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RESEARCH ARTICLE

Lava penetrating water: the different behaviours of pāhoehoe and ‘a‘ā at the Nesjahraun, Þingvellir, Iceland

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Abstract The Nesjahraun is a basaltic lava flow erupted from a subaerial fissure, extending NE along the Þingvellir graben from the Hengill central volcano. It produced pāhoehoe lava followed by ‘a‘ā. The Nesjahraun entered Iceland’s largest lake, Þingvallavatn, along its southern shore during both phases of the eruption and exemplifies lava flowing into water in a lacustrine environment in the absence of powerful wave action. This study combines airborne Light Detection And Ranging (LiDAR), sidescan sonar and Chirp seismic data with field observations to investigate the behaviour of the lava as it entered the water. Pāhoehoe sheet lava was formed during the early stages of the eruption. Along the shoreline, stacks of thin (5–20 cm thick), vesicular, flows rest upon and surround low (<5 m) piles of coarse, unconsolidated, variably oxidised spatter. Clefts within the lava run inland from the lake. These are 2–5 m wide, >2 m deep, ~50 m long, spaced ~50 m apart and have sub-horizontal striations on the walls. They likely represent channels or collapsed tubes along which lava was delivered into the water. A circular rootless cone, Eldborg, formed when water infiltrated a lava tube. Offshore from the pāhoehoe lavas, the gradient of the flow surface steepens, suggesting a change in flow regime and the development of a talus ramp. Later, the flow was focused into a channel of ‘a‘ā lava, ~200–350 m wide. This split into individual flow lobes 20–50 m wide along the shore. ‘A‘ā clinker is exposed on the water’s edge, as well as glassy sand and gravel, which has been locally intruded by small (<1 m), irregularly shaped, lava bodies. The cores of the flow lobes contain coherent, but hackly-fractured lava. Mounds consisting predominantly of scoria lapilli and the large paired half-cone of Grámelur were formed in phreatomagmatic explosions. The ‘a‘ā flow can be identified underwater over 1 km offshore, and the sidescan data suggest that the flow lobes remained coherent flowing down a gradient of <10°. The Nesjahraun demonstrates that, even in the absence of ocean waves, phreatomagmatic explosions are ubiquitous and that pāhoehoe flows are much more likely to break up on entering the water than ‘a‘ā flows, which, with a higher flux and shallow underlying surface gradient, can penetrate water and remain coherent over distances of at least 1 km.

Keywords LiDAR · Lava · Iceland · Pāhoehoe · ‘a‘ā · Rootless

Introduction

Lava flows that penetrate water are common in ocean island and in rift zone settings, where interaction between the lava and the water produces a mixture of both lava and clastic lithofacies. Understanding the formation and consequently the internal structure of such deposits is important because the collapse of material into the water is hazardous (both local bench

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collapses or larger flank collapses, e.g. Kauahikaua et al. 2003; Masson et al. 2006) and because volcanic rifted margins, such as the Faroes–Shetland basin in the North Atlantic, are increasingly becoming targets for hydrocarbon exploration (Passey and Bell 2007).

Here, we describe the Nesjahraun, a prehistoric basaltic lava flow that entered Þingvallavatn, a lake in Iceland's western rift zone (Saemundsson 1992). It comprises both pāhoehoe and ʻaʻā lavas, allowing comparison of how the different lava types behave on penetrating water. The distribution of lava and clastic deposits and their relationship to explosive rootless cone formation (e.g. Fagents and Thordarson 2007) are described and interpreted. As a single lava flow, differences in lava composition or ambient conditions are minimal, and differences in local flow behaviour are related to changes in effusion or local flux rate.

Background

Lava penetrating water

The behaviour of lava as it enters water depends on the lava flow type. The division of basaltic lava flows into pāhoehoe and ʻaʻā based on their surface texture is well-established and can afford some insight into the emplacement mechanism of the flow. Pāhoehoe lavas, which have smooth or ropey surfaces, tend to be emplaced at lower effusion rates, on relatively flat surfaces, as successive small lobes that coalesce and thicken by inflation (Hon et al. 1994; Kauahikaua et al. 2003). They are often tube fed. ʻAʻā lavas, with surfaces covered by angular lava fragments, are usually emplaced when strain rates are higher (often as a consequence of a high discharge rate; Rowland and Walker 1990), or when lavas are cooler or more crystalline. They advance by the avalanching of clasts down the flow's simple front and are often fed by open channels (Kilburn 2000). Observations of pāhoehoe and ʻaʻā flows entering water and their deposits are summarised below.

