Glacial influences on morphology and eruptive products of Hoodoo Mountain volcano, Canada

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Abstract: Hoodoo Mountain volcano (HMV), a Quaternary composite volcano in northwestern British Columbia, is a well-exposed example of peralkaline, phonolitic ice-contact and subglacial volcanism. Its distinctive morphology and unique volcanic deposits are indicative of subglacial, within-ice, and/or ice-contact volcanic eruptions. Distinct ice-contact deposits result from three different types of lava–ice interaction: (1) vertical cliffs of lava, featuring finely jointed flow fronts up to 200 m in height, resulted from lava flows being dammed and ponded against thick masses of ice; (2) pervasively-jointed, dense lava flows, lobate intrusions, and domes associated with mantling deposits of poorly-vesiculated breccia are derived from volcanic eruptions contained beneath relatively thick ice; and (3) an association of pervasively-jointed, highly-vesicular lava flows or dykes encased by vesicular hyaloclastite of identical composition formed by eruption under and/or through relatively thin ice. The distribution of these three deposit types largely explains the distinctive morphology of Hoodoo Mountain and can be used to reconstruct variations in ice thickness surrounding the volcano since *c.* 85 ka. Our analysis suggests that at *c.* 85 ka Hoodoo Mountain erupted underneath ice cover of at least several hundred metres. At *c.* 80 ka eruptions were no longer subglacial, but the edifice was surrounded by ice at least 800 m high that dammed lava flows around the perimeters of the volcano. After a period of eruptions showing no apparent evidence for ice interaction, from <80 to >40 ka, subglacial eruptions began again, signalling the build-up of regional ice levels. Local ice thickness during these eruptions may well have been over 2 km thick.

The morphology of volcanoes and the character of volcanic deposits ascribed to subglacial volcanism are functions of the type (i.e. wet-based v. dry-based; Smellie 2000) and thickness of ice (i.e. thin v. thick; Smellie & Skilling 1994), the length of time over which the edifice developed and the history of ice fluctuations during that development, and the chemical composition of the erupted lavas. Our current understanding of subglacial eruption processes and our models for the formation of subglacial volcanic deposits are heavily influenced by observations and data collected on relatively small, basaltic volcanoes erupted in glacial environments (e.g. Mathews 1947; Jones 1969*a*, 1970; Allen *et al.* 1982; Smellie 2000). Basaltic subglacial deposits are the most widespread and have been extensively described from Iceland (Jones 1969*a*, 1970; Allen *et al.* 1982; Bergh & Sigvaldason 1991; and references therein), British Columbia (Mathews 1947; Allen *et al.* 1982; Hickson *et al.* 1995; Moore *et al.* 1995; Souther 1992; Hickson 2000; and references therein), South America, (Larsson 1940), Antarctica (LeMasurier 1976; Smellie *et al.* 1993; Skilling 1994; Smellie & Hole 1997), and Hawaii (Porter 1987). Smellie (2000) has recently provided a comprehensive review of the unique features of mafic subglacial deposits.

Many subglacial volcanoes, however, are not basaltic in composition. These include andesitic stratovolcanoes of the Cascade volcanic arc (Mathews 1951, 1952*a*,*b*; Lescinsky & Fink 2000) and in Argentina (Larsson 1940), dacitic and rhyolitic centres in Iceland (Gronvold 1972; Furnes *et al.* 1980; Tuffen *et al.* 2001) and peralkaline phonolitic to rhyolitic edifices in north-western British Columbia (Souther 1992; Edwards 1997; Edwards *et al.* 2000) and in Antarctica (LeMasurier 1976, 1990). Since many of these studies have documented features not commonly seen at basaltic subglacial centres (e.g. Furnes *et al.* 1980), the models and principles developed for subglacial basaltic volcanism

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cannot necessarily be used as a paradigm for interpreting the processes attending subglacial eruption of more siliceous lavas.

Hoodoo Mountain volcano (HMV) is a Quaternary phonolitic volcano situated in northwestern British Columbia (Fig. 1; Souther 1992; Edwards 1997; Edwards & Russell 1997; Edwards *et al.* 2000). The volcano comprises fragmental and non-fragmental phonolitic volcanic rocks and was formed during the last 100 ka. Much of its eruptive history involved volcano–ice interaction, which accounts for its distinctive shape and many of its volcanic deposits. Detailed studies of HMV offer unique advantages over other peralkaline subglacial volcanic edifices, especially those found in Antarctica, because it is relatively free of ice at most elevations. Hoodoo Mountain volcano exposes a nearly complete stratigraphic sequence from the base of the volcano to the top (except for the present-day ice cap), allowing for detailed study of its overall morphology, as well as the origin of volcanic deposits resulting from subglacial volcanism (Edwards 1997; Edwards & Russell 1997).

The purpose of this paper is threefold. First, described in detail are three associations of volcanic deposits that result directly from interactions between phonolitic volcanism and ice at Hoodoo Mountain. Second, the physical characteristics of these deposits are used to constrain conceptual models for their formation. Third, the morphology of the volcano and the distribution of these ice-contact volcanic deposits are used to establish the syn-eruptive presence and thickness of bounding ice masses through time at HMV. In this regard, the volcanology of

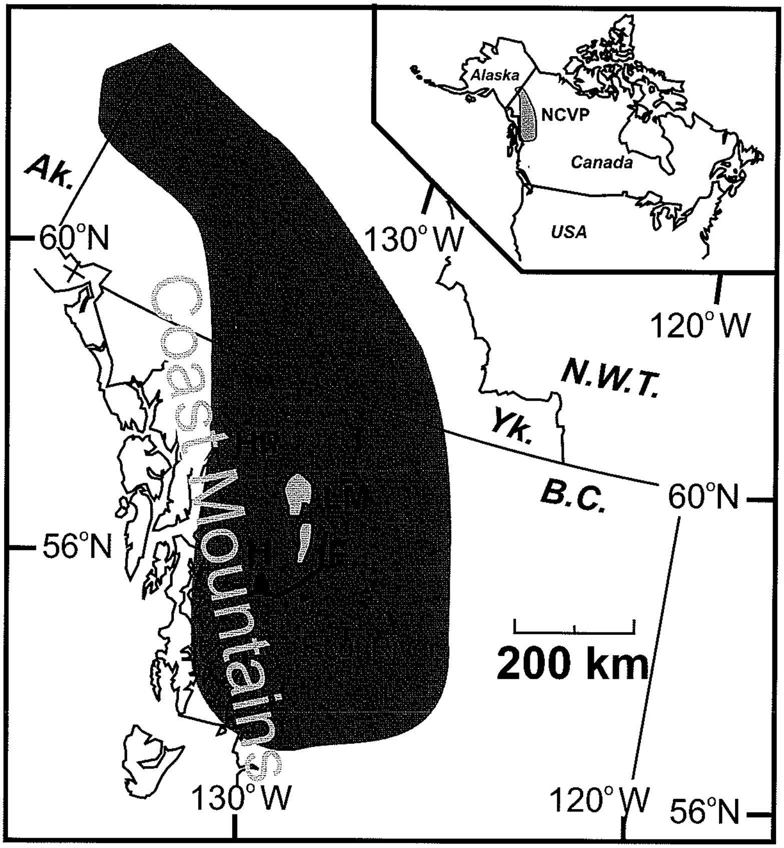


Fig. 1. Map showing the location of Hoodoo Mountain volcano (H). It is situated in the southern part of the northern Cordilleran volcanic province (NCVP in inset; Edwards & Russell 2000) and is considered to be part of the Stikine subprovince, which includes Mount Edziza (E) and Level Mountain (LM). The Tuya–Teslin volcanic district (T) comprises several of the tuya volcanoes that were initially described by Mathews (1947). Other abbreviations: Ak, Alaska; N.W.T, North West Territories; B.C., British Columbia; HP, Heart Peaks.

