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Discovery of modern (post-1850 AD) lavas in south-central British Columbia, Canada: origin from coal fires or intraplate volcanism?

Dante Canil[1*], Mitch Mihalynuk[2], Terri Lacourse[3]

1. School of Earth and Ocean Sciences, University of Victoria, Victoria, B.C. Canada
2. British Columbia Geological Survey, Victoria, B.C., Canada
3. Department of Biology, University of Victoria, Victoria, B.C., Canada

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*corresponding author dcanil@uvic.ca

Abstract

We describe three unusual lavas in the Northern Cordillera in south-central British Columbia, Canada, occurring as spatter, scoria and blocks over small ~ 400 m^2 areas. The lavas coat and weld cobbles and pebbles in glacial till and are vesicular and glassy with microlites of clinopyroxene and plagioclase, and xenocrysts of quartz, feldspar or clinopyroxene. Chemically the lavas are basaltic trachyandesite (55 – 61 wt% SiO_2) with trace element patterns similar to average British Columbia upper crust, except for having higher V and lower Zr, Hf, Nb, Th and U. Melting experiments and plagioclase-melt thermometry on the glasses, and phase equilibrium in simple systems, require liquidus temperatures of 1150 - 1300°C. Interaction of the liquids with carbonaceous matter at low pressure formed Fe metal spherules and SiC. Radiocarbon ages of charcoal and dendrochronology show the lavas are modern, emplaced in the last ~120 years. The similar bulk composition of these lavas to several other Quaternary-aged volcanic centers in the North American Cordillera, some of which show recent seismic activity, could suggest a possible tectonic origin, but the deposits are unusually small and show no central vent for emplacement. Conversely, the balance of evidence would suggest an origin from coal fires or hot gas venting, but is less consistent with the observed calc- and per-alkaline lava compositions, and the lack of known local coal-bearing strata as a heat source. Other anthropogenic origins for the lavas are considered less plausible.

Introduction

The modern North American Cordillera in British Columbia is currently in a transpressive tectonic regime, with thin lithosphere and high heat flow (Hyndman et al, 2007). Several Neogene and younger lavas related to transpression occur throughout the orogen with the youngest known volcanism dated at ~300 yrs B.P. (Edwards and Russell, 2000; Higgins, 2009). Recent seismicity (in 2007) beneath a Quaternary volcanic edifice (Nazko – Fig. 1) in central British Columbia have been interpreted as modern magma movement at depth (Cassidy et al., 2011). A similar interpretation was made previously for other occurrences of intraplate seismicity in the region (Rogers, 1981).

Two young lavas , near Cache Creek, and in the southeast corner of British Columbia (Fig. 1) are not of tectonic origin, but rather are paralava related to coal fires (Church et al, 1979; Bustin et al, 1982). The natural burning of coal seams, induced by lightning strikes, wild fires or spontaneous combustion, can fuse the surrounding country rock to form paralava that may intrude or escape upward in chimneys (Cosca et al., 1989; Grapes et al., 2008). Other anthropogenic heat sources for the formation of paralava include biomass burning and land-clearing practices (Thy, 1995; Coombs et al., 2008). The study of the unique and varied chemistry and mineralogy of paralavas (Bentor et al. 1978; Bustin et al, 1982; Cosca et al 1989; Clark and Peacor, 1992) has informed other lines of inquiry such as biomass fuel production (Thy et al., 1999), the environmental impact of coal gases (Stracher et al., 2005) and the uplift and geomorphologic development of land surfaces (Heffern et al, 2007; Piepjohn et al., 2007).

In this study, we document three hitherto unknown lava occurrences in British Columbia, Canada, encountered during mapping of the surface bedrock (Mihalynuk et al., 2015), or discovered by local hikers. These lavas are unique by being modern in age and within Quaternary glacial alluvium, with liquid compositions similar to those of recent volcanism in British Columbia and unlike most other paralavas reported in the literature. The heat or source for these lavas is not immediately evident but we consider two possible origins: gas venting from coal burning in strata at depth below the glacial overburden, or incipient melts with a possible tectonic origin.

Regional Geology

The lavas were initially recognized during regional bedrock mapping within the Quesnellia terrane in south-central British Columbia (Fig. 1). Quesnellia consists of Paleozoic arc volcanic and plutonic rocks, overlain by Triassic mafic volcanic and volcaniclastic rocks of the Nicola Group (Mihalynuk et al, 2015). These were intruded by Jurassic plutons, and capped by Cretaceous volcanic rocks of the Spences Bridge Group.