Pāhoehoe

For over 20 years, pāhoehoe flows from the Puʻu ʻŌʻō-Kūpaianaha eruption of Kīlauea, Hawaii, have been observed entering the ocean, where they form tube-fed lava deltas, typically a few hundred metres wide. Lava deltas are defined as 'all the land built beyond the pre-eruption coastline' (Kauahikaua et al. 2003, p. 73) and include lava benches, which are unstable parts of the delta built within the scar of a previous collapse. Umino et al. (2006) described formation of a lava delta by lobes flowing parallel to the shoreline that inflated and fed smaller lobes. Phreatomagmatic explosions, often triggered by bench collapse, were common on the lava deltas where the entrance flux was relatively high (>4 $m^3\ s^{-1}$; Mattox and Mangan 1997). Open mixing between lava and seawater due to a bench collapse exposing molten lava to the waves produces tephra jet explosions, whereas confined mixing when seawater infiltrates a lava tube produces rings of spatter in littoral lava fountains (Mattox and Mangan 1997). The largest littoral cones produced by explosions from tube-fed pāhoehoe flows on Hawaii are 400 m in diameter and are associated with high (5–20 $m^3\ s^{-1}$) lava fluxes (Jurado-Chichay et al. 1996).

Information on the submerged parts of lava deltas comes from direct observation, geophysical surveys and studies of ancient deposits. Lobate sheet flows, pillow lavas and hollow, tumulus-like lobes have been photographed on gentle slopes by remotely operated vehicles (Umino et al. 2000), but steeper slopes (25–40°) were observed by Tribble (1991) to be dominated by loose debris with only 20% pillow lavas. Narrow, tube-fed active lava streams, 0.7–1.5 m wide, were observed carrying lava directly down-slope beyond the maximum visible depth of 50 m; bathymetric data suggest that this slope continues to 250 m depth (Tribble 1991). Similarly, multibeam echo-sounder results from the Azores found offshore gradients of 25–35° extending to beyond 120 m depth offshore of lava deltas (Mitchell et al. 2008). Shallower dips (4–7°) in the upper 20–30 m were interpreted to be a result of wave erosion. Ancient lava delta deposits are best exposed in subglacial volcanic successions (e.g. Laugarvatn, Iceland; Jones 1970). They comprise angle-of-repose material derived by gravity-driven, non-explosive fragmentation of coherent lava facies, with additional fluidal clasts derived from the collapse of ponded lavas or the gravity-driven pinching of pillows or sheet flows (Skilling 2002).

ʻAʻā

Fewer observations relating to ʻaʻā flows penetrating water exist, although contemporary descriptions of flows as 'relentless fiery rivers', 'hissing' and 'detonating' were made of the 1840, 1868 and 1919 flows at Kīlauea and Mauna Kea, Hawaii (Moore and Ault 1965). These flows produced large littoral cones up to ~100 m high and 500 m in diameter, which are dominated by ash and lapilli, although bombs and spatter are present to a lesser degree. The cones were formed during tephra jet explosions resulting from open mixing between lava and seawater (Mattox and Mangan 1997), and the lava fluxes required to generate such explosions may be ten times greater than those involved in pāhoehoe littoral cones. The Pu‘u Hou cones of the 1868 eruption are two kidney-shaped half-cones around the lava channel. They have this form because material deposited on the lava surface was carried away by the flow (Fisher 1968).

