RESEARCH ARTICLE

John A. Stevenson · David W. McGarvie ·
John L. Smellie · Jennie S. Gilbert

Subglacial and ice-contact volcanism at the Öræfajökull stratovolcano, Iceland

Abstract Eruptions of Öræfajökull have produced mafic and silicic magmas, and have taken place in both glacial and interglacial periods. The geology of the volcano records the differing response of magmas of contrasting composition to interaction with ice of variable thickness and gives insight into the development of a long-lived ice-covered stratovolcano. Vatnafjall, a ridge on the southeast flank of Öræfajökull, is the first area of the volcano to have been mapped in detail and the geological map is presented here alongside descriptions of each erupted unit. The oldest units comprise pillow lavas, hyaloclastite and jointed lava flows that were formed during subglacial basaltic eruptions involving abundant meltwater. The products of a subsequent explosive, initially phreatomagmatic, subglacial rhyolite eruption were confined by ice to form a tephra pile over 200 m thick that was intruded by dense rhyolite magma towards the end of the eruption. Confinement by ice caused a later trachydacite lava flow to form buttresses and a steep pillar. Whilst some of the meltwater produced infiltrated the lava (to generate red and black glassy breccias and cause localised steam explosions), it is likely that much of it drained down the steep topography. The most recently-erupted units are subaerial basaltic lava flows, the oldest of which were erupted during an interglacial period and have subsequently been partially eroded and scoured by advancing ice. Ice has been important in shaping the edifice by confining eruptive products to form constructional features and by later eroding parts of them to form deep valleys. Reconstructions of volcano-ice interaction allowed the local thickness of the glacier at the time of each eruption to be estimated, and demonstrates that the upper surface of the ice has varied in elevation by over ∼700 m.

Keywords Subglacial · Silicic · Ice-contact · Explosive · Phreatomagmatic · Öræfajökull · Glaciovolcanism · Stratovolcano

J. A. Stevenson (✉) · D. W. McGarvie
Department of Earth Sciences, The Open University,
Milton Keynes, MK7 6AA, UK
e-mail: johnalexanderstevenson@yahoo.co.uk
Tel.: +44 1524 593574
Fax: +44 1524 593985

J. A. Stevenson · J. S. Gilbert
Department of Environmental Sciences, Lancaster University,
Lancaster, LA1 4YQ, UK

J. L. Smellie
British Antarctic Survey,
High Cross, Madingley Road, Cambridge, CB3 0ET, UK

Introduction

Öræfajökull is Iceland's largest active stratovolcano (Thorarinsson 1958). It is located on the southeast coast (Fig. 1) at the southern margin of the Vatnajökull ice cap, and has erupted mafic and silicic magma during historical time. It has a summit caldera 5 km in diameter, which is filled with ice that spills down several deep valleys carved into the flanks of the volcano. During the last 3 Ma, ice has entirely covered Iceland and its continental shelf at least 12 times (Einarsson and Albertsson 1988). At the last glacial maximum, 21 ka ago, the thickness of the ice cap was estimated to be 1000–1500 m in central Iceland, decreasing to 300–500 m at the current coastline (Bourgeois et al. 1998). Eruptions at Öræfajökull have occurred during both glacial and interglacial periods (Prestvik 1979). Consequently, the edifice provides an unusually good opportunity to investigate the long-term evolution and growth, during fluctuating ice conditions, of a high-latitude stratovolcano.

Volcano-ice interactions have been described across the globe, with a concentration of studies in Iceland (e.g. Guðmundsson et al. 1997; Tuffen 2001; Loughlin 2002), Antarctica (e.g. Smellie and Skilling 1994; Smellie 2002), and British Columbia (Mathews 1947; Kelman et al. 2002). Smellie (2000) provided a review of the literature, which is dominated by studies of basalts. Deposits with more evolved compositions, (dacite, trachyte) are fewer, but have been described at Mt Rainier, Washington (Lescinsky

Öræfajökull stratovolcano, SE Iceland

and Sisson 1998), and Hoodoo Mountain volcano, Canada (Edwards and Russell 2002; Edwards et al. 2002). The products of Icelandic rhyolitic eruptions beneath thick ice-sheets have been described at Torfajökull (Tuffen et al. 2002a), and Kerlingarfjöll (Stevenson 2005).

Three main lines of evidence indicate the presence of ice during the growth of a volcano. These relate to the interaction of the lavas and tephras with meltwater, the physical confinement of volcanic products by the glacier, and the effects of glacial erosion. Pillow lavas, quench-fragmented hyaloclastite, peperite and blocky-shaped ash shards are evidence of magma-water interaction (Heiken and Wohletz 1985; Kokelaar 1986; Skilling et al. 2002). In high-latitude areas, and in the absence of evidence for a submarine setting, tectonic uplift or a recently-drained lake, melting ice is a probable water source (Smellie 2000). Within thick (>150 m), impermeable ice this water may pond near the vent; if the ice is thinner and fractured, or the topography is steep, it may flow down tunnels and channels (Smellie and Skilling 1994). Low melting rates (10^{-5} to 10^{-6} m s^{-1} for effusive silicic eruptions (Höskuldsson and Sparks 1997) allow ice to confine lavas, which may be dammed or moulded by ice walls (Tuffen et al. 2001; Edwards and Russell 2002). The chilled margin of the lava in contact with the ice will be glassy and fractured, often with columnar joints formed perpendicular to the contact, i.e. subhorizontally for contact with a near-vertical ice wall (Lescinsky and Fink 2000). Steep-sided piles of tephra, sometimes hundreds of metres high, and often unconsolidated and intruded by lava lobes, are also likely to have been confined by ice walls during eruption (Tuffen 2001; Stevenson 2005). Prominent angular unconformities, striated or polished surfaces and beds of till within a volcanic sequence are strong evidence for the presence of glacial ice during at least some stages of the evolution of a volcano (Loughlin 2002).

The present study aimed to map the geology of Vatnafjall, a ridge on the lower flanks of Öræfajökull, and in doing so gain new insights into the response of eruptions of different magma compositions to ice of varying thickness, the effect of relatively thin ice on silicic volcanism and the morphological development of a long-lived, high-latitude stratovolcano.

Geological setting

Öræfajökull

The Öræfajökull stratovolcano unconformably overlies the remains of two extinct volcanoes that lie near Skaftafellsjökull in the west and Breiðarmerkurjökull in the east (Fig. 1). Lacustrine sediments above the unconformity have been dated at 600–890 ka, and the entire edifice, being normally magnetised, has formed since the Brunhes reversal (i.e. in the last 780 ka, Prestvik 1979). It consists mainly of palagonitised basaltic hyaloclastite tuffs and breccias, in addition to basaltic lava flows, glaciofluvial sediments and tillites (Thorarinsson 1958). The abundance of hyaloclastite implies formation mainly during glacial times, and this is corroborated by work in the Skaftafell region, 25 km to the west, by Helgason and Duncan (2001), which suggested that the region was under permanent but variable ice-cover since the Brunhes reversal. They presented a model for the topographic evolution of Skaftafell in which the bulk of the relief was formed by basaltic subglacial eruptions, which constructed hyaloclastite ridges where magma erupting from fissures was chilled and fragmented by meltwater. They concluded that present-day valley locations are therefore principally controlled by the absence of hyaloclastite ridges rather than by glacial erosion. A similar scenario was envisaged by Loughlin (2002) for the ice-covered

