The age of the Tseax volcanic eruption, British Columbia, Canada

Glyn Williams-Jones, René W. Barendregt, James K. Russell, Yannick Le Moigne, Randolph J. Enkin, and Rose Gallo

Abstract: A recent volcanic eruption occurred at Tseax volcano that formed a series of tephra cones in northwestern British Columbia, Canada. The explosive to effusive eruption also formed a 32 km long sequence of Fe-rich Mg-poor basanite–trachybasalt lavas covering ~40 km². Oral histories of the Nisg̱a’a Nation report that the eruption may have caused as many as 2000 fatalities. The actual eruption date and question of whether there was one or multiple eruptive episodes in the 14th and 18th centuries are, as of yet, unresolved. New radiocarbon dating of wood charcoal from immediately beneath vent-proximal tephra deposits and complementary age information suggest an eruption in 1675–1778 CE (95.4% probability) was responsible for the formation of the tephra cone. New paleomagnetic and geochemical data from the tephra cone and lava flows suggest there is, in fact, no statistically significant difference in time between the explosive and effusive deposits and that they formed during a single eruptive episode.

Key words: Tseax volcano, lava flow, tephra cone, paleomagnetism, radiocarbon dating, geochemistry.

Introduction

Tseax volcano, situated in northwestern British Columbia, Canada (55.11085°N, 128.89944°W), comprises several small tephra cones and a 32 km long basanite–trachybasalt lava (e.g., Hanson 1923; Sutherland Brown 1969). The eruption is believed to have occurred in the 1700s (e.g., Lowdon et al. 1971; Higgins 2009) and to have destroyed at least three Nisg̱a’a Nation villages (Laxksilux, Laxksiiwihlgest, and Ts’oolii’sup, Fig. 1) located on the banks of the Nass River, ~20 km from the volcano. The eruption may have caused as many as 2000 fatalities (Nisg̱a’a Nation 2004). These fatalities would make it Canada’s second-worst recorded natural disaster (Hickson and Edwards 2001) after the near contemporaneous Newfoundland hurricane of 1775 that caused at least 4100 deaths (Ruffman 1996). There are no direct written accounts of the Tseax event; however, the rich oral history (adaawak - traditional histories) from the Nisg̱a’a people provides important observational data for the eruption (Nisg̱a’a Nation 2004; see Appendix A). Previous studies have included volcanological and geomorphological mapping (Hanson 1923; Sutherland Brown 1969; Roberts and McCuaig 2001; Le Moigne et al. 2020), petrological and geochemical studies (Nicholls et al. 1982, 1997; Higgins 2009; Gallo 2018), and dating (Lowdon et al. 1971; Symons 1975; Wuorinen 1978; Higgins 2009).

The Tseax vent area comprises a number of short eruptive fissures and two small tephra cones; the larger of the two cones is partially enclosed by a spatter rampart described previously as a dissected tephra cone (Sutherland Brown 1969; Wuorinen 1978). This original description, along with radiocarbon dating of a tree from the spatter rampart, raised the possibility of two distinct eruptive episodes occurring in 1325 CE and 1700 CE (Wuorinen 1978). Recent field work has established the relative sequence of volcanic events (Le Moigne et al. 2018, 2020), but the published radiocarbon dating is sparse (three samples), leaving ambiguity concerning the absolute timing and duration of eruptive activity. Importantly, the question of whether the volcanic field represents a monogenetic or polygenetic system (e.g., Németh and Kereszturi 2015), which may have had more than one eruption, has important implications for future activity and hazard mitigation efforts and thus merits further study.
Here we present new geochemical, paleomagnetic, and radiocarbon data for samples collected from the Tseax volcanic deposits (Figs. 1, 2) supported by detailed mapping of the tephra cones and lava flows (Gallo 2018; Le Moigne et al. 2018, 2020). The new radiocarbon dates derive from samples of charred wood collected from beneath explosive tephra deposits 890 m northwest of the main tephra cone (Fig. 2). The paleomagnetic data sets derive from the lava field, tephra cone, and spatter rampart. Our sampling campaign was specifically designed to test whether all the Tseax volcanic deposits, representing explosive and effusive activity, share a common paleomagnetic direction acquired during cooling. The implication would be that all events have the same paleomagnetic age. The alternative is that the apparently earlier stratigraphic unit (i.e., the partially dissected spatter rampart; Fig. 2) has a different paleomagnetic direction and age than the stratigraphically youngest units (i.e., tephra cone and the valley-filling lavas), as suggested from 14C dating by Wuorinen (1978).

**Tseax volcano**

Tseax volcano, Wil Ksi Baxhi Mihl, formerly known as Aiyansh volcano, Aiyansh River volcano, or Tseax River cone, is located in the Anhluu’ukwsim Laxmihl Angwiga’asanskwhl Nisg’a (Nisg’aa Memorial Lava Bed Provincial Park) near Gitlaxt’aamiks (formerly New Aiyansh) and Gitwinkshilkw (formerly Canyon City), 60 km northwest of Terrace in northwestern British Columbia, Canada (Fig. 1). Tseax (pronounced see-ax) is the southernmost volcanic centre of the Northern Cordilleran Volcanic Province (Edwards and Russell 2000) and is notable for a 32 km long basanite–trachybasalt lava flow (approximately 0.5 km³ covering ~36 km²; Fig. 1). More importantly, it is the site of the second-youngest (after Lava Fork in ~1800 CE; Elliott et al. 1981) and the deadliest volcanic eruption in Canada (Hickson and Edwards 2001). The tephra cones and valley-filling lavas overlay intercalated sandstone to siltstone and mudstone from the Late Jurassic Bowser Lake group (van der Heyden et al. 2000; Evenchick et al. 2008).
Fig. 2. Volcanological map of Tseax cone and spatter rampart after Le Moigne et al. (2018, 2020). Basement geology from Evenchick et al. (2008). Inset images: Tseax crater (top right) and inner wall of the spatter rampart (bottom right). RB (white diamonds) indicate locations of new palaeomagnetism sites and green triangles show locations of new and published radiocarbon samples. Contour interval is 50 m. Map produced using ESRI ArcGIS 10.7. [Colour online.]