Submarine observations of an ‘a‘ā flow that entered the ocean on Hawaii show that the flow remained coherent beneath the water (Moore et al. 1973), with a circular cross-section and a jagged, breadcrust-like surface. At 25 m depth, it budded a series of 1 m diameter lobes. Mitchell et al. (2008) used multibeam sonar to map coherent flows <200 m wide on slopes with gradients of 2–5° on the shelves of the Azores islands. One flow extended 1.5 km offshore to a depth of 380 m across a slope of ∼17°. Tucker and Scott (2009) examined an ancient water-penetrating basalt-to-basaltic-andesite block flow in the Northern Cascades that had an intensely fractured interior caused by the penetration of water along cooling joints. This flow was associated with hyaloclastite interpreted to have formed in phreatomagmatic explosions and produced peperite where it intruded lake sediments. Crudely bedded hyaloclastite breccias and water-chilled lava bodies were also described in northern Victoria Land, Antarctica, by Smellie et al. (2010). They formed where a basaltic ‘a‘ā lava flow entered an ice-dammed lake. Some of the hyaloclastite breccias contain oxidised clasts that had initially formed subaerially by autobrecciation of the surface of the flow and had been carried on top of it into the water.

Rootless cones

Studies of littoral cone formation are dominated by examples from the coastlines of Hawaii, but phreatomagmatic explosions caused by lava–water interaction also occur inland, where they produce rootless cones. These are common in Iceland, with good examples at Myvatn (Greeley and Fagents 2001), and associated with the Eldhraun and Laki lava flows (Greeley and Fagents 2001; Hamilton et al. 2010). The water source for these explosions is typically waterlogged sediments, as found in shallow lakes, or wetlands, or on a glacial outwash plain (Fagents and Thordarson 2007). The cones are usually found in groups of tens or hundreds associated with a particular basin or source of water (Hamilton et al. 2010). Rootless cones are typically circular, 4–450 m wide, 2–40 m high, and consist of a lower sequence of well-bedded scoria lapilli capped with an upper sequence of crudely bedded spatter and agglomerate (Fagents and Thordarson 2007). According to dynamic models of rootless cone formation, explosions are caused by cracking of the base of an inflating flow as it subsides into the substrate, thus allowing hot lava to mingle with the unconsolidated wet sediment beneath (Fagents and Thordarson 2007), and substrate materials are usually found within the deposits, particularly in the lower parts (Hamilton et al. 2010). The explosivity is controlled by the mixing ratio of lava/water and the degree of mixing, and explosions can end when the supply of either lava or water is cut off (Fagents and Thordarson 2007).

Geological setting

The Nesjahraun is located in Iceland's western volcanic zone, a zone of crustal extension running approximately SW to NE from Reykjanes to Langjökull that accommodates part of the 18–20 mm year^{-1} spreading of the northern Mid-Atlantic Ridge (Fig. 1; inset map). Postglacial volcanic activity in the region has erupted 110 km^3 of magma since 12 ka, with 64% of this material erupted as 11 shield volcanoes during the first 3,000 years since deglaciation (Sinton et al. 2005). Þingvallavatn is a lake located 10 km NE of Hengill central volcano that formed because the axis of tectonic subsidence is offset from the axis of volcanic activity, resulting in a deep, fault-bounded, depression (Sinton et al. 2005). The lake is generally 40–80 m deep and is fed by spring water that has percolated through the postglacial lava shields of Eldborgir and Skjalbreiður (Saemundsson 1992). Consequently, the sedimentary record in the lake is dominated by windblown and biogenic material, with marker beds of dated volcanic tephra. This gave Bull et al. (2003) tight control on subsidence and fault movement, allowing them to estimate extension rates across the Þingvellir graben of 3.2–8.2 mm year^{-1} (i.e. 17–43% of the total mid-Atlantic spreading).

The lava flow Þingvallahraun, which flowed into the northern end of the lake at 10,200 B.P. and is the oldest sub-division of the lavas called Eldborgir by Saemundsson (1992), crops out on the northern shore of Þingvallavatn. The front of the lava forms a 40–90-m-high subaqueous scarp, identifiable in the bathymetric maps (Bull et al. 2003). Such scarps are commonly associated with compound lava flows that brecciate as they enter water (Saemundsson 1992). The Þingvallahraun dammed the outflow from the lake, causing the surface