Fig. 2 Geological map of Vatnafjall, Öræfajökull, Iceland. The ridge was mapped between Kvíárjökull to the west and a stream gully and gorge to the east. The mapped units, their relationships to each other and the geological history of the area are described in the text. h/c=hyaloclastite. Contours after Army Map Service C762 (1950)
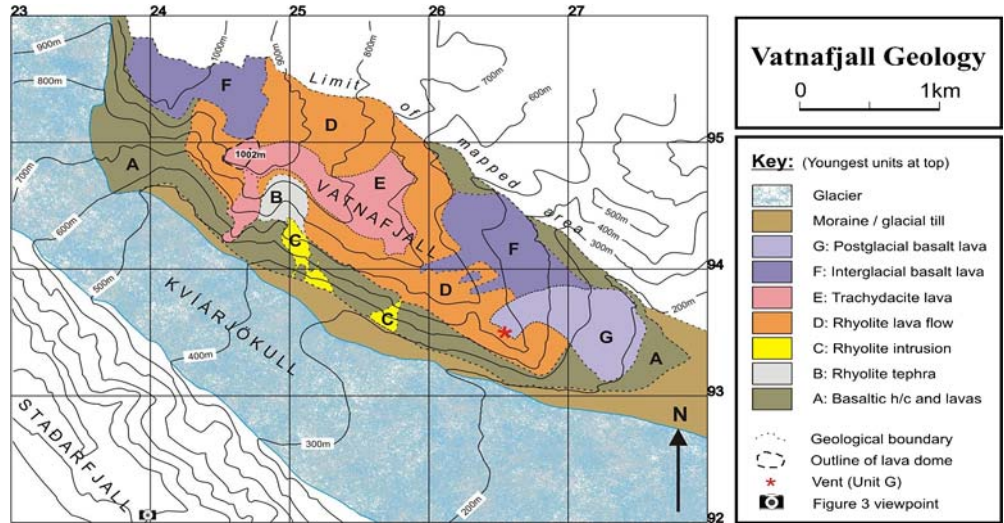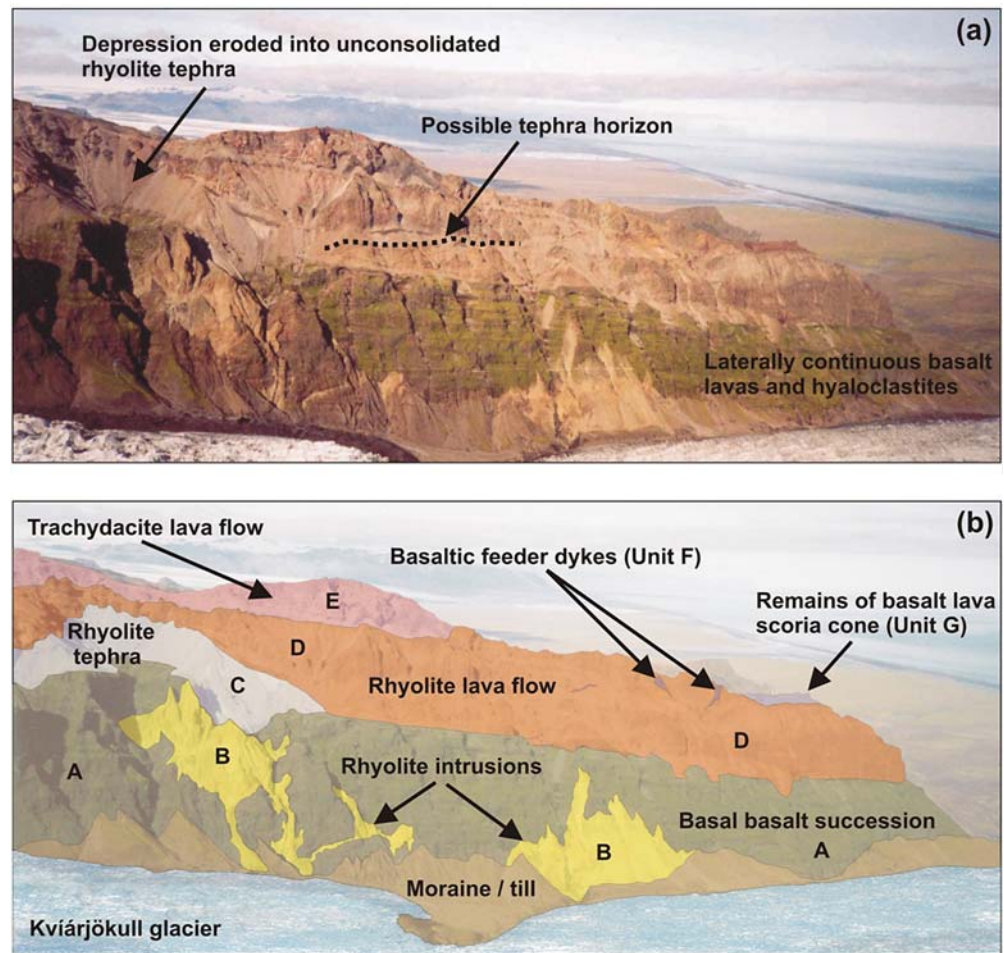

Fig. 3 **(a)** Vatnafjall, as seen from Stadarfjall (see location on Fig. 2). The ridge is 500 m high and 4 km wide in the image. **(b)** An annotated and interpreted view showing the main geological units. The key is as in Fig. 2. The contrast between basaltic and silicic units, the rhyolitic intrusions and the bowl-shaped depression can be seen

stratovolcano, Eyjafjallajökull, located 160 km to the west.

Vatnafjall

The area of specific interest is located on the east flank of the Kvíárjökull glacier, SE Öræfajökull (Figs. 1– 3) and consists of silicic lavas and associated pyroclastic material resting unconformably upon mafic hyaloclastite and lava flows. Erosion by Kvíárjökull has created a valley up to 600 m deep that exposes a unique cross-section through the stratigraphy of this flank of the volcano. Such exposure is rare in the rhyolite areas of Öræfajökull (e.g. Goðafell, Fig. 1) which are commonly blanketed by thick screes.
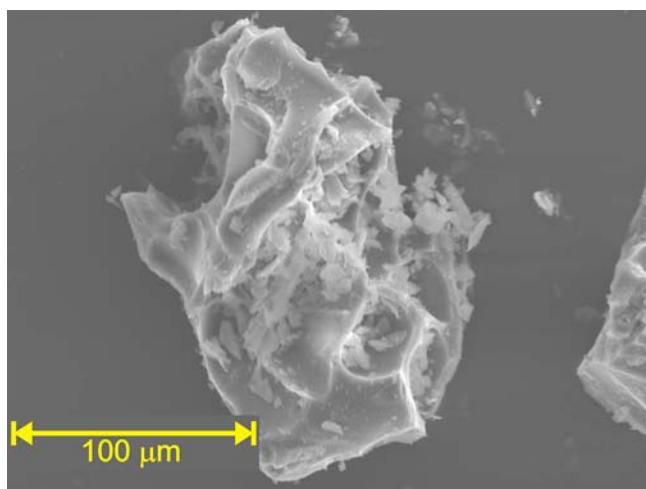
Fig. 4 Scanning electron micrograph of a typical ash shard from the base of rhyolite tephra (Unit B). The shard is 100 μm in diameter. Preserved bubble walls demonstrate that the magma was vesicular on fragmentation. Extremely fine-grained ash particles have aggregated on the shard surface

Vertical cliffs and angle-of-repose scree slopes dominate the valley walls, and fieldwork was only practical on Vatnafjall, to the east of the glacier, which was mapped in July 2003. The resulting map (Fig. 2) shows the main geological units and the relationships between them, and provides the framework for the geological history presented here.

Analytical methods

The area was mapped at 1:10,000 scale using enlarged 1:50,000 topographic maps and aerial photos. Pyroclastic material was examined by scanning electron microscope (SEM) (Fig. 4). A small number of samples from the silicic units was analysed by XRF to provide chemostratigraphic data to corroborate/confirm field mapping. This technique is possible because individual silicic units erupted in Iceland typically have a limited compositional range and a unique geochemical fingerprint (most apparent in trace element concentrations and ratios; e.g. McGarvie (1985); Macdonald et al. (1990)). Consequently, trace element data can be used to aid mapping by allowing correlation of co-erupted but physically separated units in areas where stratigraphic relations are obscured. This, and the chemical classification of eruptive compositions, was the sole purpose of the XRF analyses; this is not primarily a geochemical study. Chemical classifications are based on the total alkali-silica (TAS) scheme (Le Maitre et al. 1989). XRF data is presented in Table 1.

Descriptions of mapped units and their interpretations

In this section the mapped units are described in order, from oldest to youngest, and their characteristics are used to in-

terpret the environment into which they were erupted, in terms of presence/absence of meltwater, ice-support etc. The implications of the inferred environments for estimating ice thickness during the eruption of each mapped unit are discussed later, and synthesised into a model for the growth and evolution of this flank of Öræfajökull. We believe that this two-stage interpretation is necessary because the estimation of ice-conditions from eruptive environments is highly subjective.

The recorded sequence is dominated by lavas; small volumes of pyroclastic rocks were present but, with one exception, the pyroclastic units are too poorly exposed and laterally discontinuous for meaningful study. A range of features relating to volcano-ice interaction are described and interpreted.

Unit A: Basaltic hyaloclastite and lavas

Description

The basalt hyaloclastite and lavas are found at the base of the exposed sequence at Vatnafjall (Figs. 2 and 3). Their composition was determined by Prestvik (1979). A variety of lithofacies is present including hackly- and columnar-jointed, sub-horizontal lava flows 2–3 m thick, pillow lavas and pillow breccias, and beds of both dense and vesicular glassy fragments formed by chilling and shattering of magma in contact with water (hyaloclastite). None of this material is red coloured or oxidised. Lava layers and hyaloclastite layers (up to 10 m thick) are intercalated and continuous for hundreds of metres along the valley wall (Fig. 3). Their orientation is the same on both sides of Kviárjökull, suggesting that they form broad sub-horizontal sheets. The base of the sequence is not exposed, and the top is defined by a gently south-easterly dipping, roughly planar erosional surface overlain by which is overlain by rhyolite (Units B and D). This unconformity is present on both sides of the glacier.

Interpretation

These rocks are the oldest on Vatnafjall and, as the entire volcano is normally magnetised (Prestvik 1979), they are less than 780 ka old. The abundance of hyaloclastite and pillow lavas and lack of surface oxidation implies interaction with plentiful water (Kokelaar 1986) and the pillow lavas and pillow breccias are interpreted as having intruded water-saturated hyaloclastite breccias at the margins of the sub-horizontal lava flows. Such close association between hydroclastic and effusive phases suggests that they are co-genetic, and the intercalation of units suggests that each was produced in different phases of a long eruption, or by closely spaced individual eruptions. The lower flanks of Eyjafjallajökull exhibit a similar intimacy between effusively erupted, gently-dipping lava flows and pillow breccia to hyaloclastite of hydromagmatic origin (Loughlin 2002).