Eocene clastic sedimentary and volcanic rocks of the Princeton, Kamloops and Okanagan groups form an overlap assemblage on Quesnellia, and despite the historical tripartite naming are all age-equivalent as shown by the consistent age range of tuffs and ashes in these strata (45 – 55 Ma) (Breitsprecher and Mortensen, 2004; Ickert et al., 2009; Bordet et al, 2014; Mihalynuk et al, 2016). The Eocene sedimentary rocks formed in extensional basins, and contain coal seams mined historically throughout the region (McMechan, 1983). The Eocene sequences are overlain by younger mafic plateau lavas of the Chilcotin Group that vary in age from 9.2 - 0.17 Ma (Mathews, 1989; Breitsprecher and Mortensen, 2004; Sluggett, 2008; Thorkelson et al., 2011). The Chilcotin lavas filled valleys to make a plateau, to be later incised by rivers and several Pleistocene glaciations between 976 and 15 ka to produce the current landscape (Clague, 1992; Roed et al., 2014). The most recent glaciation deposited tills and glacio-fluvial sediments of varying thicknesses throughout south-central British Columbia (Clague, 1992).

South-central British Columbia is dissected by several high angle N-NE and N-NW trending faults in several horsts and half-grabens, some of which show minor seismicity (Fig. 1). These structures are inherited from Eocene or dextral transpression that produced isolated basins in half-grabens, filled with sediments and volcanic rocks. Tilting and folding of the Eocene units has varied their dip from sub-horizontal to nearly sub-vertical (McMechan, 1983), though recent mapping shows that some of the steeper orientations are artifacts of paleo–landslides (Mihalynuk et al, 2015).

Lavas

The first lava occurrence (Shrimpton) was originally recognized at surface east of Merritt near Shrimpton Creek, in a forested area that has been selectively logged and now hosts a planted stand of lodgepole pine (*Pinus contorta*) trees. The area contains sporadic outcrops of Triassic Nicola Group and younger Chilcotin lavas in stream valleys (Fig. 1). The Shrimpton lava is typified by loose blocks of reddish and blackish-brown scoria up to 40 cm in diameter on the surface of Quaternary till, over a circular area of 300 m^2 adjacent to a small outcrop of Nicola Gp. volcanic rocks (Fig. 2a). Within the area in which the scoria occurs, the till is a few meters thick, and a distinct reddish brown, whereas it is light grey outside of this area. The scoriaceous blocks occur on and within till to depths of at least 50 cm. The rock has a vesicularity of up to 80%, is reddish-brown on surface grading to a bluish-black and glassy underneath, with 1 – 4 cm long driblets, always oriented downwards (Fig. 2b). The lava spatter coats granitic cobbles, many of which are spalled and discolored to a reddish-brown (Fig. 2c). Several scoria blocks contain carbonized wood up to 6 cm in diameter and 20 cm in length, and/or their casts, preserving well-defined boxworks of radial and longitudinal septa in the wood fragments (Fig. 2d). The lava contains numerous xenocrysts of quartz, feldspar or lithic fragments (Fig. 3a). In some cases the lava surrounds carbonized tree stumps. Living Lodgepole pine trees grow out of and on top of the deposit, as evidenced by a hole dug beneath one of these trees.

A second lava (Tranquille) was recognized NW of Kamloops in a hilly forested area underlain by sandy grey till and volcanic and sedimentary rocks of the Eocene Kamloops Gp (Fig. 1). The scoria occurs over a 400-m^2 circular area in open forest and shows evidence of surface flow in the form of ropy or stretched fluidal structures (Fig.

2e). As at Shrimpton, the Tranquille scoria contains carbonized wood, coats cobbles and pebbles and has undersides with 1 – 3 cm long glassy driblets again pointing downward (Fig. 2f). Living Ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) trees grow out of and on top of the deposit.

A third lava near Asp Creek, 20 km northwest of the town of Princeton, was sampled by L. Diakow (B.C. Geological Survey) but not investigated in the field.

Petrography

The lava at Shrimpton is hypohyaline, highly vesicular and contains variable amounts of entrained quartz, feldspar and lithic fragments (Fig. 3a). In thin section, some of the quartz and feldspar xenocrysts at Shrimpton are rounded, and appear to have originally been pebbles (Fig. 3b). Rare xenocrysts of subhedral pyroxene show dissolution rims < 20 μm in thickness in contact with heterogeneously distributed brown glass (Fig. 3c). The glass contains euhedral microlites of plagioclase and pyroxenes (< 100 μm) (Fig. 3 bc). Phenocrysts of olivine are rare. Vesicles are often rimmed with opaque minerals.

The Tranquille samples are notably lacking in xenocrysts, but unlike at Shrimpton can be hypocrystalline, containing dominantly euhedral plagioclase laths (50 to 200 μm) and pyroxene microphenocrysts (0.2 – 0.5 mm) set in brown glass (Fig. 3d). Some blocks in this deposit resemble volcanic bombs with reddish hematized cores surrounded by black glassy edges. Vesicles are mostly empty, but can be rimmed with conspicuous angular opaque phases (Fig. 3e).

