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To cite this article: Yannick Le Moigne, Glyn Williams-Jones, Kelly Russell & Steve Quane (2020) Physical volcanology of Tseax Volcano, British Columbia, Canada, Journal of Maps, 16:2, 363-375, DOI: [10.1080/17445647.2020.1758809](https://doi.org/10.1080/17445647.2020.1758809)

To link to this article: <https://doi.org/10.1080/17445647.2020.1758809>



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Physical volcanology of Tseax Volcano, British Columbia, Canada

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ABSTRACT

Tseax volcano erupted ~250 years ago in NW British Columbia, Canada producing tephra deposits and lava flows. Field mapping has defined the stratigraphy of Tseax and the lava flow morphologies. Aerial photogrammetry and bathymetry surveys were used to create a high resolution digital elevation model of the volcano to facilitate mapping and estimates of erupted material volumes. Tseax volcano ($\sim 10.4 \pm 0.7 \times 10^6 \text{ m}^3$) comprises an outer breached spatter rampart and an inner conical tephra cone. Tseax is associated with a 32 km long and $0.49 \pm 0.08 \text{ km}^3$ basanite-to-tephrite lava flow field covering $\sim 36 \text{ km}^2$ and divided into 4 distinct lava flows with heterogeneous surface morphologies. We present a volcanological map of Tseax volcano at a scale of 1:22,500. This will serve as supporting information for further research on the eruptive history of Tseax volcano and the lava flow field emplacement.

ARTICLE HISTORY

Received 23 October 2019
Revised 16 April 2020
Accepted 17 April 2020

KEYWORDS

Tseax volcano; lava flow; mapping; DEM; bathymetry

1. Introduction

Tseax volcano (pronounced ‘See-Ax’, *Wil Ksi Baxhl Muhl* in the Nisga’a language) also known as Aiyansh volcano (Sutherland-Brown, 1969), Aiyansh River volcano or Tseax River Cone (Hanson, 1924; Hickson & Edwards, 2001) is a volcano located in northwestern British Columbia (55.11085° N , $128.89944^\circ \text{ W}$; see Main map). The volcano is associated with a 32 km long lava flow and forms the Nisga’a Memorial Lava Bed Park (*Anhluut’ukwsim Laxmihl Angwinga’a-sanskwhl Nisga’a*). The eruption of Tseax volcano, occurred in the late eighteenth century and is the second youngest volcanic eruption in Canada after Lava Fork (Elliot et al., 1981; Hickson & Edwards, 2001). This eruption is believed to be responsible for the destruction of 3 villages and the deaths of up to 2000 people (Barbeau, 1935; Higgins, 2009; Nisga’a Tribal Council & B.C. Parks Committee, 1997; Sutherland-Brown, 1969) making it one of Canada’s deadliest natural disasters (Hickson & Edwards, 2001; Higgins, 2009).

Tseax volcano and its associated lava flow field was initially mapped by Sutherland-Brown (1969) who provided a preliminary morphological map of the lava flow. Recently, new mapping has been conducted on Tseax volcano including extensive fieldwork, bathymetric surveys, high resolution mapping aerial photography and photogrammetry. Here we present a 1:22,500 volcanological map (Main map) of the

volcanic field supported by detailed descriptions of the volcanic landforms and deposits. The aim of this detailed map is to provide the context to help with understanding the eruptive dynamics of Tseax volcano (i.e. sequence and duration of the volcanic events).

2. Regional and local geology

Tseax volcano lies in the Northern Cordillera Volcanic Belt (NCVP; Main map; Edwards & Russell, 1999, 2000). The NCVP is an approximately 1200-km-long and 400-km-wide volcanic province extending from northwestern British Columbia, Canada, to eastern Alaska, USA. Volcanism in the NCVP is attributed to continental rifting of the North American plate due to changes in the relative motion of the Pacific and North American plates. More than 100 Neogene to Quaternary volcanic centres (ranging from individual tephra cones and lava flows to stratovolcanoes) with a dominantly basaltic and high alkali compositions have been mapped (Edwards & Russell, 1999, 2000). Tseax volcano is the southernmost volcanic centre of the NCVP located near the towns of *Gitwinksihlkw* and *Gitlaxt’aamiks*, about 60 km north of Terrace and ~1200 km north of Vancouver, British Columbia (Figure 1, Main map). The region surrounding Tseax volcano is part of the Coast Belt plutonic complex (Edwards & Russell, 1999; Woodsworth et al., 1991) traversed by the Nass River which is 3rd the largest

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Supplemental data for this article can be accessed <https://doi.org/10.1080/17445647.2020.1758809>

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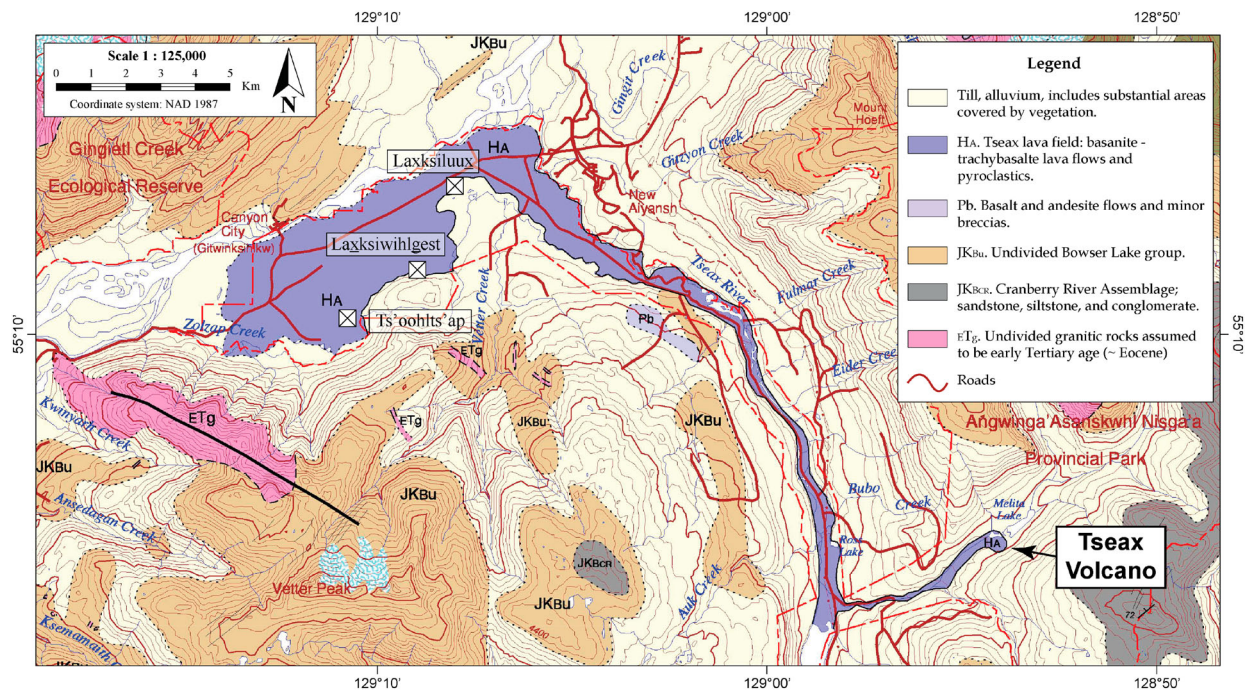