Table 1 Whole rock chemical composition data for individual samples of silicic rocks collected from Vatnafjall obtained by J.A.S. at the WD-XRF facility at the Open University, UK

Sample	JS202	JS203	JS226	JS230	JS242	JS244	JS257	Error
Location	4 269$_{20}$	4 258$_{40}$	4 248$_{52}$	4 251$_{89}$	4 253$_{19}$	4 251$_{52}$	4 249$_{59}$	
(GPS coordinates)	70 932$_{48}$	70 941$_{46}$	70 950$_{15}$	70 939$_{94}$	70 945$_{58}$	70 946$_{24}$	70 949$_{42}$	
Mapped Unit	D	E	E	C	B*	B*	E	
Major elements (wt%)								
SiO_2	73.39	68.00	68.96	73.72	72.31	72.75	66.26	0.23
TiO_2	0.192	0.691	0.604	0.214	0.297	0.305	0.854	0.00
Al_2O_3	13.39	14.67	14.48	13.53	14.10	13.77	14.95	0.04
Fe_2O_3	2.80	4.52	4.11	2.43	2.83	2.77	5.31	0.01
MnO	0.078	0.088	0.084	0.049	0.085	0.069	0.094	0.00
MgO	0.08	0.92	0.78	0.16	0.29	0.30	1.19	0.01
CaO	0.91	2.52	2.24	0.85	1.13	1.16	3.06	0.01
Na_2O	5.33	4.80	4.85	4.89	4.81	4.71	4.71	0.01
K_2O	3.80	3.66	3.75	4.13	4.11	4.11	3.38	0.02
P_2O_5	0.018	0.148	0.133	0.025	0.045	0.054	0.190	0.00
LOI	0.2	0.22	0.19	0.37	3.71	4.92	0.25	0.00
Original total	99.83	100.33	102.29	101.31	100.96	101.01	101.45	
Trace elements (ppm)								
Rb	91	92	92	97	101	106	79	1
Sr	65	134	119	49	63	61	165	1
Y	103.0	64.9	64.4	84.4	84.7	82.8	60.9	0.4
Zr	498	494	479	434	442	437	471	2
Nb	77	52	52	68	65	64	47	1
Ba	744	607	601	690	698	698	575	12
Pb	7	6	7	8	9	9	4	1
Th	12	10	13	15	14	12	9	1
U	2	4	3	4	5	4	3	1
Sc	0	7	7	3	3	3	9	1
V	3	34	22	4	12	4	47	4
Cr	13	10	31	7	4	4	9	1
Co	2	6	4	2	3	3	7	3
Ni	3	2	2	2	3	3	6	1
Cu	7	24	21	9	15	12	29	1
Zn	137	80	75	95	114	92	69	1
Ga	26	23	22	22	23	24	23	1
Classification	Rhyolite	Trachy-dacite	Trachy-dacite	Rhyolite	Rhyolite	Rhyolite	Trachy-dacite	

Note. Major element data were obtained from glass discs; trace element data were collected from pressed pellets (see Stevenson 2005 for further detail). Data are normalised to volatile-free basis; original totals and LOI's are presented for reference. Analytical errors represent standard deviation among eight repeated analyses of known standard. Symbol (*) represents pyroclastic rocks; note higher LOI. Classification after Le Maitre et al. (1989). Sample locations obtained by GPS are in UTM/UPS format using Hjorsey 1955 datum (different projection to Fig. 2)

At Eyjafjallajökull the cause of rapid switching between lava and clastic lithologies was interpreted to be sudden drainage of meltwater from the vent area (Loughlin 2002) and a similar origin is likely for these deposits.
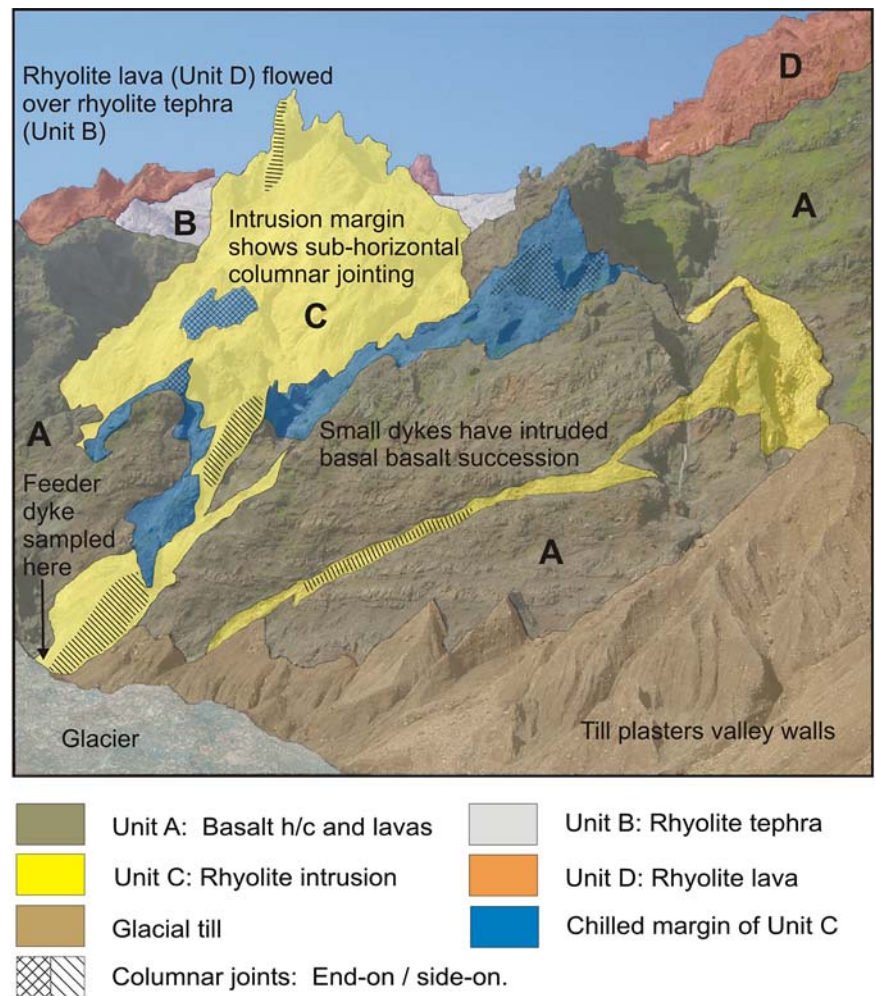
Unit B: Rhyolite tephra

Description

An amphitheatre-shaped depression towards the north-western edge of Vatnafjall contains a succession of unconsolidated rhyolitic tephra, which is mainly exposed within gullies beneath the scree cover (Fig. 3). The base of the amphitheatre is defined by the top of Unit A (basalt hyaloclastite and lavas) and is 250 m lower than the local ridge crest. The depression is ∼300 m wide and centred around the top of a rhyolite intrusion. The tephra consists of massive, poorly-sorted breccias of pumiceous lapilli (up to 50 mm) in a matrix of very fine-grained ash (<32 μm), some of which forms subspherical aggregates 1–2 mm in diameter. Matrix vesicles within the ash are often present, and granules of obsidian and flow-banded rhyolite comprise up to 1–2 vol%. At the bottom of the amphitheatre, the tephra contains mainly very fine-grained ash, with few small pumiceous lapilli. SEM demonstrates

Fig. 5 Annotated and interpreted photograph of the intrusive rhyolite body (Unit C). The body consists of an irregular central mass, over 200 m high, that extends deep into the rhyolite tephra (Unit B). Thin, parallel-sided dykes penetrate the basalt hyaloclastite and lavas (Unit A). The margins of the rhyolite are glassy and columnar joints are common. The intrusion was sampled at the base (JS230)

Rhyolite lava (Unit D) flowed over rhyolite tephra (Unit B)

Intrusion margin shows sub-horizontal columnar jointing

Small dykes have intruded basal basalt succession

Feeder dyke sampled here

Glacier

Till plasters valley walls

Unit A: Basalt h/c and lavas   Unit B: Rhyolite tephra
Unit C: Rhyolite intrusion   Unit D: Rhyolite lava
Glacial till   Chilled margin of Unit C
Columnar joints: End-on / side-on.

that the ash grains are vesicular, with a coating of extremely fine-grained particles (<10 μm; Fig. 4). Larger, coarse lapilli-size pumice grains are more common at the top of the succession and the vesicles within the clasts are larger (mm-scale rather than microvesicular).

Interpretation

The amphitheatre-shaped depression was formed by the preferential erosion of an unconsolidated rhyolite tephra pile. The tephra pile sits unconformably upon the eroded upper surface of Unit A, and the relatively flat basal topography suggests that it was erupted before the Kviárjökull valley formed. Because of extensive erosion it is not possible to determine the dimensions of the original tephra pile, and the material examined here has only been (fortuitously) preserved where the younger rhyolite lava of Unit D has flowed over and around it. The shape of the amphitheatre suggests that the tephra pile was initially over 200 m thick, yet it is only 300 m wide. Subaerial rhyolite tephras are typically dispersed thinly over wide areas and a tephra deposit 200 m thick would be extremely widespread. However, there is no evidence elsewhere on Vatnafjall

for such a deposit, and so the thickness and high aspect ratio is proposed to result from eruption within a confined space.

The massive, poorly-sorted tephra is interpreted as the deposits of extremely vent-proximal, granular fluid-based pyroclastic density currents (Branney and Kokelaar 2002) (or pyroclastic flows (Cas and Wright 1987)). Similar deposits have been studied in greater detail at Kerlingarfjöll, Iceland (Stevenson 2005). The very poor sorting is consistent with a lack of transport-derived sorting, which would be expected for a confined eruption.

Investigation of the fragmentation mechanism can give insight into magma-water interaction involving meltwater. Extremely fine-grained ash has been attributed to the violent interaction between silicic magma and abundant water (Self and Sparks 1978; Self 1983), and the presence of matrix vesicles within tephras has also been linked to magma-water interaction (Lorenz 1974). The lack of accidental clasts in the deposit implies that this water was encountered at the surface and was therefore not groundwater. The SEM image (Fig. 4) of a typical ash grain from the base of the sequence shows ash particles less than 10 μm in diameter adhering to a larger grain. This is a common feature of phreatomagmatic tephras (Buttner et al. 1999). It

also demonstrates that the magma was vesiculating when it made contact with the water (Heiken and Wohletz 1985). The combination of pumice lapilli and very fine-grained ash imply that only some of the magma was phreatomagmatically fragmented.