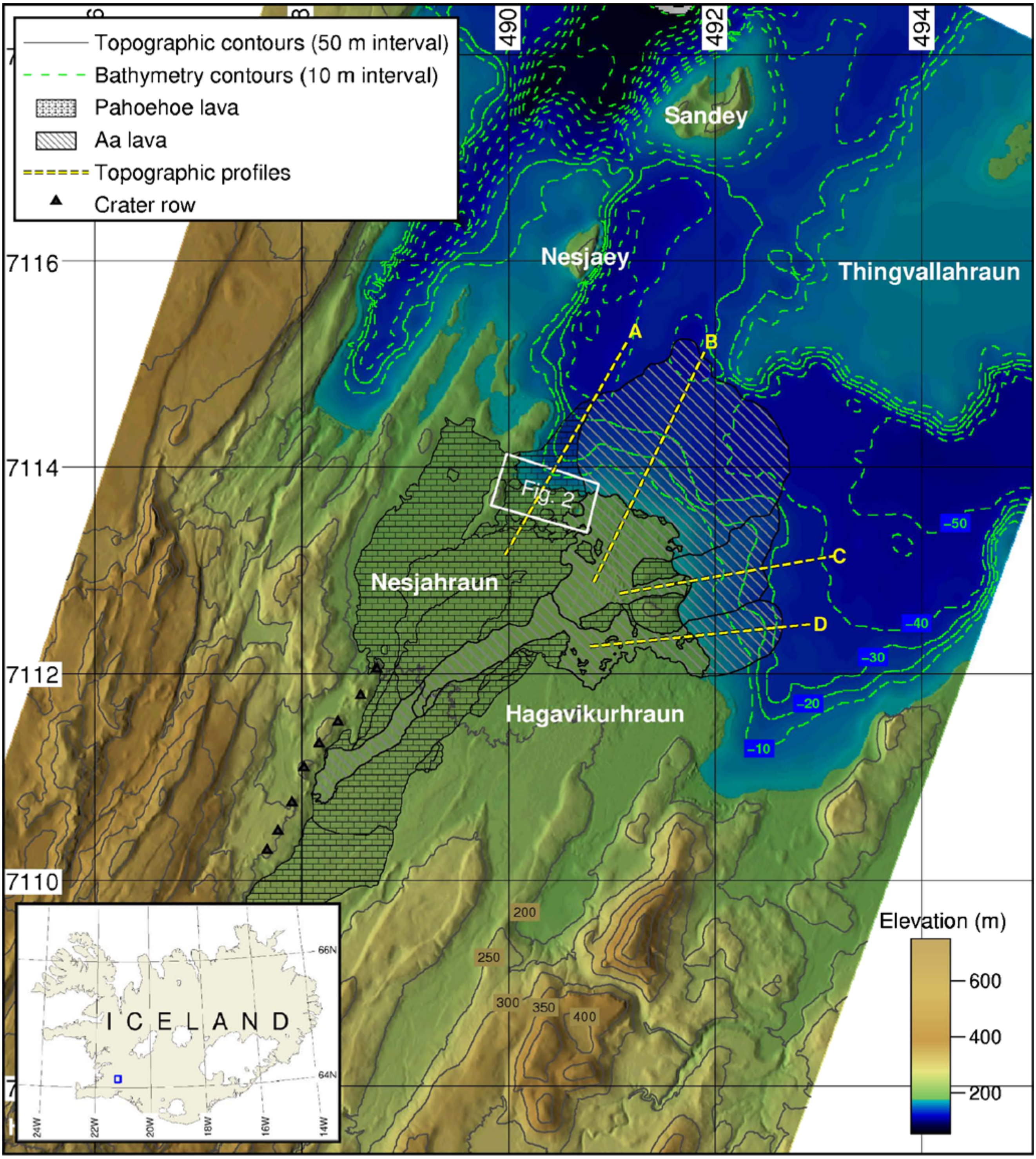

Fig. 1 Topography and bathymetry of the Hengill–Thingvallavatn region (coordinates in UTM Zone 27W, WGS84 datum, grid size 2 km). The topography was measured by LiDAR; the bathymetry is a combination of survey data from the Hydrological Survey of the National Energy Authority (Landmaelingar Islands 1988) and Chirp data (Bull et al. 2003). These data were combined by kriging and smoothed with a denoising algorithm. The Nesjahraun fissure extends from Hengill to Sandey. Þingvallahraun (10.2 ka) and Hagavíkurhraun (5.7 ka) are two older flows that also entered the lake

to rise to 11 m above the current level (Saemundsson 1992). Post-emplacement subsidence of the graben by up to 20 m has since submerged parts of the flow (Saemundsson 1992). Hagavíkurhraun was erupted 5,700–5,800 B.P. to the south of Þingvallavatn from a fissure parallel to and near that of the Nesjahraun