Figure 1. Local geology around Tseax volcano from the regional map by the Geological Survey of Canada. Tseax lava field is shown as a single unit and represented in purple, HA. The locations of the 3 former Nisga'a villages are shown by white squares. Modified from Evenchick et al. (2008).

river in British Columbia (Roden, 1967). Tributary to the Nass River, Tseax River flows in a narrow 15 km-long V-shaped valley that separates the Vetter peak massif from the Hazelton Mountain Ranges (Mt Hoelt, Mt Phillipa; Figure 1). Tseax is located at ~600 m above sea level in the steep sided Crater Creek valley, a 5 km-long E-W tributary valley to Tseax River valley. The surrounding area is heavily vegetated and most of the mountain slopes are covered by a thick and dense rainforest.

Tseax volcano rests on the sedimentary Bowser Lake group (dated at Jurassic-Cretaceous, JK_{BU} and JK_{BCR} on Figure 1; Evenchick et al., 2008; van der Heyden et al., 2000). These rocks are grey sandstones intercalated by dark grey and black siltstones, mudstones and conglomerates. Some Eocene plutonic rocks (ET_g, Figure 1), mostly granites and granodiorites belonging to the Coast Belt plutonic complex, are present near Tseax volcano. A few occurrences of tonalites and monzogranites have also been documented by Carter (1981). Pleistocene volcanic products including basaltic and andesitic deposits (Pb, Figure 1; Evenchick et al., 2008; van der Heyden et al., 2000) are found within 50 km around Tseax volcano. They are columnar-jointed basalts and basaltic breccias assumed to be 175-50 ka old and not associated to the volcanic history of Tseax.

3. Methodology

Fieldwork was carried out during the summers of 2016, 2017 and 2019 focussed on the Tseax volcanic field with the goal of mapping the extent, distribution,

volumes and stratigraphy of volcanic products. The volcanological map of Tseax volcano and the lava field was produced on ESRI ArcGIS 10.7 from field-work observations, bathymetry, aerial photos and satellite imagery (Figures A.1, A.2, A3).

A dataset of aerial photos was acquired (see Appendix A.1 for details) and was used to build a 3D model of the Tseax lava flow field using the Agisoft PhotoScan software. It is an advanced image-based solution for creating professional quality three-dimensional content from images (Agisoft LLC, 2019). PhotoScan is widely used in geology (e.g. Bemis et al., 2014; Gwinner et al., 2000; James & Robson, 2012) to reconstruct and visualize objects or topographic surfaces in 3 dimensions. The 3D model supported the investigation of the different surface morphologies and the calculation of the lava volumes.

The calculation of the lava flow volumes of Tseax are challenging as the base of the flow field was never observed. The volumes of the lava flows were calculated by multiplying the thickness with the area. The thickness of the lava flows in the Nass Valley and in the Tseax River and Crater Creek Valleys were estimated differently. The calculation details are in Appendix A.4. The pyroclastic edifices observed are tephra cones and a spatter rampart. We simplified the tephra cones as truncated cones with a summit circular crater and the spatter rampart as a semi-elliptical truncated cone with a semi-cylindrical inner. The calculation details are in Appendix A.4.

The lava flow field is partially submerged at the northern end of Lava Lake and Melita Lake (see

Main map). In order to fully map the extent of the volcanic products, we collected bathymetry data for these two lakes using a Lowrance Elite 5Ti chart plotter with a 10 Hz internal high-sensitivity GPS receiver with DGPS and WAAS correction.

The GIS processing of the field and remote data allowed for the production of the main map. Figure 2 shows an example of the datasets used for mapping.

4. Description and volumes of the pyroclastic deposits and lava flow morphologies

The following sections provide brief descriptions of the volcanic products within the Tseax volcanic field. All products from Tseax volcano (lava flows and pyroclastic deposits) are Fe-rich, Mg-poor basanite to trachybasalt lavas (45.8–47.4 wt% SiO₂, 14.0–16.0 wt% Fe_T, 4.2–4.6 wt% MgO, 5.6–6.3 wt% Na₂O + K₂O; Gallo, 2018; Hanson, 1924; Higgins, 2009; Le Moigne et al., 2018; Sutherland-Brown, 1969).

4.1. Tseax volcano and other pyroclastic vents

Tseax volcano (*Wil Ksi Baxhl Muhl*) has been described as two imbricated yet asymmetric volcanic cones: an outer horseshoe shaped cone and an inner tephra cone. Our mapping shows that there is, in fact, one main tephra cone partially surrounded by a spatter rampart (Figure 3). A Satellite cone is located north of Tseax volcano. A few other pyroclastic vents present near these main cones are also described below (Figure 3).

4.1.1. Spatter rampart

The spatter rampart sits on the southern slopes of Crater Creek Valley and has a horseshoe shape that opens northwards (maximum opening is ~280 m). This horseshoe feature consists of two walls ~15–25 m high (the base is not visible) and ~75–125 m long. The eastern spatter wall is oriented N170–180° and the south-western wall is oriented N150–160°. The spatter ramparts are not fully visible as they are partially collapsed and covered by dense forest, especially along the southernmost parts. The spatter edifice is 550–600 m wide and 360 m long maximum with a ~320 m wide caldera. The estimated volume is $\sim 1.1 \pm 0.3 \times 10^6 \text{ m}^3$ (Equation A.2). The spatter walls consist of reddish to brownish and black to grey agglutinated spatter, scoriaceous spatter and scoria. The spatters are generally more coalesced at the bottom of the rampart forming thick and dense layers. The outermost deposits are completely covered by forest.