Deposits at the top of the sequence are coarser, with more pumice lapilli. This could suggest that the influence of water was waning during the later stages of the eruption. The same pattern is seen in the plinian deposits of the AD 1362. Öræfajökull eruption, which began beneath the ice of the summit caldera. It also produced extremely fine-grained ash initially, progressing to highly-inflated pumice lapilli and blocks (Thorarinsson 1958). The pumices are more inflated at the top of Unit B. This may reflect either lower pressure at the vent or a lack of water interaction to 'quench in' the small vesicles before they had a chance to expand (Gardner et al. 1996). Overall, the tephra grain size characteristics suggest that the involvement of water in fragmentation declined over the course of the eruption.

Unit C: Rhyolite intrusions

Description

An irregular rhyolite mass intrudes both Unit A (basalt hyaloclastite and lavas) and Unit B (the overlying rhyolite tephra) (Figs. 2– 5). The main body is 100 m wide, 300 m tall and has its top within the amphitheatre-shaped depression where it is in contact with, and has baked and discoloured, the tephra. It is fed by two rhyolitic dykes, 20 and 50 m wide. Additional dykes up to 10 m thick run to the southeast, for distances up to 1 km. Importantly, the intrusion does not penetrate Unit D. It consists of pale grey, plagioclase-phyric, dense, microcrystalline rhyolite with flow bands parallel to its margins, which are often glassy and obsidian-rich, and contain columnar joints up to 40 cm in diameter.

Interpretation

Because the Unit C rhyolite intrudes only Units A and B, it is therefore older than Unit D, which overlies it, but younger than Unit A and either younger than or contemporaneous with Unit B. The irregular margins of the intrusions are a result of the unconsolidated state of the tephra pile of Unit B at the time of intrusion. Trace element data indicate that the composition of this intrusive rhyolite is near-identical to the rhyolite tephra of Unit B (Fig. 6). This suggests, on chemostratigraphic grounds, that they formed during the same eruptive event (McGarvie 1985; McGarvie et al. 1990). If this is the case, then the lack of vesicles within the intrusion suggests that the magma was able to degas during the later stages of ascent. The location of the intrusion convincingly demonstrates that this was a true flank eruption during the construction of Öræfajökull. Flank eruptions are
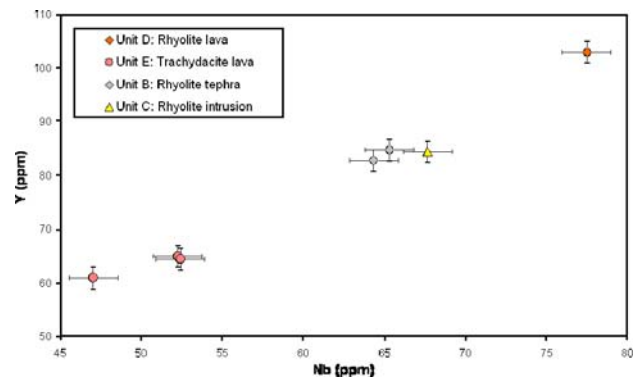

Fig. 6 Y versus Nb plot for selected silicic rocks at Vatnafjall, as obtained by XRF. The data have been recalculated on a volatile-free basis. Although water was absorbed to a greater degree by the pyroclastic rocks than the lavas (Table 1) there is no evidence, such as leaching of mobile elements (e.g. Na, Ca), to suggest that the relative concentrations of stable trace elements (Y and Nb) have been altered by this. Error bars represent instrument detection limits. Rhyolite eruptions in Iceland typically produce magmas with a very limited compositional range (McGarvie 1985) and this plot indicates that the Units B and C may be cogenetic

a common feature of composite volcanoes (Davidson and De Silva 2000).

Unit D: Rhyolite lava

Description

Unit D (Figs. 2 and 3) is the largest rhyolite unit in the mapped area yet it is the least examined due to thick scree cover on the upper and eastern surfaces, and the dangerous nature of the cliffs on the western side. It is a lava flow which lies unconformably upon Units A, B and C and extends for over 4 km along Vatnafjall. Fig. 2 illustrates the NW–SE elongation of the lava flow. It appears to be comprised of two flow units, with a suspected thin layer of tephra in between (Fig. 3); however, direct access to this layer was not possible. The maximum thickness of the individual units varies between 75 and 150 m, and they have a combined volume of approximately 0.2 km^3 (calculated from the mapped area and a mean thickness of 75 m). In hand specimen the lava is pale grey and microcrystalline with 1% white feldspar phenocrysts (<1 mm long). Vertical columnar joints up to 2 m wide are present in the centre of the flow, and these narrow toward the basal 2–10 m of the lower flow unit, which displays vertical columnar joints 10–30 cm in diameter. Frost action has exploited flow banding and caused the lava to break into flat plates. The flow bands are horizontal at the base of the lower unit, but have a variety of orientations on the ridge crest. There are 0.5–1 m high, sub-spherical hollows within the undulating base. The lava bordering these is glassy with hackly fractures. Within the hollows, the lava has broken to form an unconsolidated breccia with clasts from 150 cm to 2 mm in diameter.
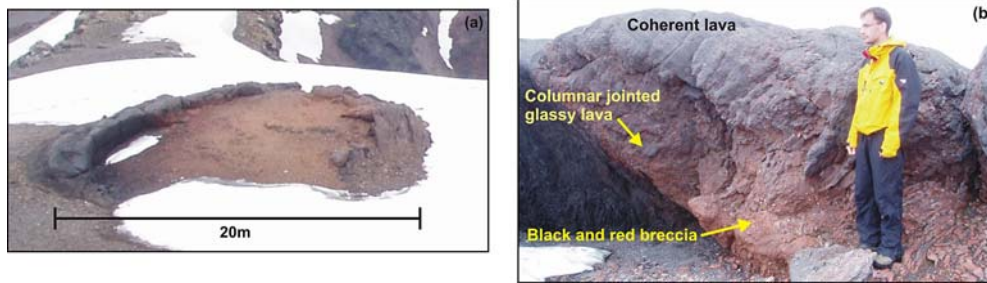
Fig. 7 (a) Circular depression on the surface of trachydacite lava, Unit E (Grid Ref: 248948). Four such depressions are found in the northwest of the lava flow. (b) Interior wall of depression, showing transition from coherent lava, via columnar-jointed lava, to breccia of glassy clasts coated by fine-grained red material. The breccia is interpreted to have formed where water has infiltrated the lava, and the circular craters may have resulted from small steam explosions

Interpretation

Lack of access to informative flow-marginal exposures, where the most useful information on eruptive environment would be found, makes it difficult to draw firm conclusions about conditions during the eruption of Unit D. The western margin has been removed by erosion, and the eastern margin is buried beneath scree and the products of later eruptions. In the southeast, the flow terminates abruptly, along with the basal basalt flows beneath it; it is likely that this area once formed a sea-cliff, eroded by undercutting of the basal basalt flows by the Atlantic Ocean, during times before the flat coastal plains or terminal moraine of Kviárjökull had formed (Thordarson and Hoskuldsson 2002).

The base lacks a flow-front breccia such as those found at many subaerial rhyolite lava flows (Fink and Manley 1987). Instead, it is chilled and glassy, with hollows containing a quench fragmented obsidian breccia. Such hollows have been interpreted as products of flow over ice-blocks (Lescinsky and Fink 2000), however the basal texture may result from the erosion of breccias derived from flow over cold, locally wet, ground. The basal topography shows that Unit D was emplaced onto a gently southeast sloping paleosurface, and this is mirrored in the flow banding. The apparent NW–SE orientation of the flow may reflect confinement on each side, but alternatively this could simply be a product of the erosion of the southwest side.

Unit E: Trachydacite lava

Description

Unit E is exposed along the crest of the NW part of the ridge, where it lies unconformably upon the eroded upper surface of rhyolite lava Unit D (Figs. 2 and 3). The thickness of this trachydacite lava varies from ∼25 m in the northwest to over 75 m in the southeast where it crops out on the glacier-side of the ridge crest. The volume is estimated to be 0.02 km^3. In hand-specimen, the lava is nonvesicular, pinkish or purplish grey with 1–5 vol% feldspar phenocrysts and sparse brown needle-shaped amphibole crystals up to 3 mm long. Clusters of plagioclase and amphibole crystals, and irregular mafic inclusions (<1 cm) are common.

At its eastern margin, the base of the lava is often associated with a pink or red clast-supported breccia of subangular lapilli-sized clasts of dark glassy lava. The pink colour is pervasive and appears to be associated with a very fine-grained matrix between the clasts, which also coats cracks and columnar joints. Flow bands within the base of the flow are also stained, as are spherulites that are common in the upper regions of the flow. At the NW end, the top of the flow has circular, crater-like, features up to 20 m in diameter and 3–4 m deep (Fig. 7a). They have flat, breccia-covered floors and raised walls in which the breccia changes from angular granules through lapilli-sized clasts (formed from broken up columnar joints), into columnar joints then into massive lava over a thickness of about 2 m (Fig. 7b). The flow bands in the lavas dip outwards. The same transition from breccia is observed at the base of the flow elsewhere. Elsewhere, the top of the flow is mainly covered in a 2–4 m thick blanket of angular blocks of varying texture.