Hoodoo Mountain traces variations in the thicknesses of regional ice sheets within the Iskut region since *c.* 85 ka.

Hoodoo Mountain volcano (HMV)

Hoodoo Mountain is located immediately north of the Iskut River, in the Coast Mountains of north-western British Columbia, Canada (Fig. 1) and comprises a maximum volume of 17.3 km^3 of Quaternary volcanic rocks. HMV lavas have maintained a relatively uniform chemical and mineralogical composition over 85 ka. All lava and glass samples from HMV are classified as phonolite or trachyte, are nepheline and acmite normative, and have a (micro-) phenocryst assemblage of alkali-feldspar, clinopyroxene, and magnetite. The phonolite at HMV was probably derived from alkali olivine basalt via assimilation–fractional crystallization processes (unpublished information of the authors). The stratigraphy comprises fragmental and non-fragmental volcanic rocks including fine- to medium-grained subglacial and subaerial lava flows, domes, spines, dykes, and pyroclastic deposits (Fig. 2). The formation of HMV overlaps, in space and time, with the formation of the Iskut volcanic field, which encompasses nine small-volume, basaltic centres (Russell & Hauksdottir 2000). HMV is also part of the peralkaline Stikine subprovince of the northern Cordilleran volcanic province, which includes Edziza and Level Mountain volcanic complexes (Fig. 1; Edwards & Russell 2000).

Hoodoo Mountain volcano has had at least six eruptive cycles since *c.* 85 ka (Edwards & Russell 1997, 2000). Individual eruptive cycles have been distinguished on the basis of changes in the physical character of eruptive products (e.g. lava flows v. lava flows and domes with associated breccias v. pyroclastic deposits), observed stratigraphic relationships, and results from ^{40}Ar/^{39}Ar geochronology (cf. Villeneuve *et al.* 1998; Edwards *et al.* 2000). The six eruptive episodes are summarized as follows (Fig. 2a):

(a) Volcanism began at Hoodoo at least as early as *c.* 85 ka with eruptions that produced aphanitic lava flows, domes, and breccia deposits.
(b) By *c.* 80 ka volcanism was manifest as a series of aphanitic lava flows that formed massive cliffs at low elevations near the base of the volcano.
(c) Pyroclastic deposits, up to 100 m thick on the north and west sides of the edifice, formed between 80 and 54 ka.
(d) Aphanitic lava flows erupted at *c.* 54 ka directly on top of the pyroclastic deposits.
(e) Between 54 and 30 ka, volcanism produced two distinct types of lava–breccia associations, one between 54 and 40 ka, and the other probably slightly younger, between 40 and 30 ka.
(f) Eruptions of highly porphyritic lava flows as young as 9 ka mark the last eruptive cycle at HMV.

Three types of glacial volcanic deposits at HMV

The focus of this research is on associated volcanic deposits produced during the (a), (b) and (e) eruptive cycles at HMV. These three eruptive intervals comprise deposits that have characteristics indicative of lava–ice interactions. Specifically, they represent the products of three distinct ice-contact relationships: (1) the damming and ponding of lava flows against ice; (2) subglacial volcanic eruptions producing an association of lavas and breccias; and (3) sub- to supraglacial eruptions driven, in part, by vesiculation and expansion of a magmatic gas phase. Each of the three deposit associations below are described below.

Ice-dammed lava (IDL)

One of the most prominent features of Hoodoo Mountain is the set of cliffs that bound and define the base of the volcano (Kerr 1948; Souther 1992; Edwards *et al.* 2000). These cliffs comprise massive, aphanitic to sparsely porphyritic trachyte and phonolite lavas that show prominent flow banding and pervasive, well-developed jointing. One of the cliff-forming lavas is dated at *c.* 80 ka (Villeneuve *et al.* 1998). This stratigraphic unit is directly overlain by pyroclastic deposits and lava flows that appear to result from younger subaerial eruptions at *c.* 54 ka.

The lava cliffs vary in height from 50 m to greater than 200 m (Fig. 3a) and they almost completely circumscribe the volcano (Fig. 2). On the north side of HMV, the lower cliffs are partly buried by recent, unconsolidated deposits of glacially-derived sediments and Twin Glacier. On the eastern and south-eastern sides the lower cliffs are obscured by the youngest (post-glacial, *c.* 9 ka) lava flows (Fig. 2a). The lava cliffs create the lowest 'step' in the overall terraced topographic profile of HMV, which is particularly clear on the eastern side of the