### Table 1. Published whole rock compositions from explosive and effusive deposits at Tseax.

<table>
<thead>
<tr>
<th>Sample</th>
<th>NR5-C*</th>
<th>RG-B7†</th>
<th>RG-B2†</th>
<th>TS-S40a†</th>
<th>TS-S19†</th>
<th>TS-S20†</th>
<th>TS-S2†</th>
<th>TS-S57†</th>
<th>RG-S16†</th>
<th>RG-S25†</th>
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<td>Lithology</td>
<td>Lava flow</td>
<td>Bomb</td>
<td>Bomb</td>
<td>Satellite cone</td>
<td>Spatter</td>
<td>Spatter</td>
<td>Lava flow</td>
<td>Lava flow</td>
<td>Tephra</td>
<td>Tephra</td>
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<td>SiO₂</td>
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<td>46.74</td>
<td>45.20</td>
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<td>3.67</td>
<td>3.58</td>
<td>3.67</td>
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<td>2.56</td>
<td>2.64</td>
<td>1.67</td>
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<td>—</td>
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<td>0.23</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
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<td>7.45</td>
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<td>Na₂O</td>
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<td>3.82</td>
<td>3.85</td>
<td>4.05</td>
<td>3.95</td>
<td>4.02</td>
<td>4.03</td>
<td>3.9</td>
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<td>K₂O</td>
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<td>1.76</td>
<td>1.81</td>
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<td>1.78</td>
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<td>H₂O⁺</td>
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</tr>
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<td>Total</td>
<td>99.39</td>
<td>99.27</td>
<td>99.55</td>
<td>97.72</td>
<td>99.09</td>
<td>98.74</td>
<td>99.41</td>
<td>98.90</td>
<td>100.13</td>
<td>99.02</td>
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<tr>
<td>LOI</td>
<td>—</td>
<td>−1.11</td>
<td>−1.34</td>
<td>0.74</td>
<td>−1.00</td>
<td>−0.37</td>
<td>−1.38</td>
<td>−0.93</td>
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</tr>
<tr>
<td>FeO†</td>
<td>15.28</td>
<td>15.35</td>
<td>15.18</td>
<td>18.32</td>
<td>14.78</td>
<td>14.69</td>
<td>14.74</td>
<td>14.63</td>
<td>15.22</td>
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<tr>
<td>Mg #</td>
<td>37.78</td>
<td>37.88</td>
<td>36.88</td>
<td>32.99</td>
<td>35.49</td>
<td>36.08</td>
<td>35.95</td>
<td>35.46</td>
<td>36.78</td>
<td>36.10</td>
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Note: See Appendix Table A1 for sample locations. LOI, loss on ignition.
*Data from Nicholls et al. (1982).
†Data from Gallo (2018).
Detailed volcanological mapping shows Tseax volcano to comprise a ~70 m high, 400 m diameter tephra cone situated within an oxidized horseshoe-shaped spatter rampart (Fig. 2) (Hanson 1923; Sutherland Brown 1969; Wuorinen 1978; Le Moigne et al. 2020). Another smaller (~20 m high, ~50–55 m diameter) highly oxidized tephra cone, unnamed and thus referred to here as Satellite cone, is located 470 m to the north of Tseax and in close proximity to an eruptive fissure consisting of small tephra mounds (Fig. 2; Le Moigne et al. 2020). These structures are surrounded by a broad tephra deposit covering ~22 km² (Fountain tephra in Fig. 2, Table 1; Gallo 2018; Le Moigne et al. 2020). Four valley-filling lavas (two pahoehoe and two `a`a flows) have been mapped and, due to their uniform composition, are believed to have been emplaced during a single eruptive episode (Fig. 1; Hanson 1923; Sutherland Brown 1969; Higgins 2009; Le Moigne et al. 2020).

Two porphyritic pahoehoe lavas (10%–15% phenocrysts of plagioclase, olivine, and oxides) initially flowed 5 km down Crater Creek before blocking the Tseax River and forming Lava Lake (Fig. 1; Hanson 1923; Roberts and McCuaig 2001). The lava flowed a further 15 km northward down the Tseax River valley to the Nass River floodplain where the first flow spread out to form an approximately 12 km long lava plain that parallels the Nass River (Symons 1975; Purssell 1993) and results in numerous basaltic pillows and pillow tubes (Le Moigne et al. 2020). Two later, stratigraphically distinct, and smaller volume `a`a lavas flowed from the source area down Crater Creek but stopped near Lava Lake (Fig. 1). All flows are characterized by numerous intact and collapsed lava tubes, both proximal and distal to the source (Sutherland Brown 1969; Marshall 1975; Le Moigne et al. 2020).