Sub-euhedral oxide minerals comprise about 5% of the rock at Tranquille (Fig. 3d), but are absent at Shrimpton. Both lavas show opaque spheres or fragments of charcoal and Fe metal spheres of 5 - 40 μm diameter set in the glass (Fig. 3f). Textures of the lava at Asp Creek are similar to those described above but coarser with intergranular pyroxene and glass between plagioclase, common in typical basaltic rocks.

Methods

Whole rock analyses

Samples of scoria were cut into slabs with a rock saw and crushed to 0.5 cm – sized fragments. Foreign rock fragments or xenocrysts were picked from the crushed samples, and the remainder was then powdered in an agate mill (Table 1). Major and trace element abundances of five rock powders were determined at Actlabs Ltd., Vancouver, British Columbia. Major element concentrations were measured by XRF analysis. Trace elements were determined by Inductively Coupled Plasma Mass Spectrometry (ICPMS) on lithium metaborate and tetraborate fusion of 0.2 g samples followed by nitric acid digestion. Analytical accuracy and precision based on analyses of standards and duplicate samples are better than 10% (Table 1, Lett and Paterson, 2011).

Electron Microprobe

Phase compositions in the glassy driblets from both the Shrimpton and Tranquille occurrences were determined in polished sections by electron microprobe analysis (EMPA) using a Cameca SX-50 instrument. Operation conditions were 15 kV accelerating voltage, and 20 nA beam current. Counting times were 20 sec on peaks for Na, Mg, Al, Si, K, Ca, Ti, Cr, Mn and Fe for silicates as well as Ni, Cr and V in oxide minerals. Calibration was done on natural mineral standards. Beam size was 5 μm, and Na was analyzed first, but with no precautions taken to avoid volatilization of alkalies in glass or feldpars. Between 10 and 20 analysis of each phase in each sample were determined. For some rarer phases (oxides, SiC, Fe metal) less than 10 points could be found in a polished section (Table 2 - Supplementary Datafile - Table 2).

Melting Experiments

Melting experiments on the glassy driblets from Shrimpton and Tranquille were performed to determine their liquidus temperatures. Rock chips of about 2 cm in size were sawed off from driblets of each lava sample, and crushed to small chips. Chips of ~5 mm diameter of the driblet were then mounted to a 0.15 mm Pt wire loop, and held between 1050 to 1200 °C in a Deltech vertical tube gas mixing furnace in pure CO_2 gas at a flow rate of 150 cm^3/min. Each experiment was between one to five hours duration, sufficient to determine the liquidus temperatures, and not intended to reproduce textures. Experiments were terminated by removing the sample from the furnace and quenched within seconds in a stream of air. The run products were mounted in epoxy and polished for examination under reflected light to determine crystal phase appearance.

Age Dating

Charcoal fragments embedded in the Shrimpton and Tranquille lavas were dated by the radiocarbon method using AMS at Beta Analytic Inc. (Miami, USA). Pre-treatment consisted of hot HCl to remove any carbonates, if present, followed by a NaOH rinse to remove secondary organic acids and isolate the primary carbon, and a final HCl rinse to neutralize the solution before drying. Radiocarbon ages were calibrated to calendar years using CALIBomb (Reimer et al., 2004, 2013; Hua et al., 2013). Additional minimum ages for the Shrimpton and Tranquille lavas were determined by dendrochronology on cores extracted from trees growing in and on top of the lavas.

Results

Geochemistry

Whole rock compositions of the lavas from all three localities are broadly trachyandesite, and overlap with Eocene volcanic rocks of the Princeton and Kamloops groups, but are higher in SiO_2 and alkalies than local Neogene and Quaternary volcanic rocks in south-central British Columbia (Fig. 4). The lavas have a Alumina Saturation Index (ASI) < 1 and are not peraluminous, unlike the vast majority of paralavas from other localities with the exception of rare peralkaline ones from Kazakstan (Grapes et al, 2012) (Fig. 5). The Mg# (molar Mg/Mg+Fe) of the lavas is 0.4 to 0.45 (Table 1).

The lavas have trace element patterns typical of the upper continental crust, with positive Pb and Sr and negative Nb, Zr and Hf anomalies when normalized to primitive upper mantle (Fig. 6). They contain much lower Th, U, Nb, Zr and Hf and higher V than estimates for the upper continental crust (Rudnick and Gao, 2003), or a glacial till-based natural average of the Cordilleran upper crust (Canil and Lacourse, 2011). Loss on ignition (LOI) values are low to nil, and suggest there were insigificant volatiles remaining in the lavas other than those degassed to form vesicles.

Mineral chemistry

We examined the chemistry of phases in the glassy driblets because they are likely the best estimate of original liquids (Fig. 2bf). The plagioclase crystallized from the glassy driblets varies in composition locally over the scale of a thin section from An_{40-52} at Shrimpton and An_{51-70} at Tranquille (Table 2 - Supplementary File).