4.1.2. Tephra cone

The main tephra cone is located towards the northern end of the eastern spatter wall. This cone is ~65–75 m high and ~350–400 m in diameter, consisting mainly

of black tephra (lapilli, scoria and ballistics). The summit defines a circular crater ~30 m deep and 80 m in diameter. The pyroclastics around the crater are oxidized (brownish colours). The flanks of the cone are between 30 and 35°. On the south and west flanks, several active scarps are present. Other small concentric scarps (less than 3 m high) are located on the south and west flanks. This may indicate diverse collapse events during construction of the cone. The volume of the cone is estimated at $2.8 \pm 0.4 \times 10^6 \text{ m}^3$ (Equation A.1) and the volume of ejected tephra is $\sim 6.5 \times 10^6 \text{ m}^3$ (Equation A.3).

4.1.3. Satellite cone and other pyroclastic features

About 150–200 m north of Melita Lake, there is a ~20 m high tephra cone, called Satellite cone. This cone has a diameter of ~50–55 m. A small crater (4 m deep, 7 m in diameter) occupies its summit. This small cone is asymmetric and the vent opens towards the Northwest. The summit is topped by a small layer of oxidized agglutinated scoria and accretionary lapilli. Descending towards the base, the cone is progressively covered by black tephra. We estimate that the Satellite cone has a volume of $1.7 \pm 0.1 \times 10^4 \text{ m}^3$ (Equation A.1).

Southwest of the Satellite cone, there is an alignment of 3–4 small tephra cones a few metres high. This cone alignment may represent a volcanic fissure oriented N10–20°. The small cones are completely covered by black and iridescent tephra. Nevertheless, red oxidized tephra are consistently found stratigraphically below the black tephra. The limit of the distribution of the red oxidized tephra was not found, however, they are only present on and in close proximity to the Satellite cone. This suggests that the oxidized red fountain deposits are only linked to the building of the Satellite cone. Assuming this hypothesis, the volume of ejected red tephra by the Satellite cone is $\sim 2 \times 10^4 \text{ m}^3$ (Equation A.3).

As a result, the total volume of pyroclastic deposits (pyroclastic edifices and ejected tephra) at Tseax is $\sim 10.4 \pm 0.7 \times 10^6 \text{ m}^3$.

4.2. The Tseax lavas

The large-scale elements of the lava flow field are most visible from aerial and satellite images. We used field mapping in combination with aerial photos to describe and understand the structural organization of the lava field.

4.2.1. The Tseax lava flow field

The term ‘lava flow field’ is used to designate all effusive products at Tseax. Due to its young age (~250 years), the Tseax lava flow field has undergone minimal post-emplacement erosion. Nevertheless, most of the lava flow field surface is covered by a few