The glacierward side of the SE end of the lava flow is dominated by thick (over 50 m) glassy exposure. A large buttress that forms a local topographic high in the southeast (Fig. 8a) shows prominent subhorizontal columnar jointing. It is glassy and fractured throughout and contains pink brecciated zones 1–2 m thick, similar to that comprising the basal breccia. The undulating base of the buttress lies upon a moderately-consolidated yellow-coloured breccia of small lapilli-sized pumice in fine-grained ash with occasional angular small blocks of flow-banded rhyolite. There is a 30 cm zone of interaction between the two units in which obsidian granules and pebbles from the overlying lava have mixed with the underlying pumice-ash breccia; ash from the breccia has been injected into cracks for up to 1 m into the overlying obsidian. In one basal cavity, a finger of the breccia 1 m wide had been injected into the lava for a distance of at least 4 m (Fig. 8b). Directly above this, on the buttress-top, is a sequence of moderately dipping (15°) beds of agglutinated glassy trachydacite clasts with fluidal shapes, capped by a layer of coarse pumiceous lapilli and blocks (Fig. 8c), which are similar in appearance to those within the pumiceous breccia finger (Fig. 8b). At the southeast edge the lavas thicken but the exposure is poor.
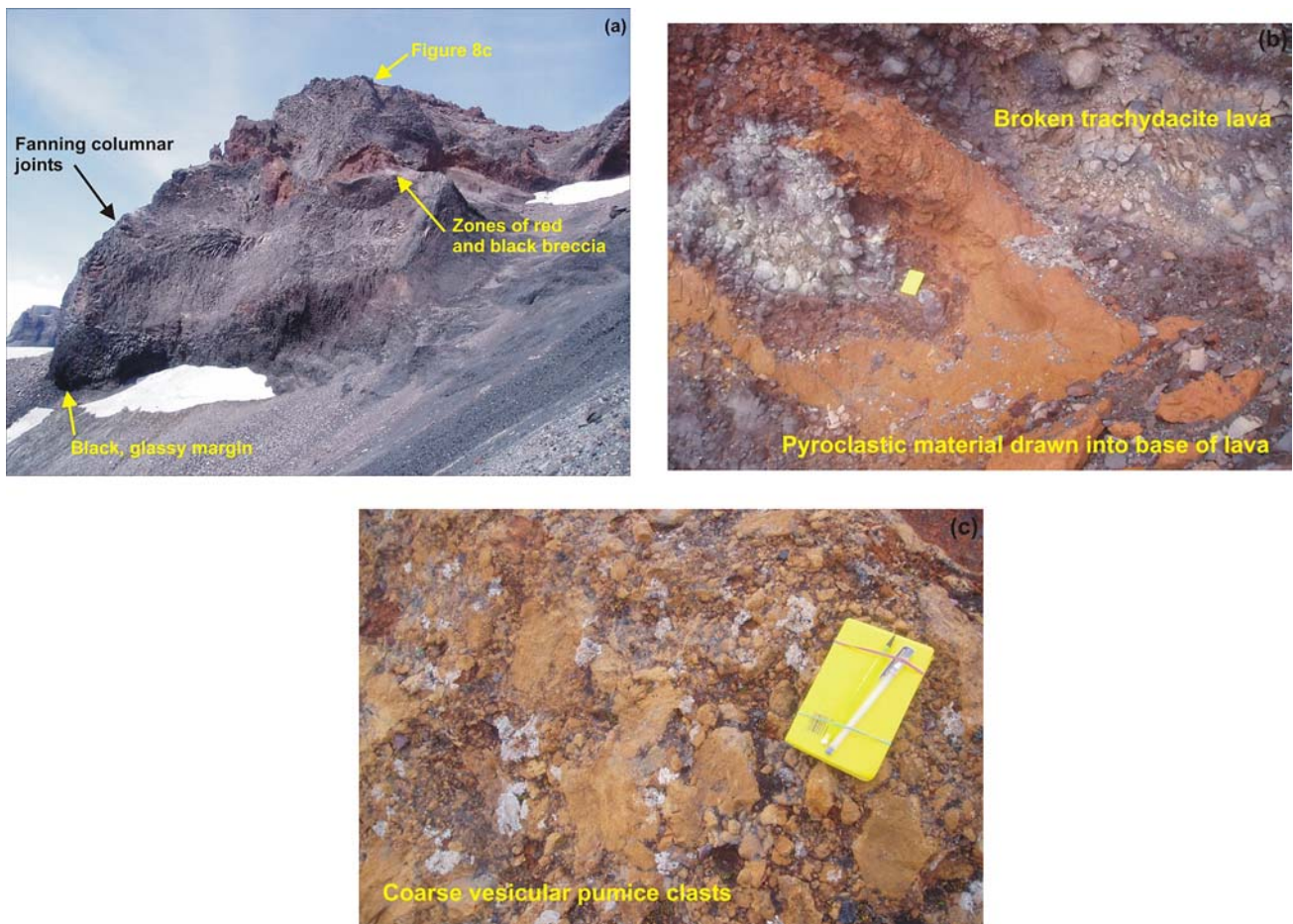
Fig. 8 (a) 50 m high buttress on side of trachydacite lava flow over-looking Kviárjökull, Unit E (Grid Ref: 257942). The flow thickness, fanning and subhorizontal columnar joints and abundant glassy material are interpreted to result from chilling of the lava against an ice wall. The brecciated zones may be due to water infiltrating the lava, and are similar to those shown in Fig. 7. (b) Base of Unit E (Grid Ref: 258942). Trachydacite lava is broken up, and a finger of the underlying coarse, orange-coloured pumice-ash breccia intrudes it. Notebook is 11×17 cm. (c) Upon the upper surface of the over-lying lava, welded rhyodacite spatter is capped by a clast-supported pumice breccia. The pumice is texturally similar to that beneath the lava and is interpreted to have been ejected onto the surface by a steam explosion

Towards the northwest end of the unit, a tongue of lava extends down the sides of the valley towards the glacier (Fig. 9). Near the foot of the valley it has thickened into a tooth-shaped pillar ∼70 m tall. Flow bands run in a slope-parallel orientation. Columnar joints are arranged subhorizontally in the vertical faces and are perpendicular to the bottom of the flow along the basal contact. The flow base is glassy and unconformably overlies both Unit A (basalt hyaloclastite and lavas) and Unit D (rhyolite lava).

At the far northwest of Unit E is a dome of lava approximately 200 m in diameter and up to 100 m high (Fig. 2). It has a volume of approximately 0.003 km^3. The margins are defined by concentric flow bands in the dense lava that define a tall dome-like outcrop. Weathering has picked out flow bands and rendered the lava fissile, causing it to form thin brown plates containing little fresh material, however in some areas, the lava grades into columnar-jointed obsidian.

Interpretation

The basal breccia formed from the glassy margins of the flow. Typically, basal breccias form at the flow front and are then over-run by the lava (Fink and Manley 1987). In this case, at least some of the basal breccia formed in situ directly from lava at the flow base, as basal columnar joints can be seen in the process of disarticulation. Much of the breccia is similar to the 'red and black breccia' of black glassy blocks and smaller fragments in a matrix of fused red oxidised ash, which have been described in the upper zones of lava flows in the Snake River Plain, Idaho, USA (Bonnichsen and Kauffman 1987). Its origin was attributed to the formation of steam from water entering cracks in the surface of the lava. With Unit E, the nature of the basal breccia suggests a laterally extensive source of water. This was possibly glacial meltwater or snow. The lack of flow-front breccia material at the flow base also indicates that development of a typical flow front did not characterise the growth of this lava flow, which might either indicate

Fig. 9 A 70 m tall, tooth-shaped lava pillar (Grid Ref: 246943) is found at the end of a trachydacite lava, which flowed unconformably over Units A and D and down the valley side. It must therefore postdate the excavation of the Kviárjökull valley. The steep-sided shape, varied columnar-joint orientations and abundant glassy material are interpreted to result from ice-confinement
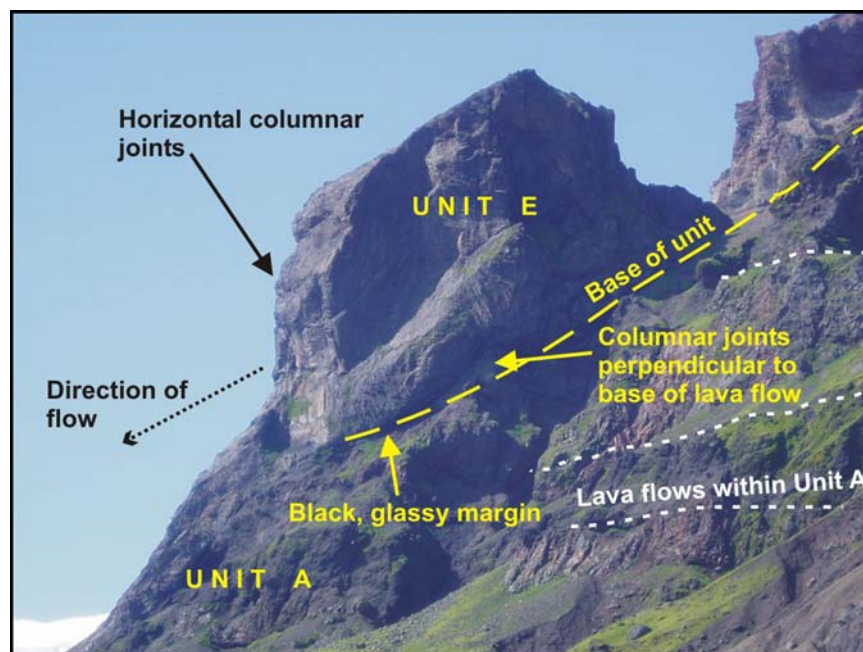
a further role for water that affected the upper surfaces of the flow, or that the flow-front abutted ice, which carried away clasts landing upon it. The brecciated zones within the flows may have been caused by deeper infiltration by meltwater and the crater-like depressions may have formed either where these have been exposed by erosion, or where steam blisters were disrupted in explosions during more violent interaction.