Plagioclase megacrysts (up to 20 mm) are present in the four lava flows (pahoehoe and `a`a) but represent less than 1% of the volume. There is nevertheless a notable difference in the crystal size distribution with the two pahoehoe flows containing less <8%–10% plagioclase phenocrysts, whereas the two `a`a flows have ~15%–20% plagioclase phenocrysts (Higgins 2009; Le Moigne et al. 2018). Higgins (2009) proposed that this indicated an eruption sourced from two separate batches of magma. Interestingly, in spite of the textural differences of the lavas, the whole rock and trace element geochemistry of select samples compiled from the literature are essentially identical across lava, tephra and ballistics, the tephra and satellite cones, and spatter rampart (Fig. 3). This strongly suggests that there has been no significant residence time, or associated fractional crystallisation, within the magmatic plumbing system (e.g., Hawkesworth et al. 2000). All samples plot as Fe-rich Mg-poor basanite–trachybasalt (Fig. 3) with a mean chemical composition (±1 σ): SiO₂ of 46.5% ± 0.5%, Na₂O + K₂O of 5.74% ± 0.1%, FeO° of 15.5% ± 1.1%, and Mg# of 36.1 ± 1.4 (Table 1; Nicholls et al. 1982; Higgins 2009; Gallo 2018).

The age controversy
The exact date of the eruption of Tseax remains unclear despite the number of previous studies. Early reports by missionaries of local Nisga’a adaawak (e.g., Collinson 1915; McCullagh 1918) mention trees cut in 1898 at a place where the Nisga’a had established their first refuge after evacuating their villages seven generations earlier (i.e., 7 × 21 years); the trunks are reported to have shown evidence of bark being stripped 128 years earlier, in ca. 1770 CE, immediately after the eruption (Roberts and McCuaig 2001; Higgins 2009). However, there is likely significant uncertainty in these estimates due to poor translation from Nisga’a to English (e.g., Higgins 2009). Hanson (1923, p. 39) reports that “trees one hundred and seventy years old have been found growing on the lava”, which would constrain the date of the eruption to before 1753 CE (Fig. 4). From his work in the Nass Valley, Barbeau (1935) concluded that the most recent eruption occurred in the late 18th century. Similarly, Wuorinen (1976) reports that the Nisga’a adaawak (see Appendix A) dates the eruption back to 1770 CE and states that it occurred over a period of a few days or at most a few weeks.

Published radiometric studies
A number of radiocarbon-dating studies were made on trees killed by the eruption. Sutherland Brown (1969) and Souther (1970) reported a date of 220 ± 130 14C years BP for a lava-encased cottonwood sampled near the Nass River; however, Lowdon et al. (1971) state that this date was uncorrected and should in fact be 250 ± 130 14C years BP (sample GSC-1124, Table 2, Fig. 4). More recently, Roberts and McCuaig (2001) dated a wood fragment of a lava-encased tree at 280 ± 50 14C years BP (sample GSC-6150); as it was missing ~8 cm of the trunk (with 5 rings/cm) and several rings
were pulverized for the bulk date, they give a corrected age of 230 ± 50 14C years BP. Higgins (2009) recalibrated the radiocarbon dates from the most recent of the three samples (GSC-6150) using the CALIB software (Reimer et al. 2004; Stuiver and Reimer 1993) and reinterpreted the age of the youngest eruption at between 1668 and 1714 CE (68.2% probability).

Importantly, Wuorinen (1978) sampled part of a carbonized tree trunk found standing in the vertical wall of the spatter rampart and dated it at 625 ± 70 14C years BP, which calibrates to between 1283 and 1436 CE (95.4% probability; sample S-1046) (Figs. 2 and 4, Table 2); we were unable to locate this tree trunk during our extensive mapping in 2016 and 2017. Wuorinen (1978, p. 1037) also notes a difference in appearance between the “well-eroded surface of the old [spatter rampart] cone and the comparatively pristine surface and form of the new [inner] cone”. Along with the “minimal vegetative growth (lichen and small bushes)” on the

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**Table 2. Compilation of radiocarbon data.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sample ID</th>
<th>Sample type</th>
<th>Radiocarbon date 14C year (BP)</th>
<th>Posterior calibrated date range 68.2% prob., CE</th>
<th>Posterior calibrated date range 95.4% prob., CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sutherland Brown (1969); Souther (1970); Lowdon et al. (1971)</td>
<td>GSC-1124</td>
<td>Standing cottonwood log encased in lava near Nass River</td>
<td>250 ± 130</td>
<td>1488–1683 (68.2%)</td>
<td>1435–1769 (95.4%)</td>
</tr>
<tr>
<td>Wuorinen (1978)</td>
<td>S-1046</td>
<td>Carbonised log in “outer cone”</td>
<td>625 ± 70</td>
<td>1339–1420 (68.2%)</td>
<td>1283–1436 (95.4%)</td>
</tr>
<tr>
<td>Roberts and McCuaig (2001)</td>
<td>GSC-6150</td>
<td>Lava-encased tree trunk in growth position</td>
<td>230 ± 50 + N(50 ± 10)</td>
<td>1564–1642 (48.9%)</td>
<td>1526–1720 (95.4%)</td>
</tr>
<tr>
<td>This study</td>
<td>CUIAMS-215254</td>
<td>Charred wood beneath tephra near cone</td>
<td>390 ± 15</td>
<td>1451–1485 (68.2%)</td>
<td>1446–1508 (86.2%)</td>
</tr>
<tr>
<td>This study</td>
<td>CUIAMS-215255</td>
<td>Charred branch wood beneath tephra near cone</td>
<td>190 ± 15</td>
<td>1662–1683 (68.2%)</td>
<td>1658–1685 (72.1%)</td>
</tr>
<tr>
<td>Combined Tseax eruption</td>
<td>Five 14C dates</td>
<td>Event postdating 14C and predating 1800 CE</td>
<td>1678–1710 (23.2%)</td>
<td>1674–1800 (95.4%)</td>
<td>1749–1799 (45.0%)</td>
</tr>
</tbody>
</table>