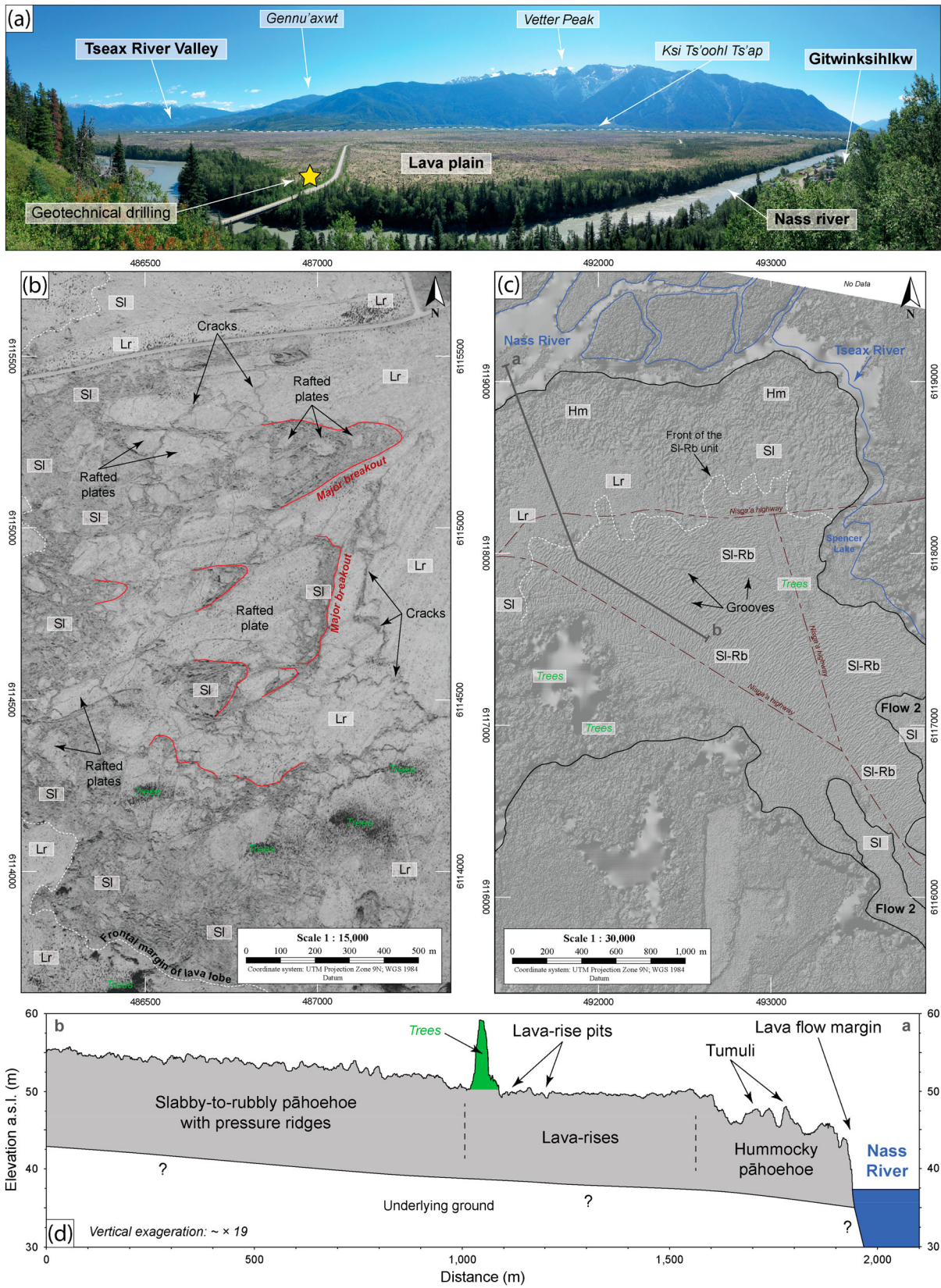


Figure 2. (a) Panoramic photograph of the lava flow plain in the Nass Valley; looking south across the Nass River above *Gitwinksihlkw*. The extent of the lava flow is delimited by the white dashed line. The field of view is about 13 km. (b) Aerial photograph used for mapping. This example shows an area with multiple major breakouts on large lava-rises and rafted plates (also called platy lava, Keszthelyi et al., 2004; Stevenson et al., 2012). *Lr*: Lava-rises; *Sl*: slabby pāhoehoe. (c) Subset of the high resolution DEM (60 cm) of Tseax lava flow. The black lines show the lava flows margins. Note the interpolated holes due to water or forests. a-b topographic profile trace shown in (d). *Sl-Rb*: slabby-to-rubbly pāhoehoe; *Hm*: hummocky pāhoehoe. (d) Topographic profile across the lava flow. The lava thickness is ~12 m according to Pursell (1993). Surface features are discussed in the text.

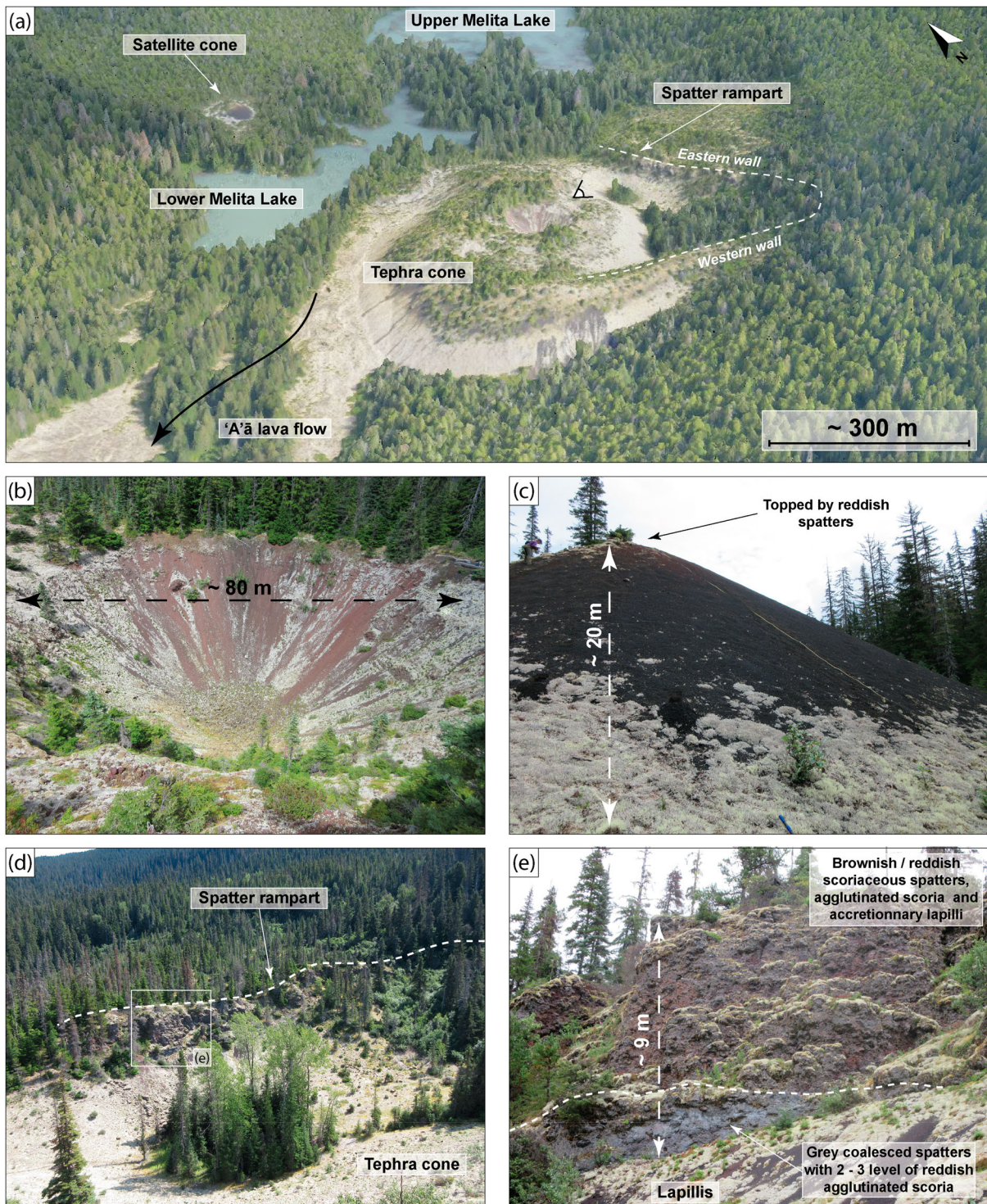


Figure 3. Images of different volcanic features in the Tseax vent area. (a) Oblique 3D view (AgiSoft PhotoScan point cloud) of Tseax volcano and surrounding area. Tseax volcano consists of a tephra cone and an outer horseshoe-shaped spatter rampart. The Satellite cone is located north of Lower Melita Lake. The symbol ‘◁’ represents the point of view of the photograph in (d). (b) Tephra cone crater (~80 m in diameter and ~30 m deep). (c) The Satellite cone is about 20 m high. (d) View of the eastern spatter wall from the tephra cone. (e) Close up view of the eastern spatter wall (~9 m high).

centimetres of green to yellow lichens and mosses. Furthermore, large portions of the lava flows are already covered by dense rainforest, e.g. the vast majority of the lava in Tseax River Valley. Moreover, in some places the lava underlies rivers, streams (e.g. Tseax River, Vetter Creek) and a few small lakes or ponds such as Ross Lake in the Tseax River Valley. The

outline of the Tseax lava flow field is nevertheless easily identified from field observations and aerial or satellite imagery.

The lava flow field originates from the vent area in Crater Creek Valley, where it forms a dam (made of a few small lava islands) separating Lower and Upper Melita Lake (*T'aam Baxhl Muhl*).