(Fig. 1, Saemundsson 1992). At this time, erosion of the lava dam at the outflow from Þingvallavatn had lowered the level to ~3 m above the present level; the surface stabilized at the current level at 4,000–5,000 B.P. and remained constant until it rose a few tens of centimetres following construction of a hydroelectric dam in 1959.

The Nesjahraun was erupted 1,880 ± 65 B.P. from two fissures, each 10 km long and running 030° to the north and south of Hengill (Sinton et al. 2005). The northern fissure extended into the lake, producing the tuff cones of Nesjaey and Sandey (Fig. 1), which deposited tephra within the lake and along the eastern shore (<40 cm thick, Saemundsson 1992). Lava from the onshore cones formed the Nesjahraun, adjacent to the Hagavíkurhraun, between Hengill and the southern shore of Þingvallavatn. The surface comprises both pāhoehoe (to the NW) and ʻaʻā (forming a channel in the east) (Saemundsson 1992). The onshore emplacement of the Nesjahraun, including the relationship between the pāhoehoe and ʻaʻā lava facies, is described by Stevenson et al. (2011). The subaqueous extent of the Nesjahraun was mapped beneath the water to 1.5 km from the shore, where it abuts the southern flow front of Þingvallahraun (Thors 1992; Bull et al. 2003).

Methods

Onshore data were collected in August 2007 by the UK's Airborne Research and Survey Facility (ARSF). They included the light detection and ranging (LiDAR) data and aerial photos used here. Processing of these data, including denoising of the LiDAR data (Sun et al. 2007; Stevenson et al. 2010), is described in Stevenson et al. (2011).

Þingvallavatn was surveyed with a Chirp sub-bottom profiler with a 2–8-kHz swept source and a 100-kHz sidescan sonar. Data were collected simultaneously from a small research vessel, with differential GPS navigation (Bull et al. 2003). Petrel$^{(\mathrm{TM})}$ seismic interpretation software was used to pick horizons in the Chirp data. The two-way travel time (TWTT) to the lake bed was extracted along each survey line and depth converted ($v = 1{,}427\ \mathrm{m\ s^{-1}}$; water at 5°C). The results were combined with depth measurements collected by the Hydrological Survey of the National Energy Authority (Landmaelingar Islands 1988) and interpolated by kriging (Pebesma and Wesseling 1998) in Geographic Resources Analysis Support System GIS (GRASS Development Team 2009) to produce a bathymetric DEM of the lake bed. Coastal exposures were examined during fieldwork in September 2008, which was informed by the ARSF data.

Onshore geology

Pāhoehoe

Description

The pāhoehoe part of the Nesjahraun flow crops out mainly at the western edge of the flow (Fig. 1) and covers 6.46 km^2. It is also found by the roadside on the eastern part of the lava flow field. To the west and near the shore, it consists of flat, smooth pāhoehoe with very little relief (which takes the form of slightly domed polygonal slabs 2–5 m in diameter). Near the vents in the south are ridges and elevated 'islands', ≤4 m tall, of shelly pāhoehoe. The formation of the platy-ridged lava and shelly pāhoehoe is discussed in detail by Stevenson et al. (2011).

The most prominent feature on the pāhoehoe shoreline is the circular cone of Eldborg (Fig. 2), which has a crater-rim diameter of 95 m, is 20 m tall and contains a small pond in the centre that is hydraulically connected to the lake. The crater walls consist of outward-dipping layers of scoria capped with ~3 m of agglutinate, comprising multiple irregular layers. A low mound SW of Eldborg similarly consists of spatter and probably has a similar origin.