**Note:** Dates are presented as 14C year BP and calibrated calendar ranges (with OxCal + IntCal13 curve) with confidence intervals for 68.2% and 95.4% probability. The age model uses the complementary information constraints which suggest that all five samples predate a single volcanic event that occurred before 1800 CE. Boldface type indicates dates with highest confidence intervals. See Appendix A for OxCal script and Appendix Fig. A1 and Table A1.
Fig. 5. Stereographic (Wulff, equal angle) plot of magnetic remanence directions. (A) Plot of five new sites (RB1–5) sampled at Tseax and their $\alpha_{95}$ ($p = 0.05$) confidence circles (see Table 3). Site RB4 is an outlier affected by post-cooling collapse of a lava tube and is not included in the mean (blue circle). (B) Mean of RB1, RB2, RB3, RB5, and the 23 sites sampled by Symons (1975) and their $\alpha_{95}$ confidence circle (blue; Table 3). The star marks the time-average geocentric axial dipole direction at the Tseax latitude (55.11085°N). (C) Quantile–quantile plot assessing goodness-of-fit of the Fisher distribution to the paleomagnetic site mean directions. Site RB4 is an outlier, while all the other new sites (black circles) are compatible with and span the range defined by the Symons (1975) study (open circles), despite sampling different phases of the eruption and 35 years difference in technology and methods. [Colour online.]

Published paleomagnetic studies

The orientation of the local geomagnetic field can be preserved in the remanent magnetization of volcanic rocks when they cool below the Curie temperature ($T_C$) of their principal ferromagnetic mineral (typically magnetite, $T_C = 580$ °C). The geomagnetic field direction changes rapidly through time and can be compared with local and global reference curves (e.g., Turner 1987; Korte et al. 2009) to constrain emplacement/deposition ages of lava flows and pyroclastic deposits. This approach has been successfully applied to a number of current and geologically recent eruptions (e.g., Vulcano, Italy, Lanza and Zanella 2003; Tongariro, New Zealand, Greve et al. 2016; El Metate, Mexico, Mahgoub et al. 2017; Colli Albani, Italy, Trolle et al. 2017; Reykjanes Peninsula, Iceland, Pinton et al. 2018).

Symons (1975) completed an extensive paleomagnetic study of Tseax based on 197 specimens from 122 cores (~20 cm long) at 23 sites on the early stage, phenocryst-poor, pahoehoe lava flows. It is important to note that no samples were collected from the later stage phenocryst-rich “a’a lavas, the tephra cone, or the spatter rampart (Figs. 1, 2). In situ orientation (to within ~1°) was accomplished using a solar compass and Brunton (for topographical control). Symons (1975) determined a mean magnetic remanence direction of 13.9° declination and 72.9° inclination with an error of 0.8° (Fig. 5B). Symons (1975) noted that the natural remanent magnetizations of the pahoehoe lavas were strong and remarkably stable, falling within 7.6–24.8 A/m; variations were ascribed to variations in lava viscosiarity.

Observations of the declination of the magnetic field for British Columbia were initially made in 1778 and 1792 CE by Captain Cook and Captain Vancouver, respectively (Herbert 1926). Between 5000 and 1500 BP, observations suggest westward drift of the non-dipole field at a rate of about ~0.075°/year in western Canada (Yukutake 1967; Turner 1987). Based on this, Symons (1975) extrapolated the observatory data linearly back from 1770 CE; the projected declination intersected the measured flow declination at 1650 ± 40 CE (Fig. 4). Higgins (2009) applied a number of regional and global models of geomagnetic secular variation (GUFM1, Jackson et al. 2000; a dipole model, Hagstrum and Champion 2002; CALS3k.2 and CALS7k.2, Korte and Constable 2005). However, while the predicted declinations were close to the observed values, inclinations were always overestimated and likely due to limitations of the databases used to define the geomagnetic secular variation models (fig. 3 in Higgins 2009).

Sampling and methods

Radiocarbon sampling and analysis

Two samples of wood charcoal were collected from a carbonized horizon immediately below the tephra deposit in the immediate vicinity of Tseax cone (Fig. 2, Appendix Table A1). Sample CUIAMS-215254 was a piece of charred wood collected at a depth of ~12–15 cm (under ~6 cm of modern surface soil overlaying ~6 cm of lapilli). Sample CUIAMS-215255 consisted of charcoal fragments of partially charred branch wood collected at a depth of ~8–14 cm (under ~8 cm of modern surface soil overlaying ~6 cm of lapilli). These samples were processed by Alice Telka, Paleotech Services (Ontario, Canada); CUIAMS-215254 was cleaned of internal and surface fine roots and rhizomes and CUIAMS-215255 had minor amounts of surface material shaved off. Suitable fragments of wood charcoal were subsequently submitted to the University of California Irvine Keck Carbon Cycle AMS Facility for radiocarbon analysis. Dates are reported as conventional radiocarbon ages corrected for fractionation with measured $\delta^{13}C$ according to Stuiver and Polach (1977). Calendar ages are presented as 68.3%
Table 3. Paleomagnetic analyses.