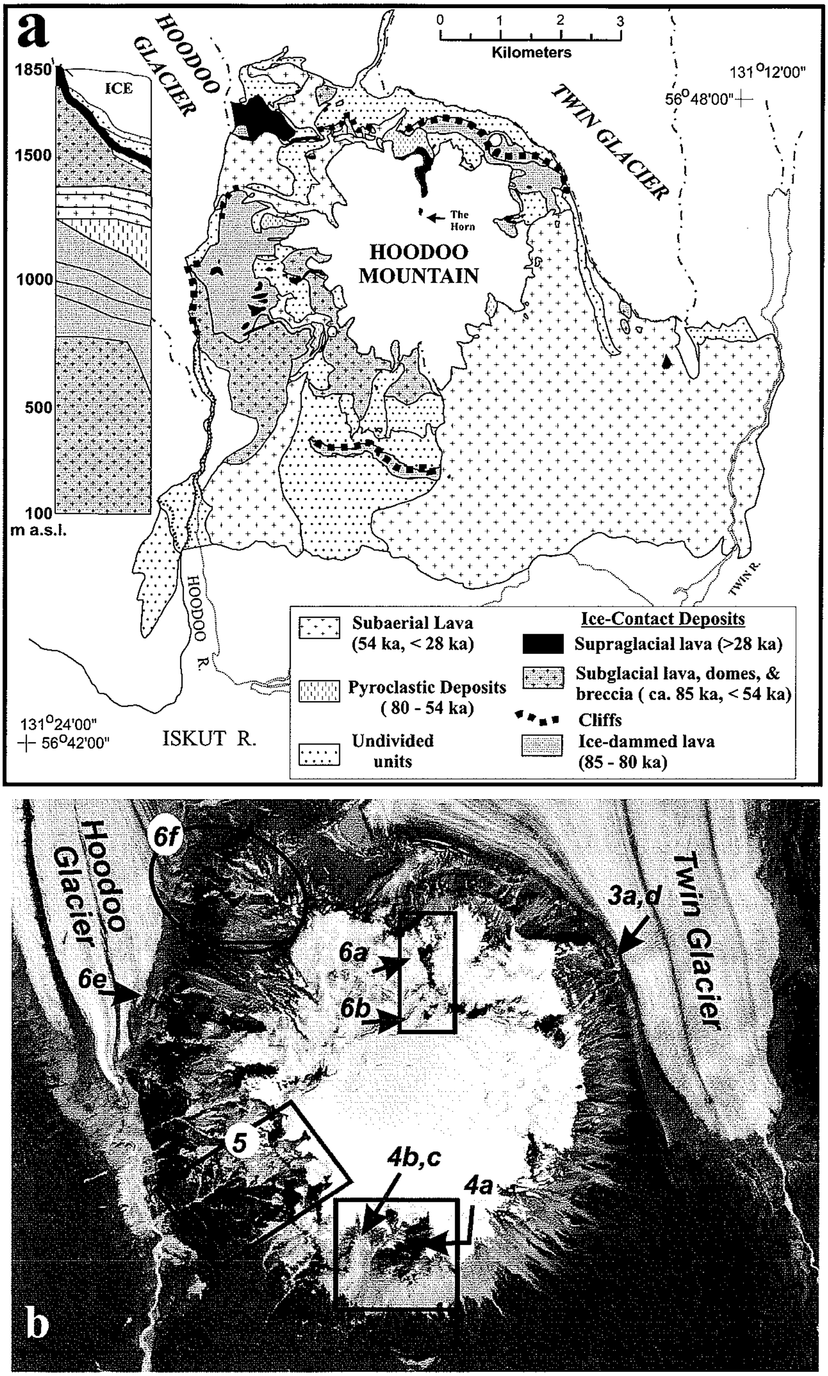


Fig. 2. Geology and physiography of Hoodoo Mountain volcano. (**a**) Geological map and simplified stratigraphic column, modified from Edwards *et al.* (2000) and highlighting ice-contact deposits described in the text. Locations of prominent cliffs defined by ice-dammed lava flows also indicated (coarse dashed line; see Fig. 3). (**b**) Aerial photograph of Hoodoo Mountain (derived from British Columbia Airphoto BC82022) showing the physiography of the volcano in plan view. Boxes delineate areas containing the outcrops with features shown in figures in this paper or discussed in text. Numbers correspond to figure numbers.

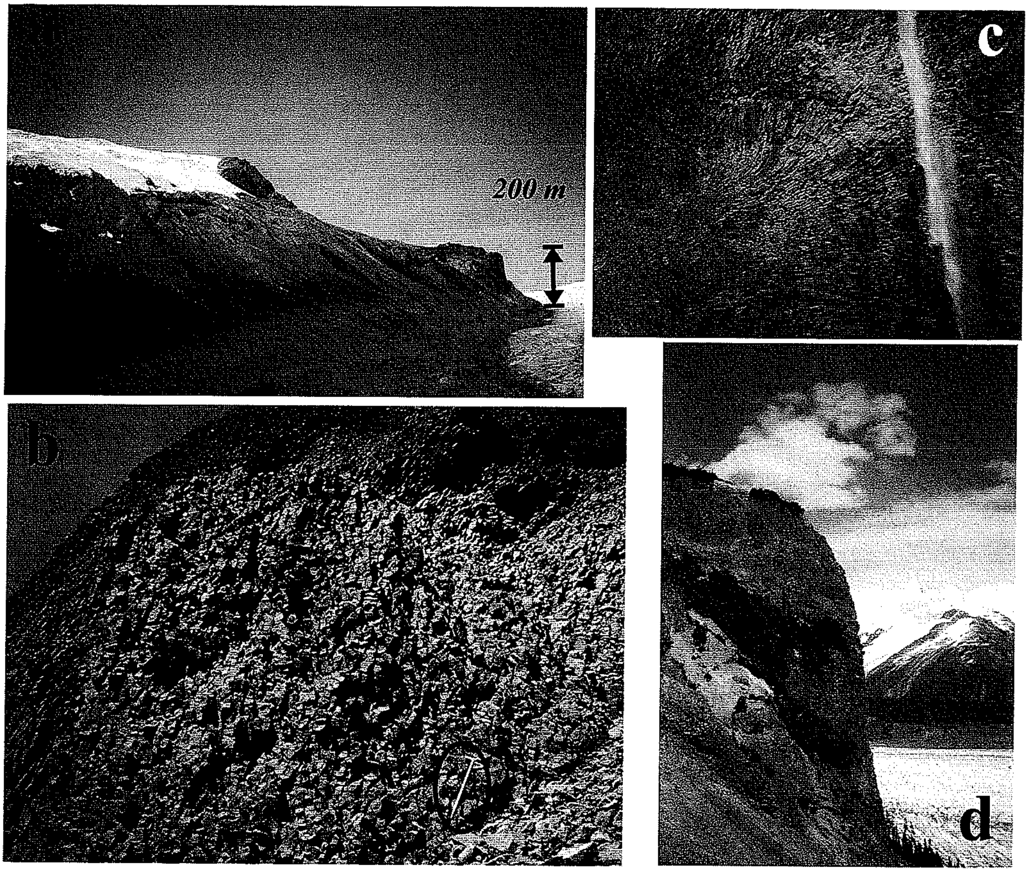


Fig. 3. Field photographs showing the character of the lower and upper cliffs produced by damming and ponding of lava flows by ice at Hoodoo Mountain (see Fig. 2b for location). (**a** & **d**) Views of prominent cliffs, 100–200 m in height, forming the base of HMV, interpreted as original quenched surfaces of lava flows that ponded against adjacent wall of former ice. (**b**) Cliffs composed of dense, aphanitic phonolitic lava featuring pervasive, fine-scale, horizontal columnar jointing. Note ice axe in bottom right for scale. (**c**) Intense radiating cooling joints on cliff face; field of view of photograph is 40–50 m.

mountain (Fig. 3a). The elevation of the upper surfaces to these cliffs of lava varies between 700–800 m asl on the west and south side, and about 1200 m asl on the north side. Taken together, these prominent cliffs of massive lava flows constitute the 'lower cliffs' and they are a discrete stratigraphic interval relative to the younger deposits of lava and breccia (see below) that form a second 'upper' set of cliffs near the top of HMV.

The cliffs of massive lava show a series of important genetic features. Specifically, samples from some cliff faces show the lava to be cryptocrystalline (nearly glassy) and pervasively jointed; both features are indicative of accelerated cooling or quenching. The cooling joint patterns and the variable nature of the orientations of columnar jointing are, in particular, diagnostic. Typically the cliff faces comprise a myriad of polygonal cooling joints with diameters generally less than 30 cm (Fig. 3b). The joints are oriented perpendicular to the vertical cliff face (cf. 'cordwood' jointing of Lescinsky & Fink 2000); in several faces the cliffs are characterized by radiating patterns of small-diameter columnar jointing (Fig. 3c). The cliffs commonly appear to be formed by a single lava flow, although several exposures (south side of HMV; Fig. 2) show at least two separate lavas. Massive slope failures on the SW flanks of HMV have exposed cross-sections through the length of the lavas that form these 'lower cliffs'. In cross section, it appears that the lava flows began as relatively thin (<30 m) flows but thickened substantially as they moved downslope from the vent. The marked thickening occurs despite the overall slope of the substrate remaining virtually constant.

The observations presented above are consistent with the inferences of previous workers (Kerr 1948; Souther 1992) that these lower cliffs represent ice-dammed lava flows. The lava flows, which appear to have originated from vents now buried beneath the main mass of the volcano, flowed down a relatively gentle incline over previously erupted subglacial deposits of lava and breccia (see next section), and then were dammed by thick ice along the flanks of the volcano. Assuming that all of the lower cliffs formed during one eruptive episode, Hoodoo Mountain must have been completely surrounded by ice at *c.* 80 ka.