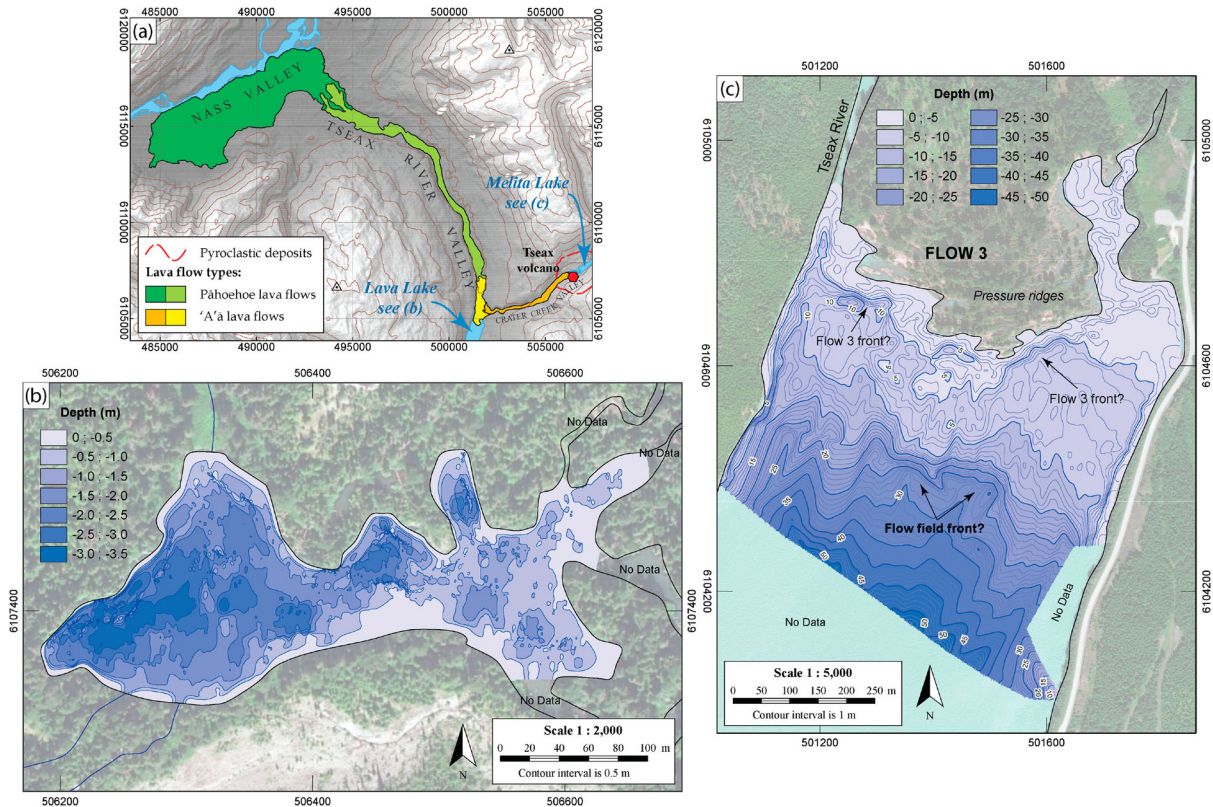


Figure 4. (a) Overview map of Tseax lava field. Bathymetry of (b) Lower Melita Lake and (c) Lava Lake. Bathymetry on Lower Melita Lake does not show any particular volcanic or lava features. On the northern shores of Lava Lake, we can identify the termination of Flow 3 at ~ 7 m depth and the termination of the flow field at ~ 27 m depth. Coordinate system: WGS 1984 / UTM Zone 9N (metres).

Investigation of the Upper Melita lake by canoe and paddle board has shown that the lava does not go more than ~ 150 m to the east. Bathymetry shows that Lower Melita lake is very shallow (~ 2 m deep on average), with the deepest part (reaching 3.5 m) found near north-western shores (Figure 4(b)). The chaotic floor of the lake suggests that it consists of lava. The lava-filled Crater Creek Valley is about 5 km long on a slope of $\sim 4^\circ$. Based on the topographic slopes on both sides of Crater Creek Valley, we estimate that the average depth of the lava in this valley is 30.5 ± 5.5 m. At the bottom of Crater Creek Valley, the lava flow debouches in the Tseax River Valley. There, the lava creates a significant dam on Lava lake. Bathymetry measurements performed on Lava lake show that the lava ends 250 m south of the shore at a depth of about 25–30 m (Figure 4(c)). The lava descends northwards along the narrow Tseax River Valley (average slope of $\sim 1.5^\circ$ on 15 km), reaching about 22 km in length with an estimated average lava depth of 21 ± 3 m. The lava then spreads out towards the southwest in the Nass Valley flood plain. There the lava forms a ~ 11 km long and up to 3.8 km wide lava plain (slope of 0.1 – 0.2°). Eastwards, the lava flow is bordered by Tseax River and Spencer Lake. The Nass River marks the northern margin of the lava flow with no lava found on the northern side of the Nass

River. A 4–7 m high lava cliff about ~ 5 km in length is one of the most notable and spectacular features of the Tseax lava flow field, forcing the Nass River to form a narrow canyon near *Gitwinksihlkw* (Figure 2(a)). The western margin of the lava field is entirely covered by rainforest, but easily mapped in the field and from aerial photos. The southern margins in the Nass Valley corresponds to *Ksi Ts'oohl Ts'ap* creek and marshlands. A significant part of the lava flow field in the Nass Valley is covered by recent forest growth in the area where Vetter Creek disappears beneath the lava. The depth of the lava in the Nass Valley is difficult to estimate, however, geotechnical drilling indicates a lava depth of 12 m near the road bridge to *Gitwinksihlkw* (Figure 2(a); Pursell, 1993). Therefore, we consider an average thickness of 12 ± 2 m for the lava in the Nass Valley as some parts of the flow may have been emplaced on irregular topography or may have undergone different magnitude of inflations.

In total, the Tseax lava flow field covers ~ 36 km². Using our thickness estimates in Crater Creek, Tseax River and Nass Valleys, we calculate a volume of 0.49 ± 0.08 km³ for the entire lava flow field, most of the volume being in the Nass Valley. This correlates with the 0.5 km³ previously estimated by Hanson (1924) and Higgins (2009) and the 0.455 km³ estimated by Sutherland-Brown (1969).

4.2.2. The 4 Tseax lava flows

We define ‘lava flow’ as an individual outpouring of lava from the vent, likely corresponding to an individual eruptive event. The margins of a lava flow are generally steep and easily identifiable in the field. Despite being emplaced during a single eruption, the Tseax lava flow field can be divided into 4 distinct lava flows, named Flow 1, Flow 2, Flow 3 and Flow 4 (see [Main map](#)). The main geometrical characteristics of the lava flows are reported in [Table 1](#).