The shoreline of the lake associated with pāhoehoe lavas consists of rocky headlands, steep-walled bays and channels with box-shaped cross sections (Fig. 2). In comparison to an oceanic setting, wave energy at Þingvallavatn is limited by moderate mean wind speeds (2.7–3.1 m s^{-1}; Einarsson 1992) and by the short fetch (10–15 km; Adalsteinsson et al. 1992), which also restricts wave activity to times when the wind is blowing. Nevertheless, erosion is not negligible and the shoreline has retreated since the lava was emplaced. This allows the deposits along the shoreline to be examined in cross section. The headlands consist of coherent lava bodies. The bays, which are 30–100 m wide, have been eroded from unconsolidated pyroclastic material, ranging from black (in part glassy) microvesicular coarse lapilli and blocks with small (<1 m) irregular, fractured intrusions to well-sorted, clast-supported lapilli of red/purple oxidised spatter with elongate/fluidal forms. The pyroclastic deposits are capped with up to 1 m of thin (<15 cm) shelly pāhoehoe lava flows, which locally show signs of plastic deformation and contain low, wide, void spaces (Fig. 3). Fragments of these thin lava flows are found

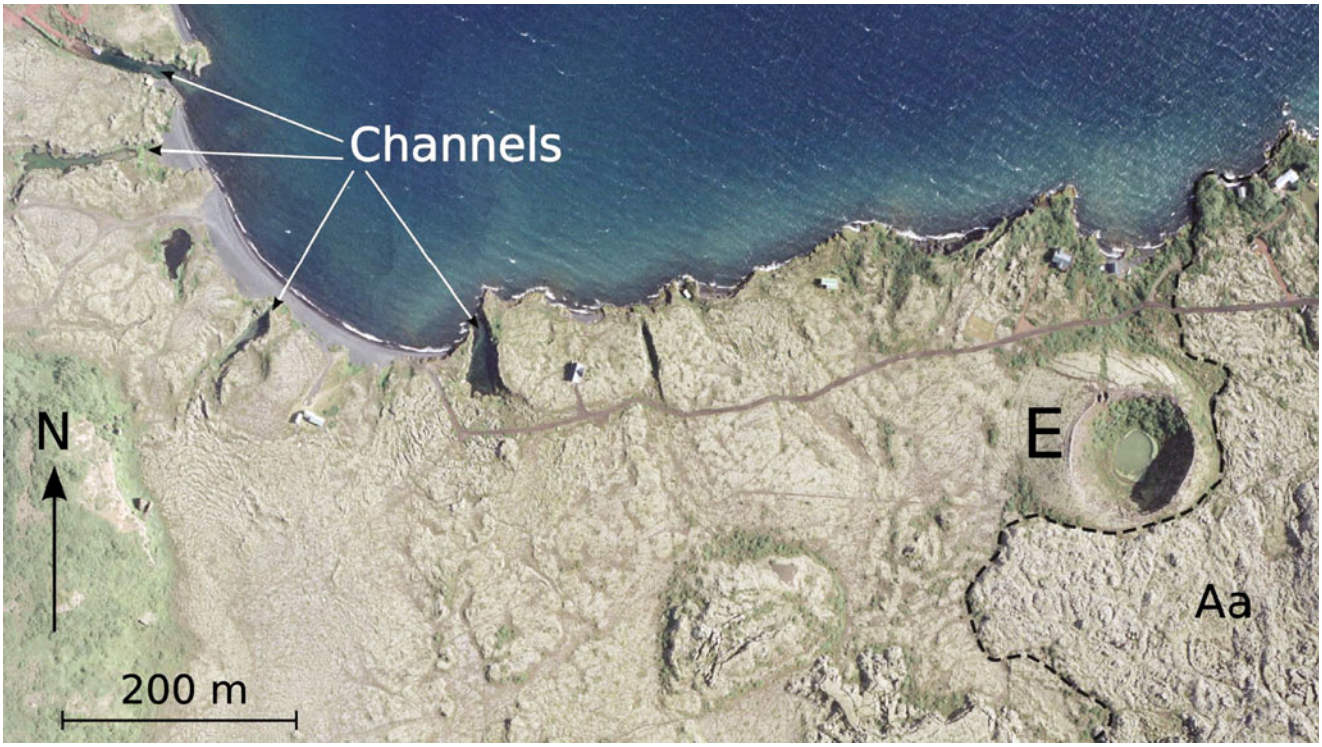

Fig. 2 Aerial photograph of the pāhoehoe shoreline. Clefts in the lava run inland from the lake. Their walls are plastered with horizontally columnar-jointed lava with sub-horizontal striations. Some are filled with broken blocks. They represent drained lava channels/tubes that previously delivered a high flux of lava offshore. Surface textures show how lava flowed through them. To the *right of the image* is the rootless cone, Eldborg (*E*), whose rim is 90 m in diameter. ʻAʻā lava can be seen flowing over the pāhoehoe and around Eldborg from the *right-hand side of the image*