The clinopyroxene crystallized in the glassy driblets is titaniferous augite and over the scale of thin section varies in Al_2O_3 (3 to 7 wt% Al_2O_3). The Mg# varies from 0.74 to 0.84 at Shrimpton and 0.69 to 0.73 at Tranquille. The Mn contents are higher at

Shrimpton. A single olivine recognized in the Shrimpton driblet is Mn-rich and has Mg# of 0.66 (Table 2- Supplementary File).

Glass compositions vary widely on a scale of millimeters within thin sections and between samples. Glasses in the Shrimpton driblets are trachyandesitic, quartz or hypersthene normative, and metaluminous. Glasses at Tranquille trend towards tephriphonolite, and are peralkaline and nepheline or leucite normative (Fig. 4, Table 2- Supplementary File). The Mg# varies from 0.3 to 0.4 at Shrimpton and 0.18 to 0.24 at Tranquille. With increasing SiO_2, the glasses at Shrimpton show decreasing Ca, Ti, Mg, Fe, nearly constant Na and Al and increasing K, but this pattern is less developed or even opposite in trend in the Tranquille glasses.

Euhedral oxides set in glass at Tranquille are nearly pure hematite or magnetite with between 16 to 28% ulvospinel component and no detectable V, Ni or Cr (Table 2- Supplementary File). No oxide phases are recognized in the glass at Shrimpton.

Small (10 – 50 μm) spheres of metal recognized in glass at both Shrimpton and Tranquille (Fig. 3f) are nearly 100% Fe (Table 2- Supplementary File), although C analyses were not carried out by EMPA to check the amount of C in solid solution (e.g. Goodrich and Bird, 2011). Anhedral opaque minerals occurring in necklaces along the borders of some vesicles (Fig. 3e) in the Shrimpton glass returned analyses containing only Si in concentrations of 70 wt%, and are thus inferred to be stoichiometric SiC (Table 2- Supplementary File).

Melting Experiments

The melting experiments on the glassy driblets determined the temperature at which the lava loses its shear strength and becomes a droplet, analogous to that displayed by samples in the field (e.g. Fig. 2f). Both driblet chips were solid and undeformed at 1100 °C but became partly molten, and lost their rigidity to become drop-shaped at 1150 °C (Shrimpton) and 1175 °C (Tranquille). At 1200 °C, both samples contained ~80% liquid (glass) and ~20% euhedral crystals of 100 – 200 µm plagioclase, clinopyroxene, and <20 µm cubic opaques.

Radiocarbon Dating and Dendrochronology

Initially, two samples of charcoal embedded in two lava samples at Shrimpton had 'post-bomb' ^{14}C levels indicating ages younger than 1950 AD (Table 3). To confirm that these post-bomb ^{14}C ages were not a spurious result of contamination, we sampled the interior of two larger (>20 cm) pieces of charcoal from two other scoria blocks. These additional samples also contained more ^{14}C than the modern (1950) reference standard. Thus, all four pieces of charcoal from Shrimpton indicate a minimum ^{14}C age of 1950. All four of the Shrimpton ages intersect both the ascending and descending limbs of the 'bomb curve' (Reimer et al., 2004; Hua et al., 2013), as is typical of post-bomb ^{14}C ages. The sample with the most reliable age using the 'bomb curve' method indicates with 100% probability a calendar year equivalent between 1963 and 1968 (#41123 with 1.664 F ^{14}C – Table 3). Calibration of the other three Shrimpton samples indicates that younger ages (e.g., 1967, 1979, 1987, and 1999 AD) are highly probable; however, their 2σ age ranges overlap the 1963-68 age associated with sample #41123 most enriched in ^{14}C (Table 3).

A sample of charcoal in lavas at Tranquille produced a pre-bomb ^{14}C result. Calibration of the pre-bomb ^{14}C age from Tranquille indicates a range of possible ages (1695-1918), with an age between 1867 and 1918 as most probable. The year with the highest probability is 1900 AD (#472224 - Table 3).

Planted lodgepole pine trees (ca. 15 cm diameter) growing on the surface of the Shrimpton lava deposit were cored in 2017 and returned ages of 13 years by dendrochronology. Assuming genesis of the lava predates reforestation and that 1 yr-old pine seedlings were planted, as is common silvicultural practice, the minimum time span since formation of the lava is 12 years (i.e., 2005 AD) - a result not at odds with the ^{14}C ages at Shrimpton.

The two largest Douglas-fir trees (ca. 22 and 39 cm dia.) growing in a natural stand on the surface of the Tranquille deposit returned ages of 38 and 42 years, respectively (i.e., 1979 and 1975 AD) consistent with the median calibrated ^{14}C age of 1886 AD for charcoal embedded in the lava (Table 3).. The Tranquille lava appears to have pre-dated the Shrimpton lava by at least a few decades, if not a century or two.