<table>
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<tr>
<th>Sample site</th>
<th>N&lt;sub&gt;s&lt;/sub&gt;</th>
<th>Lithology</th>
<th>N&lt;sub&gt;s&lt;/sub&gt;</th>
<th>Longitude (°W)</th>
<th>Latitude (°N)</th>
<th>Decl.</th>
<th>Incl.</th>
<th>k</th>
<th>α&lt;sub&gt;95&lt;/sub&gt;</th>
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<td>LLM001–LLM012</td>
<td>Coherent lava</td>
<td>10</td>
<td>129.20435</td>
<td>55.18505</td>
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<td>72.9</td>
<td>379</td>
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<tr>
<td>RB2</td>
<td>LLM013–LLM022</td>
<td>Large pyroclastic blocks in tephra</td>
<td>13</td>
<td>128.89856</td>
<td>55.11148</td>
<td>20.1</td>
<td>72.3</td>
<td>221</td>
<td>2.8</td>
</tr>
<tr>
<td>RB3</td>
<td>LLM023–LLM036</td>
<td>Inner rampart wall and spatter</td>
<td>14</td>
<td>128.89600</td>
<td>55.11108</td>
<td>8.9</td>
<td>77.8</td>
<td>248</td>
<td>2.5</td>
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<tr>
<td>RB3v</td>
<td>LLM026–LLM036</td>
<td>Inner rampart wall only</td>
<td>3</td>
<td>128.89600</td>
<td>55.11108</td>
<td>6.0</td>
<td>77.6</td>
<td>490</td>
<td>5.6</td>
</tr>
<tr>
<td>RB4</td>
<td>LLM037–LLM046</td>
<td>Coherent lava in collapsed tube</td>
<td>13</td>
<td>128.90291</td>
<td>55.11151</td>
<td>50.0</td>
<td>77.9</td>
<td>482</td>
<td>1.9</td>
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<tr>
<td>RB5</td>
<td>LLM047–LLM054</td>
<td>Coherent lava</td>
<td>9</td>
<td>129.22176</td>
<td>55.18524</td>
<td>13.3</td>
<td>73.4</td>
<td>403</td>
<td>2.6</td>
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</table>

Mean (RB1–RB5) | 23 | 15.8 | 73.5 | 1083 | 0.7 |

Mean (excl. RB4) | 4 | 11.7 | 74.2 | 641 | 3.6 |

Note: N<sub>s</sub>, sample numbers for each site; N<sub>s</sub>, total number of samples used in calculation of mean direction for each site; Decl., declination; Incl., inclination; k, precision parameter; α<sub>95</sub>, radius of 95% confidence level. See Figs. 1 and 2 for location.

Paleomagnetic sampling and analysis

Oriented cylindrical samples were collected from coherent lava and large intact blocks in pyroclastic deposits at the Tseax cone and nearby sites (Figs. 1, 2, Table 3). Cylindrical cores 2.5 cm in diameter were extracted using a portable gasoline-powered rock drill and water swivel attachment, commonly used in standard paleomagnetic work (Fig. 6). Ten to fourteen cores were collected at each site, usually spread out over several metres to minimize the chance of lightning or localized disturbances affecting results. Five sites were sampled on the valley-filling lava, tephra cone, and outer spatter rampart, providing 54 independently oriented cores (Fig. 1, Table 3). All samples were oriented using a solar compass as the Brunton magnetic compass displayed large deflections due to the significant magnetic field created by the outcrop.

Magnetic measurements were made in the paleomagnetic laboratory at the University of Lethbridge, Alberta. Magnetic susceptibility was measured with a Sapphire Instruments (SI-2B) susceptibility meter. The magnetization of each sample was measured with an AGICO JR-6A spinner magnetometer prior to demagnetization and again after each level of stepwise demagnetization. Samples were stored in magnetic shields following field collection and between laboratory measurements. Most samples were subjected to alternating field demagnetization with one-third of the collection subjected to thermal demagnetization. Directions of characteristic remanent magnetization were calculated for each site and an overall mean was also calculated (Table 3).

Results and implications

Radiocarbon results

To provide some insight on the age of the eruption and for consistency, we recalibrated the published radiocarbon age estimates (Fig. 4, Table 2). Note that for Robert and McCuaig’s (2001) sample (GSC-6150), we corrected for the missing 50 years (due to missing trunk material) by adding a Gaussian likelihood of 50 ± 10 years after calibration, rather than to the C14 age; this results in a similar likelihood function but with less likelihood of a modern age. It is important to note that these wood charcoal fragments were not all from in situ trunks and are considered to be the maximum ages.

Based on our analysis of the mapping, geochemistry, and the paleomagnetism, we interpret that there was a single eruptive
event that postdated all the charred wood measured in the 14C samples. We combined the five dates as a “phase” using the OxCal age analysis (Ramsey 2009) and set the age of the Tseax eruption to postdate that phase. See Appendix A for OxCal script. The oral history and dendrochronology suggest that the eruption occurred by 1780 CE and the paleomagnetism declination constrains the age to predate James Cook’s first direct observation in 1778. Thus, we constrain the lower bounding age at 1778 CE. The OxCal Bayesian age modelling of the five 14C ages defines a relatively constant likelihood between 1675 and 1778 CE (95.4%) (Fig. 4).