Subglacial lava flows, domes and breccia (SGL)

Another distinctive manifestation of volcano–ice interaction at HMV is an association of highly jointed lava flows, domes and spines that are commonly encased in deposits of low-vesicularity, monomict breccia (Fig. 4). Rocks of this association are found at the very base and top of the edifice. At lower stratigraphic levels (and elevations) the association is buried except

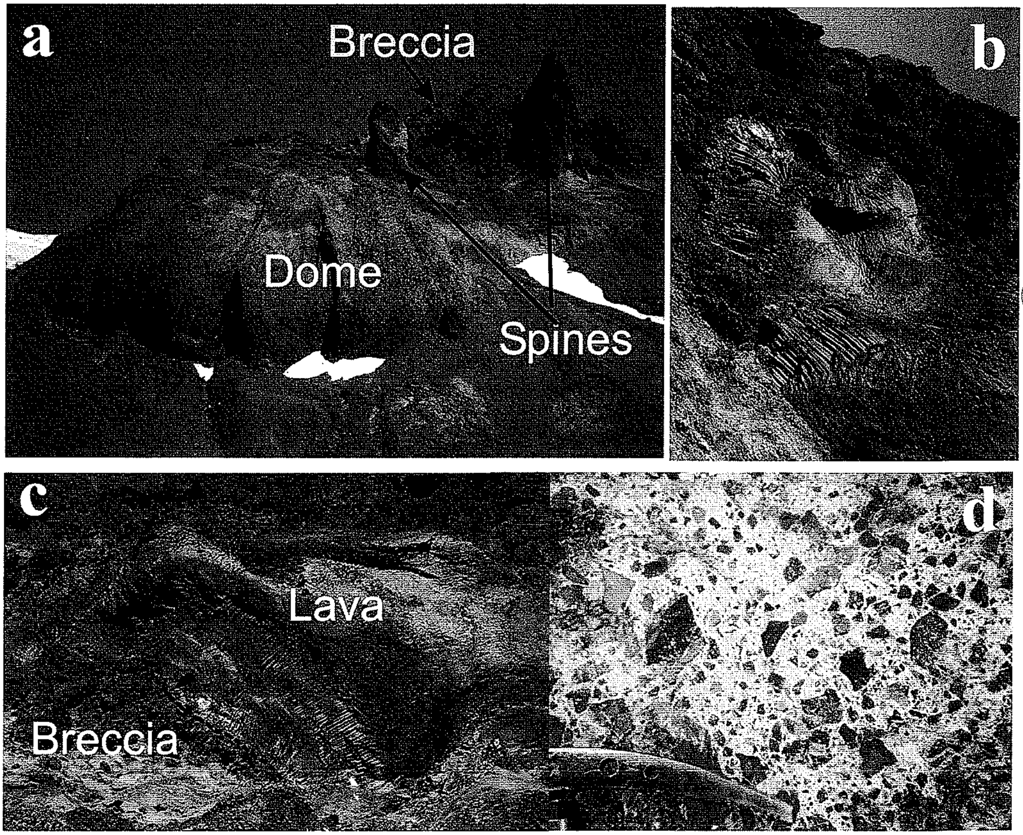


Fig. 4. Photographs of non-vesiculated lava flows, domes and associated breccias (see Fig. 2b for locations). These deposits probably formed during eruption beneath ice that was thick enough to inhibit vesiculation. (**a**) Bulbous, pervasively jointed lava dome and spines overlain by breccia of similar composition. The lava is dome-shaped and about 60 m in height. (**b**) Intense radially-oriented jointing in lava lobe encased by breccia. Lobe is approximately 10–15 m in height. (**c**) View of pervasive columnar jointing paralleling the contact between the lava lobe and breccia. Columnar joints are about 1–2 m in length. (**d**) Close view of angular, non-vesiculated clasts that comprise the monomict breccias that encase massive bulbous lava lobes and domes. Head of ice axe is about 30 cm long.

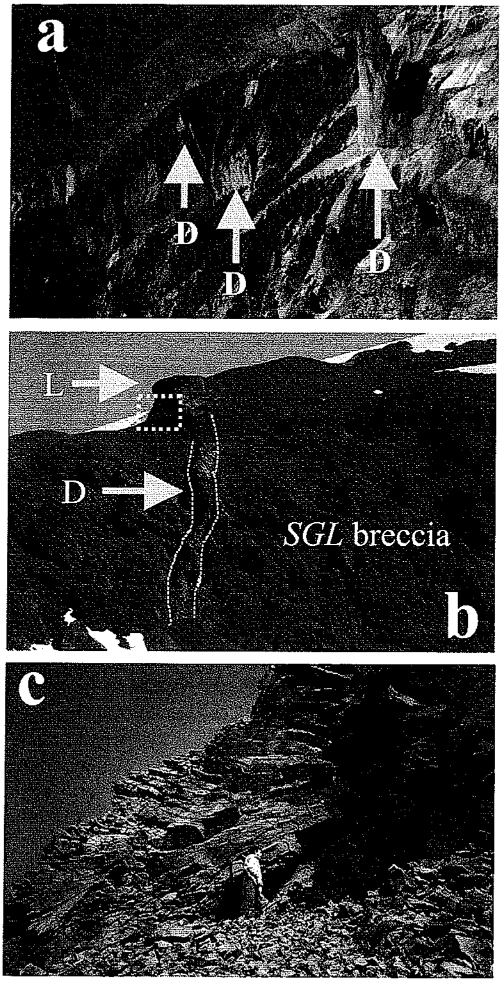


Fig. 5. Field photographs showing features of dykes that feed highly vesiculated lavas and breccias (cf. Fig. 2b). (**a**) Westward view of a large (20 m thick), discontinuously exposed, dyke (D; arrows) of phonolite that cuts through older HMV lava flows. (**b**) View of 50 m-high rock face that exposes a near-vertical feeder-dyke (D) that ultimately becomes a lava flow (L). Lava overlies and dyke intrudes breccias associated with the poorly-vesiculated subglacial lavas. HMV ice cap is visible in top right corner of photograph. (**c**) Detailed view of ice-chilled lava flow showing well-developed radially-oriented columnar jointing. The location of this exposure is shown in (**b**) by outlined box.

where exposed in the walls of a massive canyon on the SW flank of HMV (Fig. 2b). The deposits at the top of the volcano form a second set of cliffs that partially circumscribe the edifice. These 'upper' cliffs crop out between about 1300 and 1700 m asl, but are below the Hoodoo ice cap (Fig. 2). They provide the best exposures of SGL deposits.