Flow 1 is the longest, most voluminous and stratigraphically earliest lava flow. It is a phenocryst-poor pāhoehoe lava 31.6 km in length with an average thickness of 12 ± 2 m in the Nass Valley. Flow 1 forms the entire lava plain in the Nass Valley, 2.8 km wide on average and ~ 12 km long. We suggest that the thickness of Flow 1 increases to 14 ± 2 m in Tseax River and Crater Creek Valleys due to narrowing. This results in a volume of 0.41 ± 0.07 km³. Flow 1 thus accounts for $\sim 84\%$ of the total flow field volume.

Flow 2 is a 21.2 km long phenocryst-poor pāhoehoe lava flow. Located along Crater Creek Valley, it ends near the mouth of Tseax River Valley where it forms two distinct ~ 2 km long lava lobes. We estimate a thickness of 7 ± 1 m. Despite the length, we estimate a volume of 0.06 ± 0.01 km³, representing $\sim 13\%$ of the total flow field volume.

Flow 3 is a 7.2 km long phenocryst-rich ‘a‘ā lava flow descending from the volcano in Crater Creek Valley and terminating in Tseax River Valley near Ross lake. We estimate an average thickness of 3 ± 1 m in Tseax River Valley and 4.5 ± 1 m in Crater Creek Valley. Therefore, the volume of this flow is 0.009 ± 0.002 km³, accounting for $< 2\%$ of the total flow field volume.

Flow 4 is a phenocryst-rich ‘a‘ā lava flow and the stratigraphically uppermost flow of the Tseax lava flow field. It is 5.3 km long and located only in Crater Creek Valley. This ‘a‘ā flow ends where Crater Creek Valley debouches in Tseax River Valley but does not reach Lava Lake. We estimate a thickness of 4.5 ± 1 m which gives a volume of 0.006 ± 0.001 km³. This corresponds to $\sim 1\%$ of the total flow field volume.

Table 1. Type (Pāhoehoe or ‘A‘ā), length, surface area and volume of the Tseax lava flow field and the 4 identified individual lava flows.

Flow #	Type	Length (km)	Surface Area (km ²)	Volume	
				(km ³)	Error (km ³)
Flow 1	Pāhoehoe	31.6	26.97	0.41	0.07
Flow 2	Pāhoehoe	21.2	6.74	0.06	0.01
Flow 3	‘A‘ā	7.2	1.11	0.009	0.002
Flow 4	‘A‘ā	5.3	1.22	0.006	0.001
Total		31.6	34.06	0.49	0.08

4.3. Subaqueous lavas – bathymetry

Melita Lake (*T'aam Baxhl Muhl*, [Figure 4\(b\)](#)), near Tseax volcano, was formed after damming of Crater Creek by the lava flow. Melita Lake consist of two lakes, Lower and Upper Melita Lake (~ 0.05 km² and ~ 0.2 km², respectively). Lower Melita lake is separated from Upper Melita Lake by a series of small and heavily vegetated lava islands. The shore of Lower Melita Lake consists of large blocks of pāhoehoe, in some places completely covered by clay and silt. Field observations suggest all the lava exposed along the shoreline and on the islands separating Lower and Upper Melita Lakes are from the same flow unit. Petrographic analysis of a lava block sampled along the northern shore of Melita Lake shows a phenocryst-poor lava, similar to Flow 1 and Flow 2. The deepest part of the lake is found near the western shores (~ 3.5 m deep). The eastern part of the lake is shallower although two deep spots are located close to the central and northeast shores. The bathymetry results show a relatively chaotic floor with no particular volcanic features. Collapsed lava blocks and agglutinated tree logs are present along the western and northern shores of the lake.

Lava Lake (*Sii Tax*, [Figure 4\(c\)](#)) is located in Tseax River Valley at the bottom of Crater Creek Valley. The Tseax River debouches from the northwestern extremity of the lake. While Lava Lake already existed before the eruption of Tseax (D. Nyce, personal communication), it's depth increased due to damming of Tseax River by Flows 1, 2 and 3. Pressure ridges of Flow 3 form the northern shores of Lava Lake. We estimate that Flow 3 ends ~ 20 – 50 m from the northern shore at a depth of about 7 m. The flow field terminates ~ 250 – 270 m from the northern shores at ~ 27 m depth.

4.4. Lava flow surface morphologies

Lavas of the Tseax flow field can be classified according to their surface morphologies. From field observations, we distinguished pāhoehoe and ‘a‘ā flows with numerous distinctive surface morphologies. In this section, we present short definitions of these surface morphological features as well as their location. We refer the reader to the [Main map](#) for a better understanding. [Figure 5](#) shows photographs of representative surface morphologies seen on the Tseax lava flow field.

The main categories of surface morphologies are ‘a‘ā (Flow 3 and Flow 4) and pāhoehoe lava flows (Flow 1 and Flow 2, see [Main map](#)). We identified hummocky (*Hm*), lava-rises (*Lr*), slabby (*Sl*), hummocky-to-lava-rises (*Hm-Lr*) and slabby-to-rubbly (*Sl-Rb*) pāhoehoe surfaces. The general characteristics of the lavas are described in details in Appendix B. The area occupied by these surface morphologies are indicated in [Table 2](#).



Figure 5. Representative photographs of different surface morphologies. Note that the lava is covered by green to yellow moss and/or lichen. (a) 'A'ā lava flow at the bottom of Crater Creek Valley. (b)-(h) These photographs were taken on the Nass Valley lava plain. (b) Hummocky pāhoehoe (*Hm*). (c) A large lava-rise area (*Lr*). (d) Hummocky-to-lava-rises pāhoehoe (*Hm-Lr*). (e) Slabby pāhoehoe (*Sl*). (f) Slabby-to-rubbly pāhoehoe (*Sl-Rb*). (g) Lava-rise pit ~2 m deep and ~15 m in diameter. (h) A surface plate; note the disrupted slabs surrounding the plate.

Table 2. Area occupied by the different pāhoehoe surface morphologies in the Nass Valley.