Paleomagnetic results
All paleomagnetic samples produced stable directions of magnetization following stepwise demagnetization. Thermal demagnetization had little effect until >400 °C and then near complete demagnetization at 550 °C, typical of fine-grained (single domain) magnetite as the magnetic carrier (see LLM014B, Fig. 7C). Alternating field demagnetization, applied to most specimens, exhibited linear decay to the origin on orthogonal projections (Fig. 7). The median destructive fields range from 20–80 mT and final directions are stable up to 200 mT alternating field demagnetization (see LLM011A, Fig. 7A) indicative of single-domain magnetite. Note that single-domain magnetite is the optimal magnetic mineral and grain size for producing reliable paleomagnetic directions. The magnetic susceptibility values of basalt range from 3.0 to 67.3 × 10⁻³ SI with a median value of 15.1 × 10⁻³ SI. Mean natural remanent magnetization for the basalts is 30.5 A/m (range 4.5–74.0 A/m).

All samples are normally magnetized, as expected for basalt from a late Holocene eruption (Table 3). The site mean directions are remarkably consistent in direction. Of the five sites sampled for paleomagnetic analysis, four have uncertainty circles that fall within the uncertainty circle about the mean (Fig. 5A). Site RB4 revealed a significantly more easterly declination (40° east of the mean declination of the other four sites). Re-examination of the field site in 2018 showed that the original sample was from a very large block on the partially collapsed and rotated wall of an exposed lava tube and this likely accounts for the deviated direction for this site. The offset is explained with a 10° dip down to the northwest (i.e., around strike 238°). The mean direction of our four sites (excluding site RB4) is 11.7° declination, 74.2° inclination (Fig. 5A, Table 3), which is only 0.9° ± 2.3° from the mean (13.9°, 72.9°) calculated from 23 sites on the early stage lavas reported by Symons (1975). The new and published sites are combined to derive the paleomagnetic direction for analysis of the eruption age: 13.5° declination, 73.1° inclination, Fisher precision factor $k = 1296$, $\phi_{95} = 0.7°$, $N = 27$ sites (Fig. 5B).

The high-precision measurements of paleomagnetic directions also addresses the question of origin of the inner tephra cone and outer spatter rampart. Importantly, site RB3 is located on the inner eastern wall of the outer spatter rampart (Fig. 2) and shows evidence of stratigraphically younger (and darker) spatter ejected ballistically and agglutinated onto the inclined inner wall (Fig. 6). Characteristic remanent magnetization directions of only the younger, darker spatter (6.0°, 77.6°) is an insignificant separation (0.8° ± 3.8°) from the mean direction of the inner rampart wall without spatter (9.7°, 77.9°) (Fig. 6). Furthermore, while the direction of site RB3 is the most distant from the $N = 27$ site mean, the outlier test of Fisher et al. (1993) shows that it is concordant with the rest of the site means ($p = 83.4%$), assuming a Fisher distribution (Fig. 5C). Note that using the same test, site RB4 has only $p = 1.53 \times 10^{-32}$% probability of belonging to the Fisher distribution of the other $N = 27$ sites. The Fisher precision factor $k = 1296$ is higher than 91% (i.e., rank 189 of 206) of the extremely well constrained lava flows measured in Hawaii (Hagstrum and Champion 2002).

Fig. 6. Images and stereographic plots (inset) from site RB3 of the inner eastern wall of the outer spatter rampart (A), with closeup of sampled agglutinated spatter (B), and inner wall (C). Stereographic plots show individual measurements (in black) and means (in red) and $\alpha_{95}$ confidence circles. See Fig. 1 for location. [Colour online.]
Fig. 7. Examples of typical, well-behaved demagnetization data obtained from two of the sampling sites at Tseax (Table 3). For each sample, the stereographic plots (left figures) show magnetization directions after stepwise demagnetization, where the filled circles lie on the lower hemisphere. The orthogonal plots (right figures) show horizontal projections as filled circles and vertical projections as open circles. Both alternating field and thermal demagnetization plots are given for sample LLM014A/B from site RB2. Natural remanent magnetization is shown with a circle and cross. Units are in amperes per metre. [Colour online.]
Thus, in spite of uncertainties in radiocarbon dates, the new paleomagnetic data, detailed geological mapping by Le Moigne et al. (2020), and uniform geochemical compositions unambiguously support the hypothesis that Tseax cone, the Satellite cone, the spatter rampart, tephra deposits, and lava flows were all components of a single contemporaneous eruptive episode.