Discussion

Emplacement conditions of the lavas

The presence of vesicles, the form of flow structures on the surface and the orientation of driblets downward (Fig. 2) are clear evidence that the lavas were liquid and emplaced at atmospheric pressure (100 kPa). The most direct means to estimate the temperatures for formation of the lava are experiments on the driblet compositions, which show that the molten droplets observed in the deposits, and the co-precipitation of clinopyroxene and plagioclase in the glass, formed at temperatures of at least 1150 – 1200 °C. The lavas also contain spheres of Fe metal on the thin section scale (Fig. 3f). This petrographic feature requires the Fe metals was once liquid, and formed above 1154 °C, the minimum melting point of Fe at 100 kPa in the Fe-C system (Chipman, 1973; Goodrich and Bird, 2011).

Plagioclase-liquid thermometry (Putirka, 2005) applied to coexisting plagioclase and glass in the driblets, assuming they were in equilibrium, produces temperatures of 1045 – 1115 and 1115 - 1125 °C for the Shrimpton and Tranquille samples, respectively, for the range in An content for both samples. Even with an uncertainty of ±25 °C for the thermometer, these temperatures are slightly lower than estimates from direct experiments on the driblets.

The feldspar components (Ab, An, Or) make up more than 60 - 80% of the normative mineralogy of the driblet glasses. Projecting the normative composition of the glasses into the Ab-An-Or phase diagram at 100 kPa suggests liquidus temperatures of ~1300 to 1150 °C (Fig. 7). A similar projection into the Di-Ab-Or system at 100 kPa (Bowen, 1915), which considers the pyroxene component in the glasses, shows they plot along the diopside-plagioclase cotectic at 1200 – 1275 °C. These temperatures are maxima, because the presence of Fe and Ti in the melt would suppress liquidus temperatures in these simple ternary systems. In summary, all of the above evidence suggests the lava liquids, if represented by the compositions of the driblets, formed above 1150 °C and likely no higher than 1300°C.

The mixing of carbonized wood fragments and carbonaceous matter in the glasses suggests they were saturated with C on a local scale. The Fe metal globules require oxygen fugacities (fO_2) below the iron-wustite buffer, IW, which is $10^{-12.6}$ at a liquid temperature of 1150 °C and 100 kPa. The precipitation of SiC at vesicle boundaries at Shrimpton, requires low pressures (< 100 bars) and even more reducing fO2 of IW-6, as has been observed in other lavas interacting with carbonaceous matter (Goodrich and Bird, 2011; Shiryaev and Gaillard, 2014). Such extremely low fO_2 values due to local C saturation in the lava, however, only occurred at local (mm) scales because the silicates crystallizing in both the Shrimpton and Tranquille glasses are too rich in Fe to be in equilibrium with metal. This is shown in the Tranquille glasses, which contain Fe metal globules on local scales in glass, but show the presence of euhedral magnetite and hematite in most parts of the rock formed at higher fO_2. At 1150 °C, the range in ulvospinel component in magnetite (16 – 28%) suggests a minimum fO_2 of 10^{-7} (Buddington and Lindsley, 1964), equivalent to IW+5, whereas the presence of hematite requires fO_2 of at least $10^{-3.5}$ (IW+9). Overall the lavas show several orders of magnitude (IW-6 to IW+9) in heterogeneity in fO_2 over cm-scale in the driblets alone.

The duration of high temperatures and possible emplacement time of the lavas can be deduced by kinetic information in the xenocryst textures in the lavas at Shrimpton. Clinopyroxene xenocrysts show fritted margins along their contact with the glass, resulting from disequilibrium and incongruent dissolution in the liquid (Fig. 3). Using the relationship $x = (Dt)^{0.5}$, where x is distance, D = dissolution rate (m^2/sec) and t is time, one can estimate the time required for such rims to form. At temperatures of 1250 – 1150 °C, the width of the dissolution margins (5 to 15 μm) would take 2 - 30 h to form using the experimentally-measured D of clinopyroxene in andesite melt (Zhang et al., 1989) or 20 – 300 h using D in alkali basalt melt (Brearley and Scarfe, 1986). The larger crystal sizes at Tranquille suggests this deposit cooled over longer time periods.

The short times for emplacement (hours, days) of the lavas are consistent with the mm-scale compositional and redox heterogeneity in the glasses, which would be homogenized by chemical diffusion in the melt phase over longer cooling times. Furthermore, the well-preserved imprints of wood septa in the lavas and the preservation of charcoal (Fig. 2d) requires short duration heating events in a low oxygen environment, with sharp temperature gradients, from below 500 °C, to preserve the charcoal from combustion (Lockwood and Lipman, 1980), to above 1100 °C, the estimated liquid temperatures.

Origin as paralavas from till?