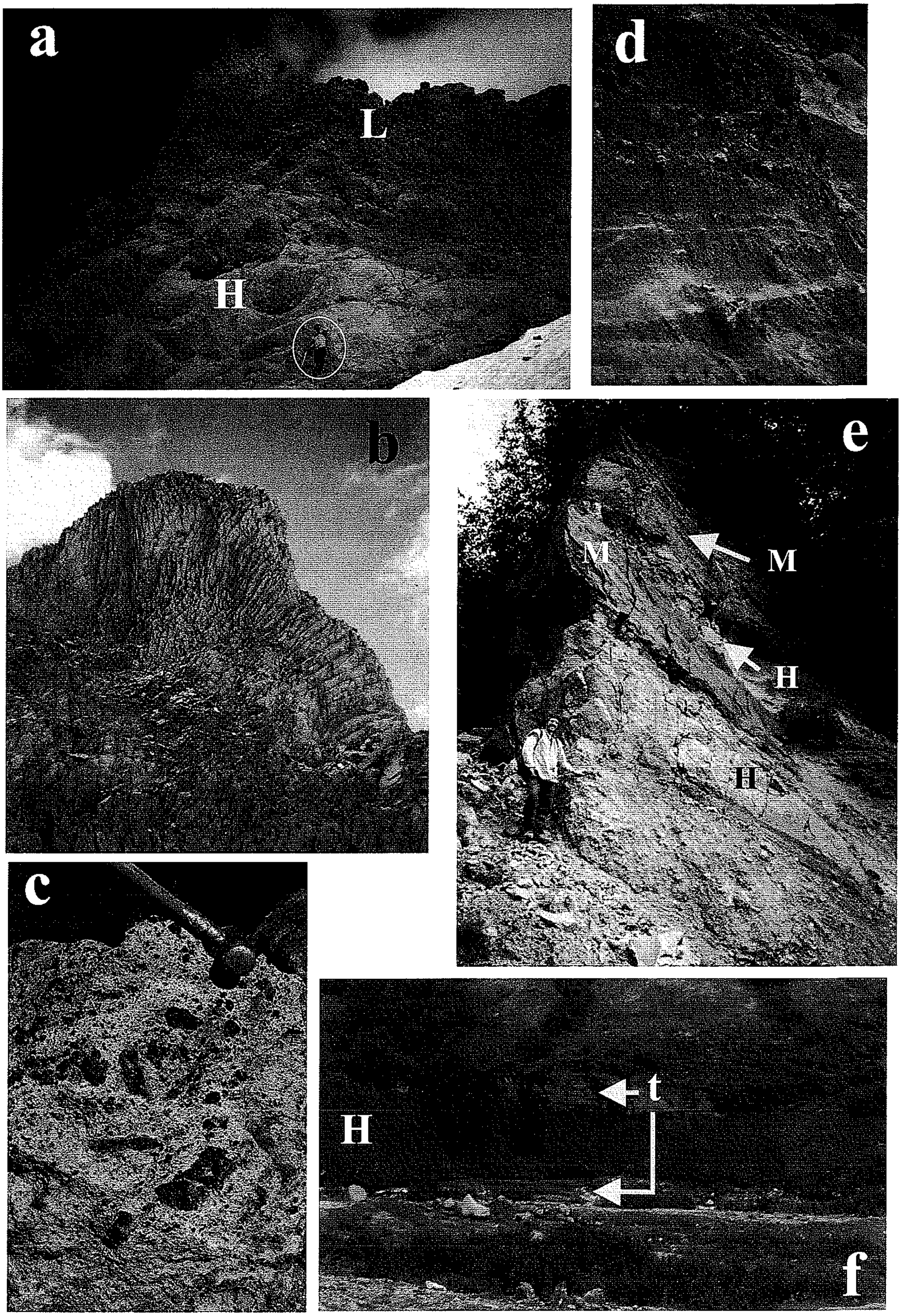
The lava flows and domes are massive, non-vesicular and composed of aphanitic to slightly (1–5%) porphyritic black trachyte and phonolite. The associated breccia deposits are monomict, poorly sorted, and made up of lapilli- to block-sized, angular to subrounded, aphanitic, low-vesicularity clasts of trachyte/phonolite in a matrix of ash-size fragments (Fig. 4d). The breccia varies locally from matrix- to clast-supported. Crude layering is observed locally and is defined by accumulations of block-sized clasts. The yellow to reddish-orange color of the matrix, in addition to discoloured rims on freshly broken clasts, is interpreted as indicating varying degrees of incipient clay(?) alteration of the matrix material.

Several different lava forms are exposed in the upper cliffs. Locally the lava appears to have been extruded as bulbous domes and vertical spines (Fig. 4a). The monomict breccia enclosing the lava bodies appears to have formed synchronously with extrusion. The lava bodies are always pervasively jointed with cooling joints that are consistent with highly irregular cooling surfaces (Fig. 4b, c). A particularly well-exposed lava lobe is pervasively jointed, comprising small diameter, columnar joints (< 50 cm in diameter) whose orientation is perpendicular to the irregular contact with the breccia (Fig. 4c).

This paper interprets the association of intensely jointed lava and monomict breccia to have formed contemporaneously during subglacial eruptions. Spatial relationships between the enclosing breccia and the lava are consistent with the breccia forming contemporaneously with the lava. The angularity of the breccia clasts and the pervasive nature, type and orientation of the lava jointing are all consistent with formation in an environment characterized by rapid cooling by water and/or ice. The limited vesicularity of the lavas and breccia clasts, as well as the topographically restricted nature of the deposit, suggest that the eruptions took place under relatively thick ice (sufficient to suppress extensive vesiculation and exceeding the height of the cliffs, i.e. ice >500 m thick).

Sub- to supraglacial lava (SSL)

The upper stratigraphy of HMV hosts a second distinctive association between lava and pyroclastic deposits. This association comprises dykes, lava flows, domes, and well-indurated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and unconsolidated pyroclastic deposits (Figs 5 & 6). The deposits are dated by $^{40}Ar/^{39}Ar$ geochronology at between 40 and 30 ka (Fig. 2; Villeneuve *et al.* 1998). The association is volumetrically small but occurs over a much broader range of elevations than the previously described SGL association (Fig. 2). For example, the SGL deposits from the upper cliff sequence are restricted to a narrow range of elevations (e.g. 1100 to 1700 m) that reflect their stratigraphic position. In contrast, deposits of the SSL association from the same stratigraphic level are found in exposures near the top of the edifice at 1720 m asl (e.g. the Horn) as well as at 700 m asl, near the base and distal edge of the volcano and near Hoodoo Glacier (Fig. 2a, b).

These deposits share a number of similarities with the SGL association. They both comprise aphanitic trachyte to phonolite lava, and massive lava flows and domes show radiating, pervasive columnar jointing and are narrow and domical in cross-section (Fig. 5b, c & 6b). However, the dykes, lava flows and associated fragmental deposits of the SSL association are different in one critical way: most of these units are moderately to highly vesicular, whereas the SGL deposits have comparatively lower vesicularities. Additionally, locally dykes can be traced directly into lava flows (Fig. 5b).

The pyroclastic deposits in the SSL association comprise two varieties. The first is well indurated, massive lapilli tuff, and contains vitric, vesicular lapilli and bombs (Fig. 6c). Typically, it forms a carapace around massive lava units and it has a characteristic yellowish white colour, which is interpreted as indicating hydrothermal (likely clay) alteration of ash-size glass particles in the matrix analogous to palagonitization of basaltic hyaloclastite. Locally pumiceous bombs are elongate and contain stretched vesicles that can be several centimetres long. The Horn (Fig. 2a) is a nunatak made of this pyroclastic unit with a core of lava. The pyroclastic deposit forms a carapace to the intensely jointed mass of lava (Fig. 6a, b) and is also found interlayered with brown to grey polymictic diamictite near the base of the west side of HMV (Fig. 6e). The diamictites comprise 10–25% subangular to subrounded clasts (from <1 cm to >50 cm) of HMV lava as well as clasts obviously not derived from HMV lavas. The contact between the diamictite and the pyroclastic deposits is irregularly shaped but marked by a sharp contrast in colour between the orange-yellow pyroclastic unit and the grey diamictite. Where a diamictite lens overlies the pyroclastic units, it locally contains subrounded pumiceous clasts.