The lava at the base of the buttress shows some interaction with the substrate over which it flowed, such as quench fragmentation and transport of ash by steam to generate peperitic textures (Skilling et al. 2002). This is an indication of the presence of water, probably meltwater, within the substrate. Where the finger of substrate material was injected far into the lava flow, the interaction was more explosive (Fig. 8b). The deposits on the upper surface suggest that an explosion may have penetrated the entire lava flow (~25 m thick), leading to deposition on the flow top of viscous trachydacite bombs derived from the flow interior and pumice (Fig. 8c) entrained from the substrate beneath. This implies that the top of the flow was open to the air. This explosion mechanism has similarities with the formation of rootless cones, which are associated with Icelandic basaltic lavas that have flowed over wet substrates (Greeley and Fagents 2001; Thordarson and Hoskuldsson 2002). This could be the first record of such interaction in silicic lava flows.

The overthickening and associated subhorizontal columnar joints in the large buttress in the southeast are a strong indication of confinement of the lava flows, probably by ice. In each scenario described above, it is important to note that only relatively small volumes of water are involved, resulting in only localised brecciation, which contrasts with the large volumes of water involved in the formation of the hyaloclastite during in the subglacial basaltic eruption (Unit A). Assuming that this water is meltwater, this suggests that either (a) only small volumes of meltwater were

produced, or (b) the meltwater was able to drain away, probably as a result of steep topography.

Based upon its elevated location, it is suggested that the dome at the NW of the unit covers the vent that produced the lava, and comprises the last-erupted increment of magma. None of the marginal features of subaerial lava domes such as pumiceous carapace or talus slopes (McPhie et al. 1993; Fink and Anderson 2000), or subaqueous lava domes such as in-situ and resedimented hyaloclastites (McPhie et al. 1993; DeRita et al. 2001) are present on the dome. This suggests that marginal zones have been removed by erosion and therefore makes interpretation of the eruptive environment difficult.

Units F and G: Basaltic lavas

Description

On the NE side of the SE end of the ridge, Unit D is overlain by basaltic lava flows up to 8 m thick with an estimated combined volume of less than 0.01 km³ (estimated from the mapped area and a mean thickness of 8 m). They were not analysed by XRF and so chemical classification is based on field observations, and on information from Prestvik (1979), who mapped them as basalts. Four of the lavas have flowed from the crest of the ridge downslope to flatter ground where they have coalesced (Fig. 2). The lava is mid grey with approximately 5 vol% white feldspar phenocrysts and clusters of amphibole up to 8 mm in diameter. Columnar joints are absent. The bases of the flows are hidden beneath soil, except at the vents, where they lie directly upon rhyolite lava which exhibits near-vertically-orientated flow bands.

Most of the basaltic lava flows have smooth, polished and striated surfaces. These are mapped collectively as Unit F.
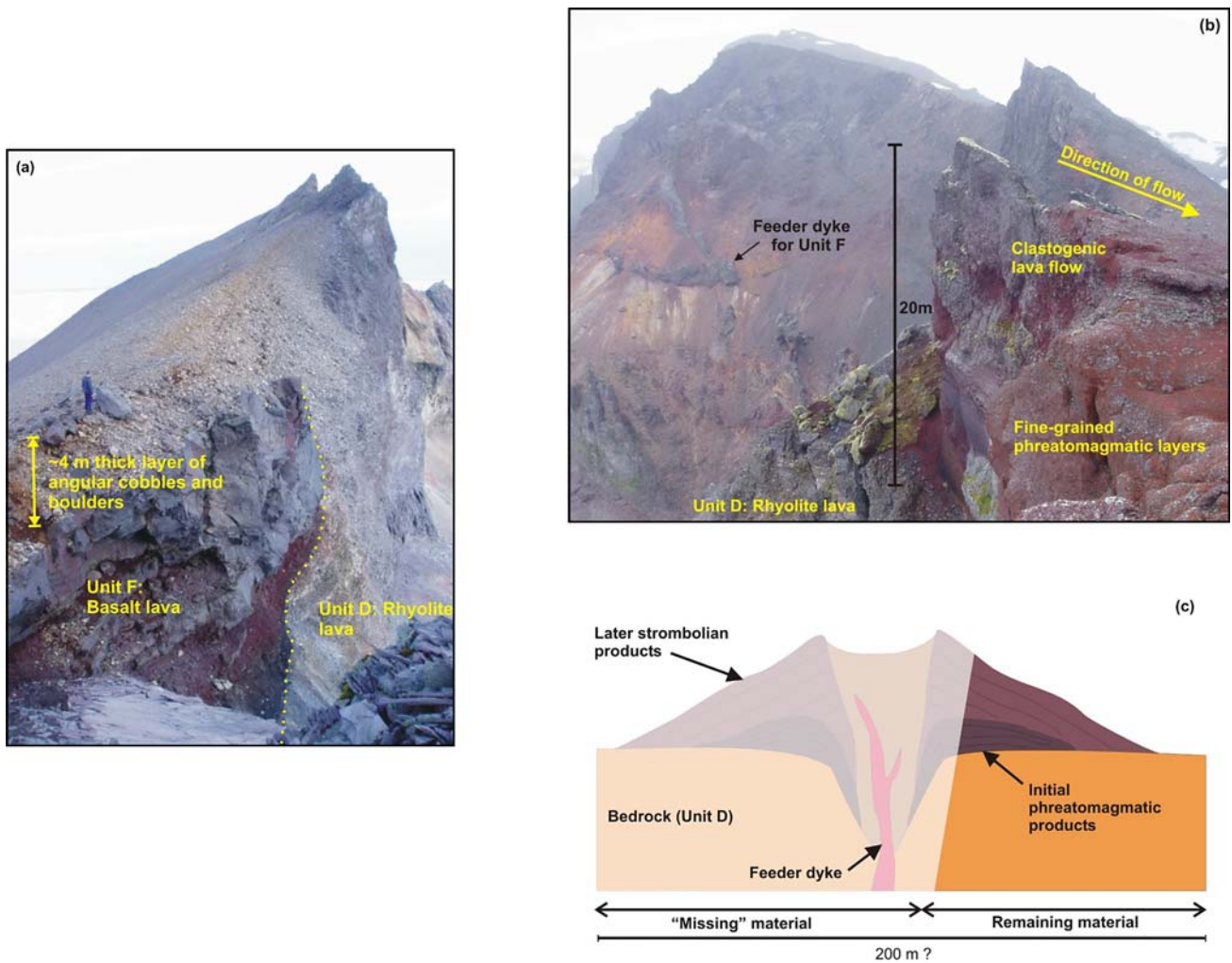
Fig. 10 **(a)** View SE down the ridge crest (Grid Ref: 263938) at the vent area of interglacial basalt lava, Unit F. The vent and lava flow have been buried by a 4 m thick blanket of angular cobbles and boulders. **(b)** 20 m thick section through the scoria cone of the postglacial basalt lava Unit G, showing products of both phreatomagmatic and strombolian activity (Grid Ref: 266935). If originally circular, the cone would have had a diameter of ~200 m. Note feeder dykes for interglacial basalt lava, Unit F, in background. **(c)** Schematic diagram of idealised scoria cone, showing hypothetical "missing" material, and material that remains today. If the cone was not symmetrical or if part was erupted onto ice, then the true extent of the erosion may be smaller. As the cone is postglacial in age, this erosion must have occurred in the last 10,000 years and is probably the result of a series of large collapses
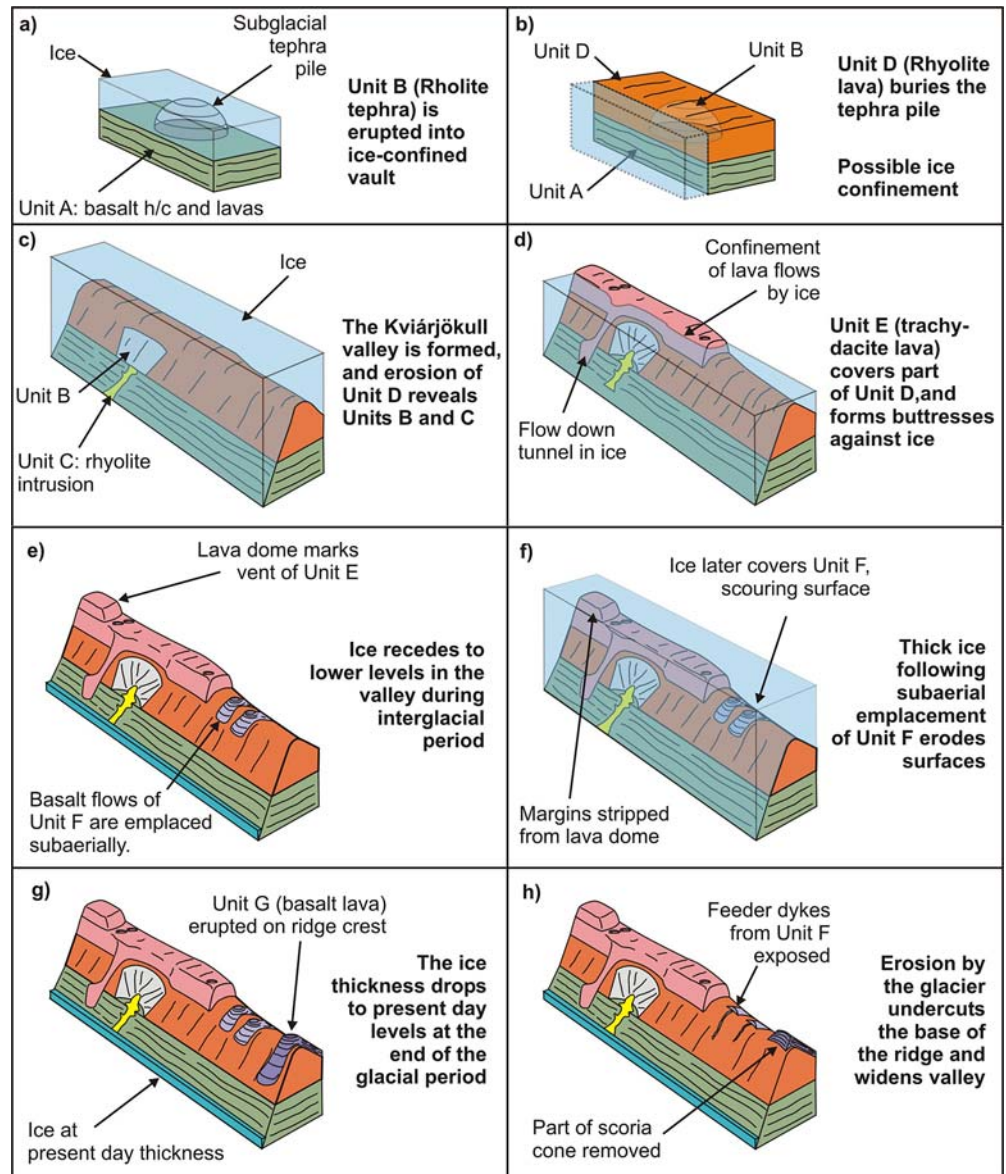
Part of one of these lava flows, and the thick layer of angular cabbles and boulders overlying it, are visible in Fig. 10a. The largest basaltic flow, Unit G, is fed from a scoria cone at the southeast end of the ridge and has a surface covered with red-oxidised ropy scoria clasts. A section through the scoria cone is visible on the southwest face. The base of the 20 m high section rests upon diamict and is dominated by lapilli and ash-sized particles, which grade into coarser scoria (Fig. 10b). The beds mantle and dip down the slope to the northeast. The middle 3–5 m of the sequence is welded.