**Combined age constraints**

The Tseax volcanic eruption took place over a short interval. The oral history and dendrochronology data constrain the event to before the end of the 19th century. The reliable written historical observations of declination (Herbert 1926) all come from a period during which the local geomagnetic field had a far greater easterly declination than the time of the Tseax eruption, 13.5°, with the implication that the eruption took place before the first direct measurements by James Cook in 1778 CE. In principle, the paleomagnetic direction could be compared with a reference secular variation curve based on written historical observations and dated archeomagnetic and paleomagnetic magnetic remanence directions. As there are no direct measurements in the region before Cook’s voyage, one can use global spherical harmonic geomagnetic models constructed from historical (Jackson et al. 2000) and archeomagnetic and paleomagnetic records (CALS3k.3, Korte et al. 2009; CALS3k.4, Korte and Constable 2011). These can be calculated for any location in northwestern North America; however, they are dominated by data from other continents. The closest compilation is from southwestern North America (Hagstrum and Blinman 2010). The directions are transferred to the study region by assuming that the geomagnetic field is 100% dipolar, converting each direction to a virtual geomagnetic pole, and then deriving the dipolar field direction for the Tseax location. Note
that Casas and Incoronato (2007) estimate a maximum relocation error of 0.25°/100 km due to non-dipole effects.

The important observation from these independent geomagnetic secular variation curves (Figs. 8B, 8C) is that they bracket the observed paleomagnetic direction from the Tseax volcanics, but the variability argues against attempting any quantitative likelihood method of age estimation. All records display a similar trend back to about 1650 CE, with a relatively uniform sweep in declination of about 7.5°/100 years. There is no apparent agreement before 1600 CE. Extrapolating 8° ± 2°/100 years declaration drift towards the north (based on the range of slopes of the declination curves in Fig. 8B), we achieve concordance with our paleomagnetic declination between 1600 and 1700 CE depending on the starting point of the extrapolation. Combining this interval with the complementary 14C constraints would suggest the Tseax eruption took place in the last quarter of the 17th century.

Conclusions

In spite of being one of Canada’s youngest and deadliest volcanic eruptions, important questions have remained, particularly whether the Tseax tephra cone was formed during two distinct eruptive episodes (14th and 18th centuries; Hiwronin 1978). The new radiocarbon data based on wood charcoal fragments from a exploratory dig in the last quarter of the 17th century.

Acknowledgements

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References


Appendix appears on the following pages.
Appendix A

Radiocarbon analyses

OxCal script for calibration of radiocarbon calendar ranges

Sequence

{Curve("Terrestrial","IntCal13.14c");

Boundary("BeforeTseax");

Phase("UnderlyingDates")

{R_Date("GSC-1124", 250,130);

R_Date("S-1046", 625,70);

{R_Date("GSC-6150", 280,50)+N(50,10);

R_Date("CUIAMS-215254", 390,15);

R_Date("CUIAMS-215255", 190,15);

{Boundary("Tseax");

Phase("UpperLimit")

{Date(1800);};};

}

Historical written and oral records

There has been speculation (e.g., Akrigg and Akrigg 1977) that the eruption of Tseax was observed by Europeans in 1775. Specifically, Lieutenant Juan Francisco de la Bodega y Quadra, commanding the schooner Sonora as part of the Hezeta Expedition, had anchored in Bucareli Bay (Prince of Wales Island, Alaska) on 24 August 1775 and noted that “The nights are exceptionally bright and mild because of seven volcanoes of snow and fire, which their vapours illuminate and temper” (Tovell 2009, p. 36). The pilot of the Sonora, Francisco Antonio Moutelle de alRua, and chaplain, Padre de la Campa, also wrote that “They felt the heat which they considered would be from the quantity of flames which were, emitted by a volcano, which erupted four or five times a day, the whole locality being illuminated at night by the glare” (de la Sierra et al. 1930, p. 241). However, as the Sonora was anchored more than 280 km west of Tseax across mountainous terrain, it is extremely unlikely that crew observed the eruption of Tseax (e.g., Higgins 2009). Despite the lack of direct written accounts, important details can be learned from local communities who have preserved information through oral traditions.

Nisga’a adaawak

Catastrophic natural disasters often become an integral part of local history (e.g., Masse et al. 2007; Cashman and Cronin 2008). In the early Indigenous communities of northwestern North America, natural disasters were often transformed into stories and legends passed from one generation to the next through oral traditions (e.g., Cashman and Cronin 2008). The catastrophic eruption of Tseax forms an important part of the Nisga’a culture, as it significantly impacted the local environment and may have caused up to 2000 fatalities. Importantly, these adaawak (traditional histories and stories) ultimately preserve a detailed observational account of the Tseax eruption (from Nisga’a oral traditions: Nisga’a Nation 2004, p. 1):

“Long ago, two children were playing down by the river. One child caught a salmon and slit open its back. The child stuck sticks into the salmon’s back, set it on fire, and returned the fish to the river. The children were amused to see the salmon swim erratically, smoke rising from its back. The other child caught a salmon and slit open its back, inserted a piece of shale, and put it back into the river. The salmon floated on its side, weighed down by the shale. The children laughed at the struggling fish. An elder happened upon the scene and warned the children: “Take care what you do. The salmon will curse you and the Creator will respond in kind”. The ground began to tremble and shake. Nature’s harmony had been upset. A scout was sent to investigate. From the top of Genuux’axwt [Fig. 1], he saw smoke and flames and ran to warn the people of their fiery destiny. In panic, some villagers fled up the mountain. Others canoed to the far side of the river but were killed by the lava. As the people watched the lava flow over their villages, Gwaxts’agat (a powerful super-natural being) suddenly emerged to block the lava’s advance. For days Gwaxts’agat fought back the lava by blowing on it with its great nose. Finally, the lava cooled and Gwaxts’agat retreated into the mountain where it remains to this day.”