The second type of pyroclastic deposit comprises green to black, non-indurated, ash- to bomb-size clasts, which locally appear to be moderately graded (Fig. 6d) and weakly stratified. The non-indurated pyroclastic deposits are only found in two locations on the lower flanks of the edifice. The deposits occur directly beneath lava flows of the association, and do not exhibit signs of extensive glass alteration. At the NW base of HMV, the deposits form a 2–3 m thick unit between two glacial tills (Fig. 6f).

The SSL association is inferred to have formed contemporaneously during subglacial to supraglacial eruptions beneath a thin ice cover. The vesicularity of the lava and pyroclastic deposits is consistent with low confining pressures and/or high volatile contents during eruption, in contrast to the poorly-vesiculated SGL deposits. Although the pyroclastic deposits in the SSL association are inferred to result from the same eruptive event, they are diverse in character and were deposited over a wide range of elevations. This aspect of the deposits is a strong indication that the eruptions breached the surface of the ice and were able to flow down the side of the edifice. The well-indurated pyroclastic deposits probably represent the proximal facies of fragmental deposits resulting from explosive lava–ice interaction. High heat content and abundant water facilitated alteration and concomitant cementation. In contrast, unconsolidated, graded and crudely stratified deposits of pyroclasts, found only near the base of the

Fig. 6. Photographs of vesiculated lava and palagonitized hyaloclastite deposits on the northern flank of HMV (cf. Fig. 2b). Deposits result from eruptions that were initiated beneath relatively 'thin' ice and may ultimately have breached the ice surface. (**a**) Field photograph of deposits near the Horn (Fig. 2a) showing the close association between vesicular, strongly-jointed lava (L) and veneer of yellow, altered hyaloclastite (H). (**b**) Pronounced, coarse–medium scale (*c.* 0.5 m), radially-oriented cooling joints in lava forming the Horn nunatak. (**c**) Close view of altered hyaloclastite showing angular, dark vitric clasts. Hammer is about 35 cm long. (**d**) Moderately stratified deposits of hyaloclastite showing variations in clast size and size sorting attributed to the effects of water transport. Large block is *c.* 0.5 m in diameter (**e**) Two lenses of yellow, altered hyaloclastite (H) interfingering with lenses of green mudstone (M) located immediately north of the Wall (see Fig. 2a for location). (**f**) View of lens, *c.* 3 m thick, of water-transported hyaloclastite (H) between deposits of glacial till (t).

edifice and overlain by lava flows from the same eruptive episode, represent the more distal, water-transported facies.

Comparison to other glacial volcanic deposits

The three associations described above, although unique in many respects, share common traits with glacial volcanic deposits. For example, Mathews (1952*a*) reported lava cliffs at Clinker Mountain up to 1500 feet high, formed by unusually thick flows at relatively low elevations. He interpreted the cliffs as having formed by flows being dammed by valley-filling glacial ice. Thus, the interpretation of the IDL association, which is very similar to deposits formed by lava flows at Clinker Mountain in southwestern British Columbia (Mathews 1952*a*), as lava flows dammed by ice is consistent with previous interpretations of similar features.

The SGL association shares some characteristics with subaqueous basaltic and subglacial rhyolitic lithofacies. Bergh & Sigvaldason (1991) described basaltic lithofacies (isolated and broken pillow hyaloclastite breccia, and lobate basalt hyaloclastite breccia) that comprise a mixture of monomict breccia and pervasively columnar jointed lava lobes very similar in appearance to outcrops of the SGL association. Bergh & Sigvaldason (1991) inferred a subaqueous marine eruption environment followed rapidly (at high temperatures) by high concentration mass flows for the genesis of both lithofacies. Tuffen *et al.* (2001) described a rhyolitic lithofacies of monomict breccia and lava lobes (Breccia B), interpreted as forming by hot mass flows during subglacial eruption. Given the similarities between the two lithofacies mentioned above and the SGL association at Hoodoo Mountain, it seems likely that hot mass flows resulting from gravitational collapse could also have been important in forming the SGL association. This paper favours a subglacial environment of formation for the following reasons: (a) the thickness of the deposits (up to >500 m); (b) the low vesicularity of the lava and breccia clasts; (c) the pervasive nature and small diameter of columnar jointing; and (d) the lack of any obvious marine fossils. However, it is not possible to rule out subaqueous eruptions into an englacial lake.

Previous workers have inferred that in water depths greater than about 500 m (Jones 1969*b*; Moore 1970), vesiculation in undegassed(?) basaltic lavas is largely suppressed (Moore *et al.* 1995). Although this depth is not well constrained for phonolite lavas, and is dependent the composition of the magma, especially its water content, it gives a crude approximation for the water–ice depth that may have existed above the SGL deposits and which may have largely suppressed their vesiculation. The morphology of the lava and the mantling relationship between the lava and breccia also seem most consistent with eruption under a substantial thickness of ice. Lava domes and highly irregularly shaped lava bodies (Fig. 5) all totally surrounded by breccia, indicate that these deposits formed by confined flow. Finally, the pervasive nature, size, and orientation of jointing in the lava flows and domes are most consistent with cooling in a water-rich environment (Long & Wood 1986; Bergh & Sigvaldason 1991; DeGraf & Aydin 1993).

The SSL association is the most unusual of the three subglacial associations at HMV. It shares some broad characteristics with previously described subaqueous to emergent volcanism reported for basaltic rocks from Antarctica (Smellie & Hole 1997) in that the association contains glassy breccia, massive lava flows, vesiculated pyroclastic material, and locally important dykes. However, as opposed to formation in an englacial lake (e.g. Smellie & Hole 1997), the SSL association appears to have largely erupted on the flanks of HMV, where lava and pyroclastic debris was able to move downslope, as opposed to accumulating in one location. The moderate to high degree of vesiculation in the pyroclastic units of the SSL association indicates that the thickness of overlying ice was not enough to suppress bubble nucleation and rapid growth. Based on the previously mentioned studies (Jones 1969*b*; Moore 1970) the ice depths were possibly much less than 500 m. Many of the large bombs have rinds of glass that are >2 cm thick, implying formation under conditions where the glass transition temperature was readily achieved. More importantly, the morphology of associated lava and breccia deposits is most consistent with eruption under thin ice in two ways. First, the half-domed shape of relatively small lava flows, pervasively fractured with joints that are horizontal on lower surfaces and radiate to vertical at top (Fig. 5b), are most consistent with the lava flow flowing down beneath the ice or in a channel melted through the ice (e.g. Lescinsky & Fink 2000). The pervasive, small diameter columnar joints indicate rapid cooling as with the SGL association. Second, the flow and its pyroclastic carapace at the Horn and flows along the northwest side of HMV appear to have formed while moving down a slope similar to the current topography of the mountain, along a confined path. The non-palagonitized, non-indurated pyroclastic deposits show evidence of some size sorting and are cautiously interpreted as deposits of pyroclasts transported in meltwater channels cut through or below thin ice formed during the initial stages of eruption. Further evidence of this derives from isolated deposits of diamictite interlayered with altered pyroclastic deposits. The apparent ease of down-slope movement, coupled with the high vesicularity of the pyroclasts, is most consistent with eruption into and/or through ice thinner than that present during formation of the SGL association.