The field occurrence, geochemistry and phase equilibria preserved in the lavas provide insight into their formation. If these occurrences are paralavas, the Quaternary glacial till in which they occur could be the source material for melting *in situ*. Physical evidence of the deposits at Shrimpton and Tranquille show driblets facing consistently downward even when found at decimeter depths in the till. These suggest a heat source from below, with gravity acting on liquids generated *in situ* from the till. Pebbles and cobbles are welded by the liquid at a variety of scales (Figs. 2c,f, 3a). Coarser-grained pebbles and cobbles from till derived from local surface bedrock are recognizable components in the Shrimpton lava, but remain mostly unmelted (Fig. 3a). The finer grained sand, silt and clay in the till would have been more fusible, yet some of that also remains as restite (Fig. 3b).

Shilts (1993) shows the silt+clay fraction of till is dominated by clays (illite), quartz and feldspars, with notable magnetite (4 – 10%). The mineralogy of the silt+clay fraction of glacial tills in south-central British Columbia has not been measured but can be approximated using the bulk chemical compositions compiled for more than 5000 glacial tills in British Columbia. Canil and Lacourse (2011) show that the silt+clay fraction in tills in British Columbia varies in SiO_2 content from granitic (70 wt%) to basaltic (45 wt%) with a covariation in loss on ignition (LOI) from 1% to 15% over this range.

Assuming the LOI values are mostly H_2O, over 90% of tills in the Cordillera contain less than 10 wt% H_2O, with a mean of 6.6 ±4%. These would be maxima if some of the LOI is CO_2 in carbonate. If the most common clay mineral in till (illite) contains on the order of 10 – 13 wt% H_2O, then the silt+clay fraction of Cordilleran tills could vary from nearly 100% to less than 20% in clay content. Quartz+feldspar or other silicates (micas, pyroxenes) would comprise a significant component of the till, and furthermore be concentrated in the coarser silt and sand size fraction.

Heating of the fine fraction in till would dehydroxylate clays and micas by 800 °C (Grapes, 1986). Experiments on fine-grained quartz+feldspar aggregates at 100 kPa show feldspars could melt by 1175°C in eutectic fashion when in contact with quartz (Devineau and Pichavant, 2005). In these experiments, as well as natural melting in pelitic xenoliths hosted in basalt lava (Grapes, 1986), the first melts that form along quartz-feldspar contacts are peraluminous and corundum normative. Quartz and feldspar occur in the Shrimpton lava as xenocrysts, but micaceous material is absent, and melts (glasses) we observe are not peraluminous, but rather metaluminous and peralkaline. Thus, if till was melted to form these lavas, the source components undergoing melting to form them were metaluminous (or psammitic), and not peraluminous (or pelitic).

The melting of quartz and feldspar components in varying proportions in till could also explain the compositional difference between the glasses in lavas at Shrimpton and Tranquille. The Shrimpton glasses plot solely on the feldspar saturation surface in the An-Ab-Or phase diagram, whereas the more alkaline Tranquille glasses plot near the feldspar-leucite cotectic or within the leucite-only field (Fig. 7). The Shrimpton glasses could have formed from melting of till containing quartz, with plagioclase or K-poor alkali feldspar, all obvious xenocrysts in the lava samples (Fig. 3b). In contrast, a quartz-free till with significantly more K-rich feldspar at Tranquille, would lead to incongruent melting of K-feldpsar to produce leucite normative liquids observed at low pressure. Indeed, at 100 KPa, the incongruent melting reaction K-feldspar == Leucite + Liquid in the Ab-Or system occurs in compositions with greater than 0.5 X_{Or} and at above 1100 °C (Schairer, 1950), consistent with the minimum temperature of 1150 °C outlined above for the lavas.

A formation of these lavas by melting of different composition feldspar components in till, inferred from the simple system phase equilibria (Fig. 7), is also consistent with the major element data for the glasses. The Tranquille glasses are distinct in showing leucite control, and lie along a tieline between leucite - whole rock and a source material on the Si+Al-poor (quartz-free) side of the feldspar join (Ksp-Plag) in Figure 8. Such a source material could be represented by the more SiO_2-poor spectrum of till compositions in southwestern British Columbia. In contrast, the Shrimpton glasses are on a trend away from K-feldspar and quartz, similar to paralavas produced from more pelitic or feldspathic sediments (Fig. 8). In this way, a lack of quartz or abundance of K-rich feldspar in tills at Tranquille may have caused a compositional difference during melting. If till was derived from Eocene volcanic bedrock underlying both regions, the trachyte below the Tranquille region (Ewing, 1981) would produce no quartz. In both locations, the overall lack of clay or mica component in the till source material, led to metaluminous or alkaline melts, rather than the peraluminous varieties typical from shale protoliths (Figs. 5, 8).