There is no indication of any feeder dyke for Unit G, but at two of the flows of Unit F, further northwest along the ridge, mafic dykes can be seen cutting through the rhyolite beneath (Fig. 10b), and up to the bases of the lavas where unconsolidated scoriaceous breccias occur.

Interpretation

The mafic lavas rest unconformably on steeply dipping and debris-free surfaces cut into Unit D (rhyolite lava), which suggests that at least one glacial period passed between the eruption of Unit D and the two basalt units (F and G). Their age is unknown relative to Unit E. The oxidised surfaces and lack of jointing or hyaloclastite suggests that all the lava flows were erupted subaerially. They were fed by the agglutination of spatter and scoria from small vents near the ridge crest and are therefore clastogenic. The smooth-topped flows of Unit F have since had their surfaces scoured by ice and are interpreted as having been erupted during an interglacial period. The significant thickness of material upon the lava flow may represent fines-poor till deposited by a glacier, or screes that would

Fig. 11 Schematic reconstruction of the topographic evolution of Vatnafjall. The ice thickness, as discussed in the text and summarised in Table 2, is shown at various stages. Ice has promoted rapid topographic development both by confining lavas and tephras during eruptions, and by eroding them in between. h/c=hyaloclastite

a) Unit B (Rholite tephra) is erupted into ice-confined vault. Unit A: basalt h/c and lavas. Subglacial tephra pile.

b) Unit D (Rhyolite lava) buries the tephra pile. Possible ice confinement. Unit D, Unit B, Unit A.

c) The Kviárjökull valley is formed, and erosion of Unit D reveals Units B and C. Unit B, Unit C: rhyolite intrusion, Ice.

d) Unit E (trachy-dacite lava) covers part of Unit D, and forms buttresses against ice. Confinement of lava flows by ice. Flow down tunnel in ice.

e) Ice recedes to lower levels in the valley during interglacial period. Lava dome marks vent of Unit E. Basalt flows of Unit F are emplaced subaerially.

f) Thick ice following subaerial emplacement of Unit F erodes surfaces. Ice later covers Unit F, scouring surface. Margins stripped from lava dome.

g) The ice thickness drops to present day levels at the end of the glacial period. Unit G (basalt lava) erupted on ridge crest. Ice at present day thickness.

h) Erosion by the glacier undercuts the base of the ridge and widens valley. Feeder dykes from Unit F exposed. Part of scoria cone removed.

imply that the top of the ridge was much higher when the lavas formed, in order to shed clasts downslope onto the lava flows. Unit G, with its intact scoriaceous top has not been glaciated and is therefore likely to be of postglacial age, a conclusion that was also reached by Thorarinsson (1958) and Prestvik (1979). The morphology of the cone suggests that the vent and feeder dyke should be located to the west of the present ridge crest. Their absence implies that they were removed by erosion of as much as 50–100 m of the SW flank of Vatnafjall since the scoria cone was produced (Fig. 10c). This corresponds to a mean lateral erosion rate of as much as 5–10 cm per year, although it is likely that such erosion would have occurred as a series of large collapses. Collapsed material would be swept away by Kviárjökull, preventing the formation of a supporting talus ramp.

Discussion

Vatnafjall has been constructed by a series of mafic and silicic eruptions and all but the most recent basalts show evidence for interaction with or modification by ice. In the following section, the degree of interaction/modification is used to estimate the thickness of the ice during each stage of the development of the ridge. Discussion of the differences between eruptions of different compositions follows, and a geological history of the area has been constructed (Fig. 11).

Ice thicknesses during the development of Vatnafjall

The thickness of ice has varied by at least ~700 m during the course of the development of Vatnafjall (Fig. 11),

Table 2 Summary of confinement/water availability in the eruptive environment during the eruption of each of the mapped units

Mapped unit	Eruptive environment	Ice conditions
G: Postglacial basalt lavas	Broad oxidised flows lacking joints/fractures implies unconfined and subaerial	Present day
	Thick ice covers whole region	
F: Interglacial basalt lava	Broad oxidised flows lacking joints/fractures implies unconfined and subaerial. Upper surface has been scoured by ice	Present day
E: Trachy- dacite lava	Development of thick buttresses and tooth-shaped pillar implies lateral confinement. Minor meltwater interactions generate black and red breccias	Valley fill
	Excavation of Kviárjökull valley	
D: Rhyolite lava	No conclusive evidence for meltwater interaction, but NW–SE elongation may indicate confinement by ice	?
C: Rhyolite intrusion	Conditions for this phase are assumed to be the same as for Unit B	Sheet>200 m thick
B: Rhyolite tephra	Confinement of tephra leads to steep-sided pile 200 m thick. Initially abundant water declines during eruption	Sheet>200 m thick
A: Basalt hyaloclastite and lavas	Variable magma water interaction, with water sometimes able to drain through permeable ice. Little lateral confinement	Sheet<150 m thick

Note. The interpreted ice thicknesses are given in the final column. These are based upon evidence for confinement of, or interaction with, volcanic products by ice, or the estimates of the permeability of the ice (see text for details)

and its effect upon the eruptive environment can be used to interpret the thickness at each stage (Table 2). Such information is of use in paleoclimate reconstructions, particularly when combined with radiometric dating (e.g. Mee 2004). The evidence for this is discussed in relation to each mapped unit in detail below. Prior to the development of the Kviárjökull valley (e.g. during the eruption of Units A, B, C and possibly D), the ice is assumed to form a continuous sheet, and an estimated thickness is given based upon the confinement of the erupted edifice and the ability of water to drain from the eruption site (e.g. impermeable ice implies thickness greater than 150 m, Smellie 2000).

Following the formation of the Kviárjökull valley, the ice thickness is related to one of three states within a continuous range: present day, valley fill or thick. This is a more useful way of visualising the ice in this area of steep and evolving topography than estimating the ice thickness above the ground, or the elevation of the ice surface because the thickness of ice will vary greatly across the mapped area. The present day ice thickness, being an interglacial period, has ice restricted to within the summit caldera of Öræfajökull and at a low level within the Kviárjökull valley where it is ∼50 m thick (Spedding and Evans 2002). During valley-fill stages, ice fills the Kviárjökull valley up to the margins (400–600 m thick within the valley). In such cases it is likely that tongues of ice may advance from the summit of Öræfajökull, and may encroach on the valley to the east of Vatnafjall, however the crest of Vatnafjall remains at or above ice-level as a nunatak. Finally, during thick ice periods, the entire topography of the region is covered, and the ice may have a surface elevation of over 1000 m and a thickness of >700 m in the Kviárjökull valley. This situation may occur during times of glacial maxima. It is impossible to give more precise estimates, and the following discussions illustrate some of the difficulties in estimating ancient ice-thicknesses.

Table 2 shows that basaltic eruptions have not occurred at Vatnafjall during times of thick ice. This may be a consequence of the suppression of production of mafic melts

in the upper mantle due to loading of the crust by thick ice sheets (e.g. Jull and McKenzie 1996), or a more local effect related to magma chamber fractionation and melt buoyancy (e.g. Edwards et al. 2002). It is not possible to come to any broad, volcano-wide conclusion from this very localised study.