Implications for edifice morphology

The combination of subaerial and subglacial eruptive products from the six recognized eruptive cycles (Table 1) has produced the most remarkable aspect of HMV, its morphological form. In plan view, HMV is symmetrical, circular, and approximately 6 km in diameter at its base (Fig. 2b). Views of all sides of the volcano (Fig. 7) illustrate the unique, step like shape of

Table 1. *Summary descriptions and interpretations of associations at HMV*

Association[1]	Description	Age[2] (in ka)	Interpretation
SSL	Lava flows; locally overlie all other deposits[3]	28–9	Subaerial
	Lava lobes, flows and dikes and monomict breccia; moderately to highly vesicular and/or amygdaloidal, pervasively jointed with irregularly oriented, fine (<0.3 m) columnar joints; breccia is varies from matrix- to clast-supported, with highly vesicular, elongated clasts up to 0.5 m long; matrix is whitish yellow; total unit thicknes *c.* 30–50 m	30–40	Sunglacial: relatively thin ice
Upper SGL	Lava lobes and domes and monomict breccia; Low vesicularity, and pervasively jointed with fine (<0.3 m) columnar joints of highly variable orientation; breccia is dominantly matrix-supported, with angular to subangular, low vesicularity clasts identical in appearance to associated massive lava; clasts range in size from 0.5 to >20 cm; matrix is orange to yellow; locally lava lobes are totally encapsulated by breccia; total unit thickness *c.* 400 m	<54 >40	Subglacial: relatively thin ice
	Lava flows; locally overlies lower SGL deposits[3]	54	Subaerial
	Lapilli-tuff; locally overlies IDL deposits[3]	<80 >54	Subaerial (?)
IDL	Lava flows; flow thicknesses vary from *c.* 30 m to >200 m forming large cliffs; flow faces show extensive entabulature development, often with horizontal oriented columnar joints; total unit thickness *c.* 200 m	80	Ice-dammed: subaerial lava flows erupted near summit (*c.* 1300–1400 m asl), dammed by ice at *c.* 700 m asl
Lower SGL	Lava flows and domes interlayered with monomict breccia, low vesicularity with pervasive small diameter (*c.* 0.3 m) columnar joints; breccia clasts are angular, matrix- to clast-supported, similar in appearance to associated lava; total unit thickness *c.* 500 to 1000 m	85	Subglacial: relatively thick ice

[1] See Figure 2.

[2] Villeneuve *et al.* (1998); Edwards *et al.* (2000).

[3] Not described in this work; cf. Edwards (1997), Edwards *et al.* (2000).

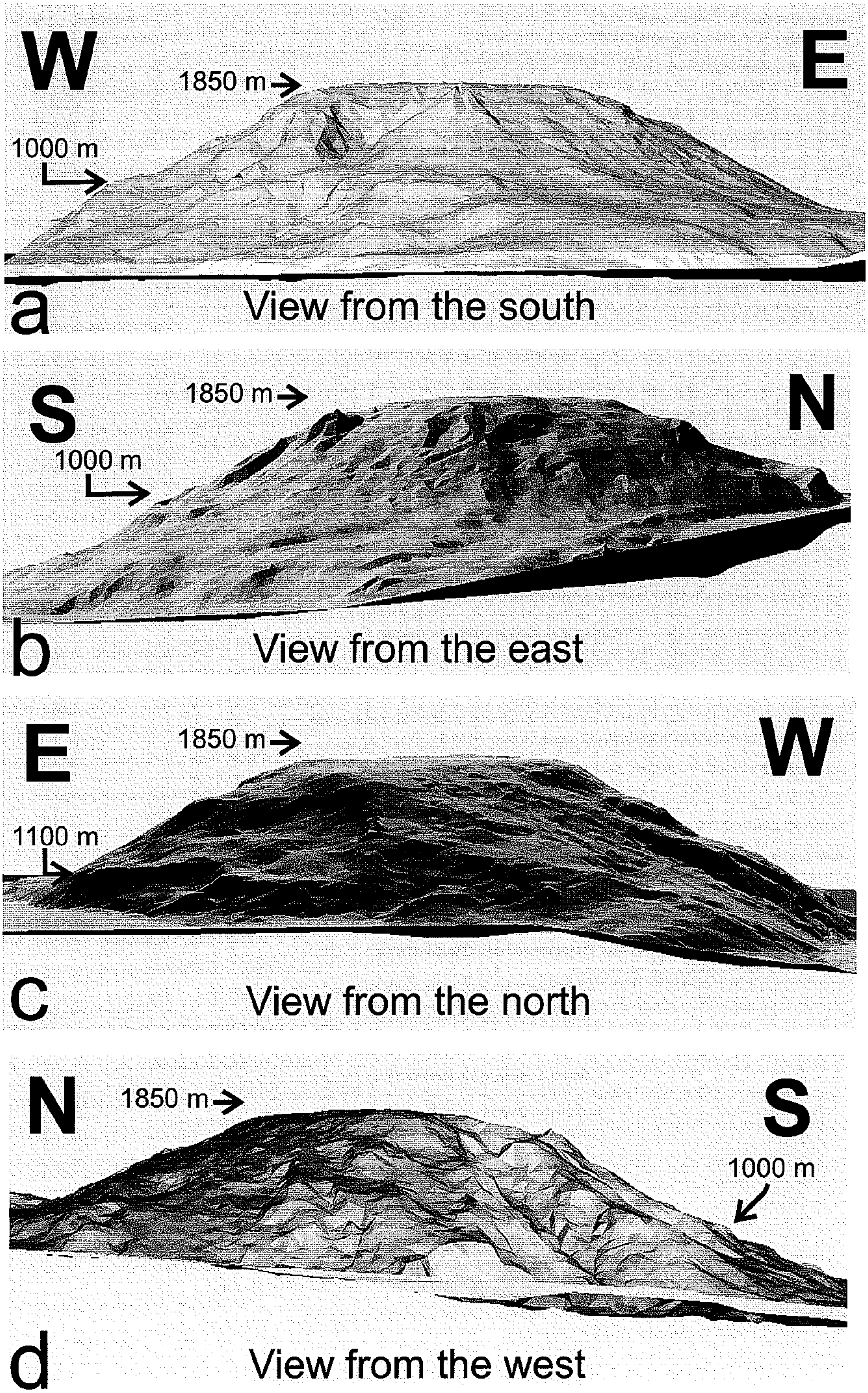

Fig. 7. Three dimensional triangulated network views of Hoodoo Mountain volcano showing profiles of the edifice as viewed from the (**a**) south, (**b**) east, (**c**) north and (**d**) west.

the edifice. It features a broad, rounded summit at 1850 m asl and an ice cap which is 3 km in diameter. Radar surveys have confirmed that the mountain has a flat top beneath the 120–150 m thick ice cap (Russell *et al.* 1998). At least two sets of prominent cliffs partly circumscribe the volcano, producing a discontinuous, step-like topographic profile (Figs 3a & 7). For example, the base of the volcano is largely delimited by a series of 100–200 m-high cliffs, except on the south-eastern side of the edifice. There, lava flows from the youngest eruptions form a veneer over the pre-existing topography; the slope of the SE flank is smooth from near the summit (*c.* 1800 m) to the Iskut River at *c.* 100 m asl (Fig. 7a). The top of the lower set of cliffs defines a broad bench at approximately 1000 m elevation that terminates against an upper set of cliffs. The second set of vertical cliffs is between 50 and 100 m high and surrounds the summit.