The above evidence for a till source for the lava could explain their similarity in trace element pattern to tills in British Columbia. There are, however, also notable differences in these patterns, explicable by certain restite minerals during melting. The V contents in till from British Columbia show a positive correlation with Fe, and negative correlation with Si (Canil and Lacourse, 2011), suggesting magnetite is the primary host for V. If fusion occurred at high fO_2, near or above the HM buffer as shown at Tranquille, then magnetite, having $D_{Nb}^{mt/liq}$ is > 1 and $D_{V}^{mt/liq}$ < 1 at these conditions (Nielsen and Beard, 2000; Arato and Audetat, 2017) would sequester Nb, and release more V to the melt, compared to the till precursor. This would produce the observed Nb depletion and V enrichment in the lava relative to till (Fig. 6). On the other hand, residual zircon during the fusion of till could sequester Zr, Hf, Th and U and cause a depletion in these elements in lava relative to that observed in till (Fig. 6).

We can also consider anthropogenic origins for the lavas, from biomass burning (Thy, 1995; Coombs et al., 2008), forestry operations, charcoal pits or coal piles from mining (Capitanio et al, 2004; Sharygin et al, 2009). Some coal piles have produced paralavas and would explain the overall circular shapes of the deposits (Thiery and Guy, 2015; Sharygin et al., 2009), but most anthropogenic heat sources fail to produce the required high temperatures to form the lavas (>1150 °C) far deep into the surface alluvium (>50 cm at Shrimpton) for sustained periods. Natural forest fires or slash-pile incineration during logging activity can achieve temperatures of >800 °C, but such conditions are lower than required for the lavas, and would be intermittent, occurring over only minutes to seconds (Busse et al., 2005; Stoof et al., 2013) not hours to days as required by the clinopyroxene dissolution and other petrographic features. The lavas are also too small in size and lack distinct chemical attributes to be surface melts caused by cosmic airbursts during meteorite breakup (Bunch et al., 2012).

If our occurrences are paralavas, by far the most common and obvious sustained heat source would be natural coal fires, which can burn over durations of thousands of years, and are known in several occurrences that vary in age from Miocene to present day (Sokol and Volkova, 2007; Piepjohn et al., 2007; Coombs et al., 2008; Grapes et al., 2009; Quintero et al., 2009, Reiners, et al., 2011). Natural coal fires producing clinker and peraluminous paralavas have been reported at two other locations in the Cordillera. Surface coal fires in the Rocky Mountains produced paralava with similar driblet formation as we observe but from melting neighbouring shale strata (Bustin et al., 1982). At Hat Creek, near Cache Creek (Fig. 1) 60 km west of the Tranquille area, paralava revealed by strip-mining formed from spontaneous combustion in Eocene coal bearing strata buried beneath Quaternary alluvium (Church et al., 1979). Nevertheless, the lavas we document are distinct and unique from these by being metaluminous in bulk composition (Figs. 4,5), and by being emplaced on or forming within the Quaternary alluvium at surface.

The main problem with the paralava explanation is that, although Eocene aged coal-bearing strata are known throughout south-central British Columbia (Church, et al., 1979; McMechan, 1983), no such strata crop out near the lavas in our study. Thus, the source of heat to produce lavas at surface from coal burning in Quaternary alluvium is not obvious. Perhaps the heat source for the lava is coal burning in strata at depth below glacial overburden at Shrimpton and Tranquille, in yet to be identified block-faulted Eocene units. Coal fires in strata beneath the alluvium may have vented hot gases to surface, leading to melting of glacial till to decimeter depths. The alignment of the three lavas with faults in south-central British Columbia (Fig. 1) could suggest hot gases vented along these discontinuities, as has been observed in other paralava occurrences that lack obvious proximal coal measures, and were produced by frequent, short duration gas events (Tulloch et al., 1993; Grapes et al, 2012).

Origins by intraplate volcanism?

The interior of the Cordillera has overall high heat flow, and intraplate volcanism at Quaternary and younger volcanic centers throughout British Columbia has erupted trachytic rocks similar to the lava compositions we observe (Edwards and Russell, 2000; Hyndman et al, 2007). Thus, we can also consider the possibility that the modern lavas we document had a tectonic origin. If so, the lava deposits, are unusually small in size (~50 m^3), have no defined central vents, and yet have textures and compositions not unlike other Recent lavas in the Cordillera. A tectonic source cannot be completely dismissed, however, given the recent seismicity observed in 2007 beneath the 340 – 7.2 ka Nazko cone in central British Columbia (Fig. 1 - Souther et al., 1987). These seismic events show attributes of modern magma movement in the crust (Cassidy et al., 2011). A similar interpretation for seismicity (Rogers, 1981) was inferred along the track of the Wells Grey volcanic belt (3.2Ma – 7.56 ka) at Clearwater, only 100 km north of the Tranquille lava (Fig. 1). If magma is currently mobile in the shallow crust of British Columbia, then perhaps the young lavas that we document are incipient melts and the initial surface manifestations of that magma movement. Why the eruptions would be so aerially restricted is problematic.

Nevertheless, the ^{14}C dating and dendrochronology on the deposits we studied show that the lavas formed over the past ~120 years, making them the youngest known lavas in Canada. The balance of evidence would suggest a paralava origin by the venting of hot coal fire gases, but a tectonic origin cannot yet be completely ruled out. Further work is required on the source and frequency of these kind of lava occurrences to evaluate whether such phenomena should be regarded as a potential hazard, or has any tectonic relevance in the modern Cordilleran orogen.