In 1874, the missionary William Henry Collinson recorded a story from an old man who was “evidently over eighty years of age … that the eruption occurred when his grandfather was a boy” (Collinson 1915, p. 269):

“The river did not always flow where it does now” said he. “It flowed along by the base of the mountains on the farther side of the valley some miles away. It was there the people were encamped when the Nak-nok (Naxnok, supernatural being) of the Mountain became angry and the fire-stone flowed down. They were all busy in catching, cleaning, and cutting up the salmon, to dry in the smoke…Then, when we saw the Nak-nok of the Mountain rushing towards us clothed in fire, we fled for our lives. All that day we fled, and at sunset, as we looked back, we saw the spirit cloud with its huge wings outspread following us. We reached the foothills on this side [current location of Gitwinksihlkw, Fig. 2], which we ascended, and there we took refuge, as all were exhausted, and could run no farther. The river of fire-stone, swept on by the cloud spirit, drove the river before it across the valley, until it also reached the base of the foot-hills. Here it heaped up, the river which quenched and cooled the fire-stone, boiling and thundering, and leaving it heaped up along the bank as it is today. As night fell, the spirit cloud disappeared in the darkness, but the whole valley was on fire, which continued for many days, until all the trees, and even the ground, were consumed. It was then that we separated and settled in the two encampments of Gaaltkdamiksh (Gitlaat’x’aamiks) and Giatwikshlkh (Gitwinksihlkw).”

The anthropologist Barbeau (1935, p. 222) also reported accounts from the Nisga’a people living in the Nass Valley at the beginning of the 19th century:

“…the volcanic eruption soon after broke out. First there was smoke, like that coming out of a house, a big pillar of smoke. It was as if a house was burning on the mountain top. The people saw a big fire. The fire came down the side in their direction, but not as fast as forest fire. It moved down slowly, very slowly. It was strange and frightful. It was dangerous! There were fumes spreading ahead, and those who smelled them were smothered. They died and their body stiffened like rock. Frightened, the people of one tribe dug holes in the ground like underground lodges, and hid within, scared as they were of the mountain spirits. Likewise, the other tribe. That did not keep other people from dying of the fumes, mostly in the lower of the villages. As soon as the smoke dispersed some people ran away; a great many others stayed on. They did not suffer any more from the smoke. The fire then rolled down like a river, filled the lake, and for a time the water was a bed of flames. The stone was red and hot there for many days. As far as it went, all the way, it was flowing red. It started from the river where the people fished salmon, away up there, and ran down to the place where the canyon now is…”

These accounts highlight potentially important observations regarding the eruption of Tseax. Salmon play a central cultural and economic role in the Indigenous communities of northwestern North America. Mention of the salmon in the adaawak may suggest that the eruption occurred during the spawning season of the pink salmon (H. Nyce, personal communication, 2019), which in the Tseax River is between June and September (Nisga’a Fisheries and Wildlife Department 2018). The accounts recorded by Collinson (1915) and Barbeau (1935) suggest that the lava flow was emplaced relatively slowly, at least where it entered the Nass Valley. The lava also likely displaced the Nass River from the southern to northern...
margin of the Nass Valley. Although speculative, possible causes of the reported fatalities may be inferred, notably that “There were fumes spreading ahead, and those who smelled them were smothered” (Barbeau 1935, p. 222). This may refer to the hazards of volcanic gases, either from direct degassing of the lava or from the interaction of lava and water bodies leading to haze and smog (“laze” or “vog”) (e.g., Williams-Jones and Rymer 2015; Carlos et al. 2018).

Table A1. Locations for $^{14}$C and geochemical samples.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Location / Sample type</th>
<th>Longitude ($^\circ$W)</th>
<th>Latitude ($^\circ$N)</th>
<th>Sample type</th>
<th>Source</th>
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<td>UCIAMS-215254</td>
<td>700 m northwest of Tseax cone</td>
<td>128.91154</td>
<td>55.114327</td>
<td>C</td>
<td>This study</td>
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<tr>
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<td>750 m northwest of Tseax cone</td>
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<td>55.114107</td>
<td>C</td>
<td>This study</td>
</tr>
<tr>
<td>GSC-1124</td>
<td>Lava-encased cottonwood tree near Nass River</td>
<td>129.13798*</td>
<td>55.214033*</td>
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<td>Sutherland Brown (1969); Lowdon et al. (1971)</td>
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<td>S-1046</td>
<td>Charred trunk in spatter rampart wall</td>
<td>128.89682*</td>
<td>55.110795*</td>
<td>C</td>
<td>Wuorinen (1978)</td>
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<td>GSC-6150</td>
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<td>Unknown</td>
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<td>NR5-C</td>
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<td>Nicholls et al. (1982)</td>
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<td>55.108679</td>
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Note: C, radiocarbon; G, geochemistry.
*Approximate locations.
Fig. A1. Radiocarbon age estimates presented as $^{14}$C year BP and calibrated date. Calibrations performed using OxCal version 4.3.2 (Ramsey 2009) and the IntCal13 atmospheric curve (1σ; blue curves) (Ramsey et al. 2013). Red curve indicates the conventional radiocarbon age (±1σ) in the sample and the grey histogram represents the calibrated probability age distribution. Calendar date ranges shown for 68.2% and 95.4% probability confidence intervals (black lines beneath histogram). Plots generated from OxCal version 4.3.2 (Ramsey 2009). [Colour online.]

References
Cashman, K.V., and Cronin, S.J. 2008. Welcoming a monster to the world: Myths,