The overall flat-topped morphology of HMV led Souther (1991) to refer to Hoodoo Mountain as a 'tuya'. Although Hoodoo Mountain volcano does not fit the classic tuya model (i.e. Mathews 1947; Hickson 2000) because of its complex stratigraphy, its unique morphology apparently results from repeated interactions between volcanism and proximal ice-sheets over the past 100 ka. Thus, we consider it to be a tuya *sensu lato.*

Implications from HMV for glacier fluctuations in the Iskut region

The three distinct styles of lava–ice interaction described above are a reflection of local environmental conditions, mainly the presence and thickness of ice deposits during eruption. As a result, it is possible to use the physical character of these ice-contact volcanic deposits, their distribution, and their relative and numerical ($^{40}Ar/^{39}Ar$) ages to put preliminary constraints on the thickness of ice masses in the Iskut region since *c.* 85 ka (summarized in Table 1; Fig. 8).

The oldest known volcanic deposits, formed at *c.* 85 ka, are part of the SGL lithofacies association. These deposits exist up to elevations of

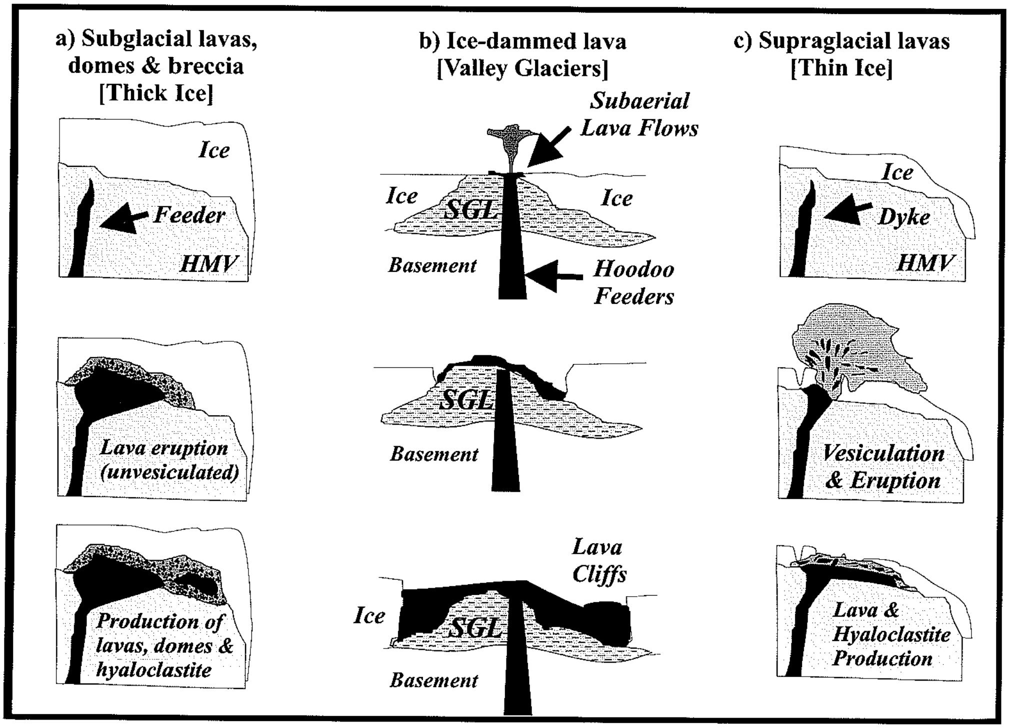

Fig. 8. Cartoon illustrating styles of volcanism that may have produced the three different types of ice-contact deposits described in the text. (**a**) Ice-contained massive, poorly vesiculated lavas, domes and associated breccias. (**b**) Ice dammed subaerial lavas. (**c**) Highly vesicular lavas and hyaloclastite. Thinner ice and possible ice breaching could have triggered explosive eruptions.

about 800–900 m asl and their presence and distribution establishes that, at this time, the local ice sheet had a minimum elevation of about 1300–1400 m asl (700–800 m of SGL deposits plus 500 m of ice). This translates into a minimum ice thickness of about 500 m covering HMV and 1200 m in the adjacent valleys (Fig. 2b). A schematic model has been developed, in this paper, for the origin of this style of relatively 'thick ice' eruption (Fig. 8a).

Situated above the basal *SGL* deposits are cliffs of the ice-dammed lavas that formed at about 80 ka (IDL; Fig. 2a). The presence and distribution of these deposits indicate that valley glaciers filled all of the river valleys surrounding HMV at *c.* 80 ka, assuming that all of the IDL were formed during the same eruptive cycle. Since valley glaciers currently bound the north, west and east sides of the edifice, this is not a surprising conclusion. However, the cliffs on the south side of the edifice, if correlative with corresponding cliffs on the north and west sides, indicate that the Iskut River valley also was filled with ice at *c.* 80 ka. Eruptions between 80 and 54 ka, which show no signs of ice-interaction (Edwards & Russell 2000), indicate that any glaciers present were confined to elevations below about 1300 m (the minimum elevation of the subaerial deposits).

The second sequence of SGL deposits, formed between 54 and 40 ka, indicate a substantial thickening of ice, with a minimum thickness of about 500 m overlying the summit of HMV and possibly up to 2000 m of ice in valleys adjacent to the edifice. The latter minimum estimate is based on the assumption that HMV was not acting as a highpoint of snow/ice accumulation, but that the ice on top of HMV was being fed by the large ice fields such as those that are currently located about 10 km N of HMV.

The distribution and characteristics of SSL deposits, formed at *c.* 40–30 ka, are indicative of eruption beneath relatively thin ice and perhaps are even a direct indication of eruptions breaching the ice surface. Figure 8c is a schematic model illustrating the sequence of events during these 'thin' ice eruptions.

Although the constraints on the absolute thickness of ice surrounding HMV since *c.* 85 ka are qualitative, the observations within this paper help to constrain the formation processes for these deposits. Understanding the variations in volcanic ice-contact and ice-proximal deposits at HMV will permit a much more detailed reconstruction of regional glacier fluctuations in the Iskut region over the last 100 ka. Future field, experimental, and geochronometric studies will allow several questions to be addressed further, including more accurately determining the relationship between ice thickness and inhibition of vesiculation in phonolitic magmas, determining if all of the lower cliffs at HMV formed during a single eruptive episode (as inferred above), and correlation between regional glacial stratigraphy in the Canadian Cordillera and local ice fluctuations in the Iskut region.

Conclusions

The morphology of Hoodoo Mountain volcano and the character of its volcanic deposits can largely be ascribed to three distinct phases of interaction between volcanism and glacial ice. Eruptions thought to be initially subaerial encountered ice probably from bounding valley glaciers and were substantially thickened to form impressive cliffs that partly circumscribe HMV. Thick ice cover produced a topographically-confined association of low vesicularity lava and breccia at least twice in the eruptive history of HMV. Eruption beneath thinner ice produced the association of lava with highly vesiculated deposits of pyroclastic breccia. The characteristics of volcanic units deposited throughout the entire eruptive history of HMV indicate an extended period of glacial-volcano interactions over the past 85 ka. Inferred fluctuations of ice thickness vary from relatively thick (1400 m?) between 85 and 80 ka near HMV and in the Iskut valley, to somewhat thinner (<1300 m?) between 80 and 54 ka, to a final build-up of >2000 m (?) between 54 and 40 ka.

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