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Figure Captions

Figure 1 – Location of British Columbia (upper inset), of Neogene, Quaternary and younger lava occurrences and the field area in the North American Cordillera (lower inset), and of the three lava occurrences (Tranquille, Shrimpton, Asp Creek) with respect to detailed geology of the field area showing Eocene volcanic and sedimentary rocks, Neogene volcanic rocks of the Chilcotin Group, Quaternary deposits and major faults in (geology after Cui et al., 2015). Also shown are the Nazko cone, the Cleaewater region and recent seismic events referred to in text.

Figure 2 – Field images of the lavas: (a) Rubbly scoria blocks in Quaternary till at Shrimpton overgrown by planted lodgepole pine. (b) Lava at Shrimpton showing glassy driblets (arrow) pointed downward (pen for scale). (c) Coating of spalled boulders and surface with lava (Shrimpton). Note the reddish-brown discoloration of till and boulders. (d) Carbonized wood and boxwork imprints in lava at Shrimpton. (e) Massive extrusion of lava at Tranquille, showing glassy margins, driblets and imprints of longitudinal septa from wood. (f) Lava at Tranquille showing glassy driblets draining from welded pebbles in till.

Figure 3- Petrographic images of hand samples and thin sections of the lavas. (a) Glassy lava at Tranquille welding pebbles and cobbles in till,(b) Xenocrysts of quartz (qz) and plagioclase (Plag) in brown glass (Gl) with microlites of plagioclase and pyroxenes at Shrimpton. (c) Clinopyroxene (Cpx) xenocrysts showing fritted margins in brown glass

containing microlites of feldspar and vesicles at Shrimpton. (d) More massive lava at Tranquille showing plagioclase (plag) laths, sub-euhedral clinopyroxene phenocrysts (Cpx) and euhedral FeTi oxides. (e) Opaque anhedral SiC mantling vesicles set in felty mass of plagioclase, glass and FeTi oxides (Plag+Ox) at Tranquille. (f) Spheres of carbon (Cb) in vesicles, and Fe metal (Met) set in glass containing microlites of feldspar in Shrimpton lava .

Figure 4 – Total wt.% alkalies (Na_2O+K_2O) versus silica (SiO_2) plot for lava whole rock compositions and their coexisting glasses from this study (Tables 1, 2) and from paralavas in the literature (Church et al, 1979; Piepjohn et al., 2007; Thy, 1995; Coombs et al, 2009; Sharygin et al, 2009; Grapes et al., 2009, 2012). Fields for rock names are after Middlemost (1994). Also shown are the bulk compositions of volcanic rocks from the Eocene Princeton and Kamloops groups, and Quaternary-aged Chilcotin Group lavas in the southern Cordillera (Ewing, 1981; Ickert et al., 2009; Sluggett, 2008; Thorkelson et al, 2011).

Figure 5- Plot comparing peralkalinity and alumina saturation indices in whole rock lava compositions and their coexisting glasses (this study), and for paralavas from the literature (data sources as in Figure 4).

Figure 6 – Trace element composition of whole rock lava samples normalized to primitive upper mantle (PUM) of McDonough and Sun (1995). Note higher V, and lower Th, U, Nb, Zr and Hf in the lava samples relative to that in average till in southwestern

British Columbia (Canil and Lacourse, 2011) and other estimates of the upper continental crust (Rudnick and Gao, 2003).

Figure 7 – Plot of the extremes in glass compositions in the lava driblets cast in the Ab-Or-An system, with liquidus temperatures after Franco and Schairier (1951) and Yoder et al (1957). Note the difference in compositions of the Shrimpton and Tranquille glasses.

Figure 8 – Molar Si+Al against molar Na+K showing the disposition of whole rocks and coexisting glasses in lavas of this study relative to the stoichiometry of possible minerals involved in their petrogenesis. Also shown are the bulk compositions of glacial tills and Eocene volcanic rocks that underlie southern British Columbia ((Ewing, 1981; Ickert et al., 2009; Sluggett, 2008; Thorkelson et al, 2011; Canil and Lacourse, 2011) and glasses in paralavas from the literature (Thy, 1995; Coombs et al, 2009; Sharygin et al, 2009; Grapes et al., 2009, 2012). The Shrimpton and most other paralava glasses, evolve from Si+Al-rich compositions in the quartz - two-feldspar ternary (dashed triangle) toward pyroxene (purple dashed arrow). In contrast, note the Tranquille glasses plot outside the quartz-two-feldspar ternary at nearly constant Si+Al along a trend toward leucite (solid arrow). Qz- quartz; Ksp – alkali feldspar; Plag – plagioclase; Lc – leucite; Cpx – clinopyroxene.