Unit A: Basalt hyaloclastite and lavas

The basaltic lava flows and hyaloclastites are very similar to those formed subglacially on the lower slopes of Eyjafjallajökull, where the ability of meltwater to repeatedly drain from the vent area was interpreted to suggest that the ice was thin (<150 m) at this time (Loughlin 2002). The morphology of the ice surface at this time cannot be reconstructed, as the paleotopography of the area was very different during these eruptions.

Unit B: Rhyolite tephra

Even if the current 200 m thick tephra pile does not represent the majority of the original deposit, it is likely that the existing high-aspect-ratio pile was supported by ice walls, implying a subglacial setting. Similar tephra piles are found at the bases of Icelandic subglacial rhyolite tuyas from Torfajökull (Tuffen 2001) and Kerlingarfjöll (Stevenson 2005), which were erupted into thick ice sheets. Examination of the erupted material indicates that significant water was present in the vent area to drive phreatomagmatic fragmentation during the early phases of eruption. It is likely that melting ice was the source. The only published theoretical calculations relating to subglacial rhyolite eruptions pertain to effusive eruptions and suggest that the magmas cannot melt sufficient space in the ice to allow water to collect at the vent (Höskuldsson and Sparks 1997). However, calculations based on effusive activity are inappropriate at Vatnafjall, where the eruption

was explosive and the high-surface-area pyroclasts would release their thermal energy more efficiently leading to more rapid melting (e.g. Guðmundsson et al. 2004). This indicates the need for a robust theoretical model for *explosive* subglacial rhyolite eruptions, and for detailed studies of their products (e.g. grain size distributions).

Phreatomagmatic fragmentation was most important during the initial stages of the eruption of Unit B, suggesting that some water may have accumulated at the vent before the eruption began. This is in contrast with the 1996 Gjálp eruption beneath the Vatnajökull glacier, where no evidence of melting was observed before the onset of volcanic tremor (Guðmundsson et al. 1997). However, it is possible for subglacial lakes to be sustained in areas of high geothermal flux e.g. Grimsvötn, Iceland (Björnsson et al. 2003), whilst Tuffen et al. (2002b) have demonstrated the ability of rising rhyolite magma to melt the base of a glacier. Water could have been retained in the vent area, provided there was a depression in the surface topography of the glacier above the vent (Björnsson 1988), and the ice was impermeable (i.e. >150 m thick). The confined tephra pile is over 200 m thick. This suggests a minimum ice thickness of 200 m, with a likely actual thickness that was much greater (Fig. 11a).

Unit C: Rhyolite intrusion

This unit was produced by part of the same eruption as Unit B, so the ice conditions are interpreted to have been the same. The exposure of the intrusion into the pile (Fig. 5) represents direct confirmation of the model proposed by Tuffen (2001) for subglacial rhyolite eruptions in which a pile of pyroclastic material was formed and later intruded by cogenetic lavas.

Unit D: Rhyolite lava

It is difficult to draw firm conclusions about Unit D, due to extensive erosion at the margins and the inaccessibility or inconclusive nature of the remaining exposures (Fig. 11b). If the NW–SE elongated shape is a result of ridge-confinement of the flow by valley glaciers on either side (e.g. Lescinsky and Sisson 1998), this would suggest that the ice was at valley-filling levels at the time, and that the Kviárjökull valley had already begun to form. However, the apparent elongation may be a result of later erosion. In either scenario, the emplacement of Unit D was followed by significant erosion and deepening of the Kviárjökull valley (Fig. 11c). Any marginal columnar joints or glass were removed by the glacier and parts of Units A, B and C beneath were uncovered.

Unit E: Trachydacite lava

Unit E flowed on the ice-confined ridge crest and to the east, where it is thin and associated with a distinctive basal breccia. On the glacierward side of the ridge the lava was confined by ice and able to thicken to form the southeast buttress (Fig. 11d). Lavas overthickened by ice damming have been reported elsewhere (Edwards et al. 2002; Kelman et al. 2002). The columnar joint orientations in the tooth-shaped pillar suggest that it also cooled against ice and flow band orientations suggest that it flowed unconformably down the side of the valley over Units A and D, possibly within a channel or tunnel melted into the ice that filled the valley. The overthickened form suggests that the magma then backed up to attain its final shape. Ice must therefore have filled the valley, to at least the level of the confined buttresses. The presence of the agglutinate and coarse pumice on the upper surface of the flow (formed by local, post-emplacement steam explosivity) suggest that the lava was not covered by ice or meltwater, but that it flowed within an open-topped, ice-bounded channel (Lescinsky and Sisson 1998). The abundant water source for the widespread formation of basal red and black breccia may have been meltwater or possibly snow.

Following emplacement, thick ice has polished and striated the top surface of Unit E and removed much of the marginal obsidian from the dome to the northwest edge of the flow. Hyaloclastites associated with the growth of a dome within a subglacial or ice-contact setting, or blocks from a subaerial setting, would be unconsolidated and easily stripped from the edifice (Kelman et al. 2002). The emplacement of Unit E was at some point followed by a period of thick ice when the glaciers spread over the current topography and into the adjacent valley, depositing the thick layer of angular blocks that cover the lower levels of the flow (similar to Fig. 10a).

Units F and G: Basalt lava flows

Subaerial mafic flows of Unit F, whose tops have been scoured and polished, probably formed during an interglacial period (Prestvik 1979). There was no ice present when the lava was erupted (Fig. 11e), but care must be taken when using this as an indication of age, as conditions necessary for ice to flow down the eastern side of Vatnafjall may not necessarily be restricted to times of thick ice during well-dated global ice advances, especially considering that the Vatnajökull icecap survives just 5 km away in our current warm climate. The striations on the flow tops were formed during a subsequent ice advance, either to a valley-fill or greater ice thickness (Fig. 11f). All of Unit G is unscoured, implying that it has only experienced present-day ice thickness and must therefore have formed in postglacial times (Fig. 11g).

Topographic development of Vatnafjall

An important edifice-forming feature of subglacial volcanism is that confinement of tephras, hyaloclastites and lavas leads to especially rapid construction of edifices (relative to the equivalent subaerial activity). This occurs in both mafic

and silicic eruptions. Loughlin (2002) presents a model for the development of Eyjafjallajökull, located 150 km to the west, by repeated small subglacial basalt eruptions, forming successive pillow lava and hyaloclastite ridges built on top of each other. With silicic lavas, where ice-confinement can lead to the development of lava flows up to 450 m thick (Lescinsky and Sisson 1998), ice-bounded lava flows form tall ridges. An important point is that the locations of valleys are determined by the absence of lava ridges, rather than by the erosive power of the glaciers, as demonstrated at nearby Skaftafell by Helgason and Duncan (2001). This style of topographic development is considered to be important at Vatnafjall, particularly during emplacement of Unit E (trachydacite lava flow), which has added large buttresses up to 75 m tall to the topography where it was ice-confined. It is not known whether the thickness of Unit D is partly related to ice-confinement.

Helgason and Duncan's (2001) model explains the rapid growth of local topographic relief in the Skaftafell region (adjacent to Öræfajökull), from <600 m to ~2000 m relief since 0.8 Ma, as a consequence of the formation of permanent ice channels, too large to be filled by volcanic eruptions during interglacial periods, that grew progressively deeper and wider. This study has demonstrated that Kviárjökull is one such channel, and that it may have initially formed as a consequence of the emplacement of the thick rhyolite lava flow (Unit D). Excavation of the surrounding subglacial basalt succession (Unit A) to reveal the rhyolite intrusion (Unit C) has deepened the valley by over 300 m. Hence the topographic relief at Kviárjökull has increased by both erosion of the valley floor and by construction of its walls. Degradation of the postglacial scoria cone (Unit G) shows that the ridge crest has retreated at least 150 m in less than 10,000 years (Fig. 11h). Additionally, the action of the ice has stripped talus, obsidian, columnar-jointed lavas and other marginal features from many lava bodies, making precise reconstruction of paleoenvironments impossible. Thus, the importance of erosion in glaciovolcanic settings should not be underestimated.

Summary

Investigation of the evolution of Vatnafjall reveals a complex history of subglacial and subaerial, basaltic and silicic volcanism. The presence of ice has influenced eruptions in two main ways: by producing meltwater and by confining eruptive products. Meltwater interactions had the greatest effect on the subglacial basaltic eruptions (Unit A), where some products were essentially subaqueous. In silicic eruptions, meltwater played a less significant role; it enhanced fragmentation during the explosive rhyolite eruption (Unit B), and infiltrated and brecciated trachydacite lavas (Unit E) as well as promoting peperite production at their bases. The differences in meltwater interaction are not solely due to compositional contrasts, as the lack of water during silicic eruptions may result from their eruption onto steeper topography leading to more efficient drainage of water from the vent region. Confinement by ice was more apparent in the more viscous silicic lavas, and led to the development of a steep rhyolite tephra pile and a pillar and high buttresses of trachydacite lava. Although these features give an indication of volcano-ice interactions, it is difficult to use them to give any more than a broad estimate of paleo-ice thickness at this locality. This is partly due to the erosive effect of the ice, which has stripped informative flow-marginal facies from the lavas, and carved deep valleys such as Kviárjökull into the volcanic pile. It is the combination of ice-confined construction and subsequent rapid destruction that have generated such complicated geology and make the ice-covered stratovolcano such a dynamic environment.

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