Surface morphology	Area (km ²)	Area (%)
Hummocky Pāhoehoe (<i>Hm</i>)	5.5	22
Lava-rises (<i>Lr</i>)	4.6	18
Hummocky-to-lava-rises Pāhoehoe (<i>Hm-Lr</i>)	2.5	10
Slabby Pāhoehoe (<i>Sl</i>)	8.2	33
Slabby-to-rubblly Pāhoehoe (<i>Sl-Rb</i>)	3.7	15
Rafted plates	0.5	2

5. Conclusions

A 1:22,500 map of Tseax volcano and its immediate surroundings is presented here and provides the first detailed and comprehensive description of the volcanic products. The mapping and characterization of the volcanic products was conducted over three field seasons with the help of high-resolution aerial photographs, photogrammetry and bathymetric surveys. The map is designed to document and characterize the lava features and the lava flow surface morphologies.

Tseax volcano consists of two imbricated volcanic structures (a central tephra cone and an outer spatter rampart) located at about 600 m a.s.l. in Crater Creek Valley. The pyroclastic products cover a surface of > 10 km². Tseax volcano is associated with a 0.49 ± 0.08 km³ and 32 km long lava flow field. We identified 4 lava flows, likely corresponding to 4 different eruptive events. Stratigraphically, we have from bottom to top: 2 long and voluminous pāhoehoe lava flows (Flow 1 and Flow 2, 0.41 ± 0.07 and 0.06 ± 0.01 km³, respectively) and 2 shorter ‘a’ā lava flows (Flow 3 and Flow 4, 0.009 ± 0.002 and 0.006 ± 0.001 km³, respectively). The pāhoehoe flows show several distinctive surface morphologies namely: hummocky, lava-rises, slabby, hummocky-to-lava-rises, slabby-to-rubblly pāhoehoe and rafted plates. Usually, we observe a complete transition between these surface morphologies in a lava lobe unit within a flow. The main sharp disturbances are marked by major breakouts on the large lava-rises that disrupted the smooth upper crust into slabby pāhoehoe.

The volcanological map for the Tseax volcanic field represents fundamental data required to understand the sequence and duration of events that ultimately led to the Nisga’a fatalities. Furthermore, the described lava flow surface morphologies are critical information for quantification of eruption parameters, key for numerical modelling of lava flow emplacement. This work is also an important contribution towards hazard assessment as forestry and fishery industries, tourist attractions and ~1000 people are located in close proximity to the volcano.

Software

The Digital Elevation Model of the Tseax lava flow field was created with AgiSoft PhotoScan Professional 1.2.4.2339 and CloudCompare v2.8. Bathymetric data

was analysed in Reefmaster underwater mapping software. Bathymetry and geological maps were produced using ESRI’s ArcGIS 10.7. The maps were edited and structured using Adobe Illustrator CC 2015.

Acknowledgements

Many thanks to Dr. Deana Nyce of the Wilp Wilxo’oskwhl Nisga’a Institute (WWNI) for her continued and enthusiastic support. Mansel Griffiths and Harry Nyce (Nisga’a Lisims Government) generously shared their extensive knowledge of Tseax and the Nisga’a Lava Beds. We are grateful to Irene Squires (WWNI) for her generous hospitality, to Rachel Warwick, Rose Gallo, Alex Wilson and Sarah Aufrère for assistance during field work, and to Margaret Vanderberg for her assistance in providing historical information and field notes. We also thank G. B. M. Pedersen, R. Pierosan and A. Labetski for their constructive reviews. This work was supported by the WWNI, the Nisga’a Lisims Government and an NSERC Discovery grant to G. Williams-Jones. This research was carried out as part of B.C. Parks / NLG permit 108312.

Disclosure statement

No potential conflict of interest was reported by the author (s).

Funding

This work was supported by NSERC Discovery [grant number RGPIN-2016-03953].

