza Peak	59.51	130.35	Pleistocene	cinder cone or other small volcano
Triangle Dome	57.72	130.65	Pleistocene	cinder cone or other small volcano
Tricouni Southeast flow	49.99	123.22	Pleistocene	cinder cone or other small volcano
Tricouni Southeast knob	49.97	123.18	Pleistocene	cinder cone or other small volcano
Tricouni Southwest flow	49.99	123.23	Holocene	cinder cone or other small volcano
Triplex Cone centre	57.80	130.63	Holocene	cinder cone or other small volcano
Triplex Cone northwest	57.81	130.65	Holocene	cinder cone or other small volcano
Triplex Cone southeast	57.79	130.62	Holocene	cinder cone or other small volcano
Trudel Creek	51.39	126.22	Holocene	cinder cone or other small volcano
Tseax Cone	55.11	128.90	Holocene	cinder cone or other small volcano
Tsekone Ridge	57.70	130.70	Pleistocene	cinder cone or other small volcano
Tuber Hill	50.91	123.46	Pleistocene	cinder cone or other small volcano
Tuber Hill East	50.95	123.40	Holocene	cinder cone or other small volcano
Tumeka Lake	57.21	129.47	Pleistocene	cinder cone or other small volcano

Tutsingale Mountain	58.78	130.88	Pleistocene	cinder cone or other small volcano
Tuya #1	59.32	130.23	Pleistocene	cinder cone or other small volcano
Tuya Butte	59.13	130.57	Pleistocene	cinder cone or other small volcano
Twin Cone	57.81	130.53	Pleistocene	cinder cone or other small volcano
Unnamed 3 miles south of	59.23	130.51	Pleistocene	cinder cone or other small volcano
Upper Rochester Creek	56.82	129.37	Pleistocene	cinder cone or other small volcano
Volcanic Creek cone	59.76	133.38	Holocene	cinder cone or other small volcano
Volcano Mountain	62.93	137.38	Holocene	cinder cone or other small volcano
Volcano Vent	59.12	130.92	Pleistocene	cinder cone or other small volcano
Walkout Creek	57.58	130.75	Holocene	cinder cone or other small volcano
Watson Lake 1	60.07	128.83	Pleistocene	cinder cone or other small volcano
Watson Lake 10	60.05	128.84	Pleistocene	cinder cone or other small volcano
Watson Lake 11	60.07	128.75	Pleistocene	cinder cone or other small volcano
Watson Lake 2	60.08	128.91	Pleistocene	cinder cone or other small volcano
Watson Lake 3	60.24	129.12	Pleistocene	cinder cone or other small volcano
Watson Lake 4	60.16	129.69	Pleistocene	cinder cone or other small volcano
Watson Lake 5	60.21	129.15	Pleistocene	cinder cone or other small volcano
Watson Lake 6	60.22	129.15	Pleistocene	cinder cone or other small volcano
Watson Lake 7	60.25	128.83	Pleistocene	cinder cone or other small volcano
Watson Lake 8	60.25	129.62	Pleistocene	cinder cone or other small volcano
Watson Lake 9	60.12	130.28	Pleistocene	cinder cone or other small volcano
Watts Point	49.65	123.22	Pleistocene	cinder cone or other small volcano
West Kettle River	49.09	119.07	Pleistocene	lava flow(s)
West Vent	59.13	131.01	Pleistocene	cinder cone or other small volcano
Wetalth Ridge	57.31	130.78	Pleistocene	cinder cone or other small volcano
White Creek cone	52.55	124.85	Pleistocene	cinder cone or other small volcano
White Horse Bluff	51.89	120.12	Pleistocene	lava flow(s)
Whitetop Mountain	52.65	124.56	Pleistocene	cinder cone or other small volcano
Williams Cone	57.78	130.60	Holocene	cinder cone or other small volcano
Wolverine Eruptive Centre	62.67	137.37	Pleistocene	cinder cone or other small volcano
Wolverine West	62.72	137.27	Pleistocene	cinder cone or other small volcano