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Appendices

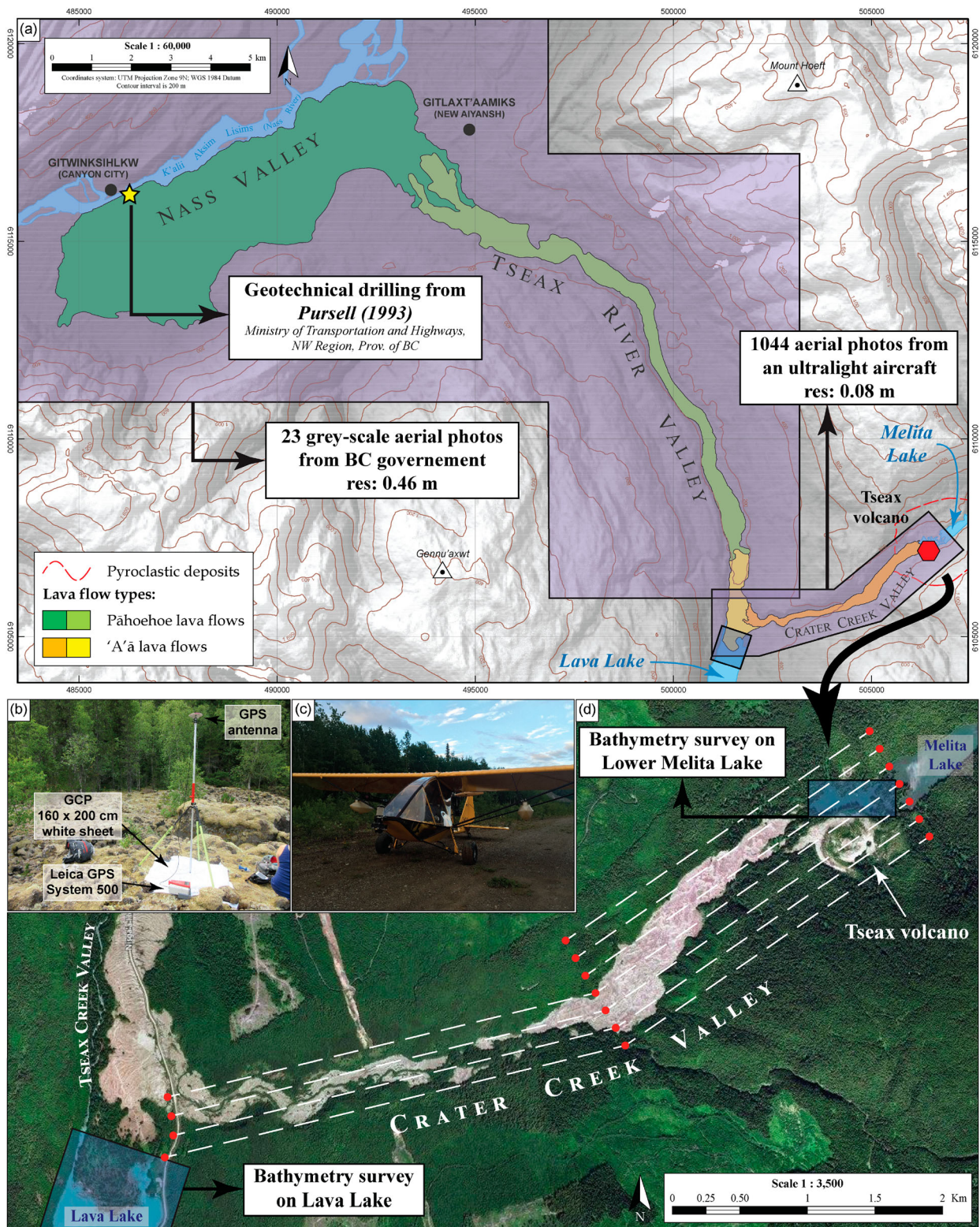


Figure A.1. (a) Locations of the aerial photographic datasets used to construct the DEM. The yellow star is the location of the only geotechnical drilling on the lava flow field. (b) Acquisition of a GCP on the lava flow. (c) Ultralight aircraft used to take aerial photographs above Crater Creek Valley and Tseax volcano. (d) Locations of the flight lines and bathymetry surveys.

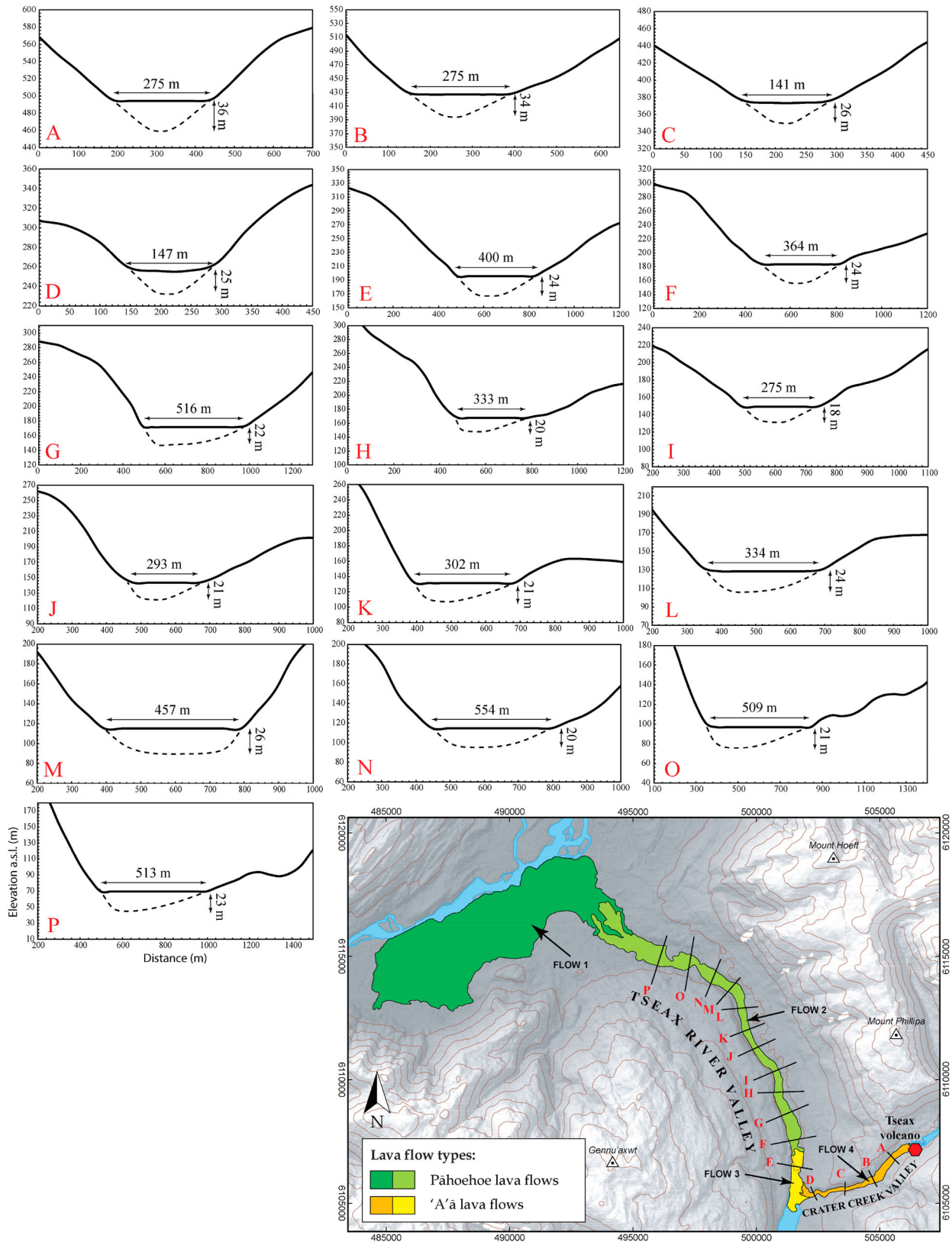
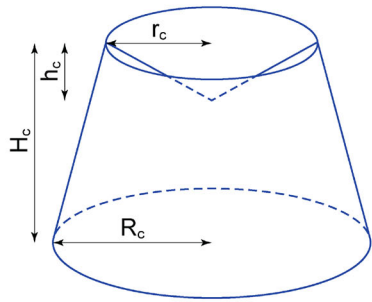


Figure A.2. Topographic profiles perpendicular to the lava flow along Crater Creek and Tseax River valleys made to estimate the flow thickness. The map shows the location of the profiles.

Tseax tephra cone and Satellite cone
truncated cone with a summit circular crater



Tseax spatter rampart
semi-elliptical truncated cone with a cylindrical inner caldera

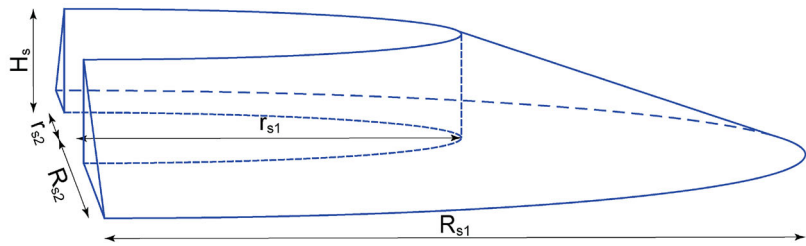


Figure A.3. Schematic of the tephra cones and spatter rampart.