amongst the spatter. No pillow lavas were found. In the west, a series of clefts run into the lake. These are 2–5 m wide with box-shaped cross sections. They are spaced ~50 m apart and some of them run through the middle of small mounds. They have very steep walls, and the floors are of many are covered in rubble. One well-exposed example (location 490070, 7114025) has a vertical-to-overhanging wall that is 5 m high with a 15-cm-thick skin of lava plastered over it. The skin has horizontal columnar joints and sub-horizontal striations scored into it. Behind the skin, the channel runs through unconsolidated spatter overlain by thin and contorted vesicular lava flows.

Interpretation

This part of the flow was emplaced as a series of lobes that coalesced into a sheet-like unit, with an absence of channel features, implying that the lava was distributed around the flow field endogenously, within preferred lava pathways. The lack of tumuli suggests that there was a steady or high supply of lava (Hon et al. 1994; Self et al. 1998). In the centre of the flow field, the surface has been pushed up as 20–50-cm-thick slabs, 1.5–3.5 m in diameter to form ridges, much like the platy-ridged lava described by Keszthelyi et al. (2004).

At the shoreline, the lava is interpreted to have flowed in channels and tubes and generated spatter and scoria piles by weak explosions due to closed mixing of lava and water (Mattox and Mangan 1997). The small proportion of ash or finer particles suggests that open mixing, as occurs in Hawaii when bench collapse exposes molten lava to the waves, was not an important process here. Unlike in the oceanic environment, where loose material is removed by waves, here the scoria remained in place and frequent overflows from the channels capped it with shelly pāhoehoe (Swanson 1973). Offshore, the channels/tubes may have supplied a front of advancing pillow lavas or sheet flows (Kauahikaua et al. 2003). As lava drained at the end of the eruption, it scoured the walls and the later collapse of tube roofs produced the clefts filled with rubble.

The circular cone of Eldborg, located far from the source vents for the Nesjahraun and not having produced a lava flow of its own, is interpreted as a rootless cone, in agreement with Saemundsson (1992). The size, shape and internal stratigraphy are similar to those of other Icelandic rootless cones (Fagents and Thordarson

Fig. 3 Characteristics of pāhoehoe lava on the lake shore, as seen within small embayments from where unconsolidated, oxidised, coarse-lapilli-sized spatter deposits have been eroded. The clasts have fluidal shapes and vary in colour from *red* and highly oxidised to *black/grey* and glassy. The coarse grain size suggests that they formed in rootless lava fountains, when water infiltrated the lava tube system. The spatter is often overlain by thin pāhoehoe flows. Spatter like this is common along the coastline, and although it sometimes forms large cones that are visible in the remotely sensed data, much of this spatter-underlain pāhoehoe is indistinguishable from thicker pāhoehoe flows in these data. Location 490410, 7113780

2007) and to cones produced by littoral fire fountaining in Hawaii (Mattox and Mangan 1997). The present day hydraulic connectivity between the cone and the lake demonstrates that the base lies below the water table. Explosions were therefore probably generated by water infiltrating the lava tube (Mattox and Mangan 1997) as opposed to cracking of the flow base (Hamilton et al. 2010). In this case, the water supply is unlikely to have been exhausted and the explosions probably stopped due to a lack of lava. The nearby scoria mound probably had a similar origin but with a shorter-lived period of mixing of lava and water (Wohletz 2002; Fagents and Thordarson 2007).

‘A‘ā

Description

‘A‘ā lava outcrops along the shoreline to the east of Eldborg and as an ~200–350-m-wide channelized lava cutting through the pāhoehoe outcrop running from the shore all the way back to the vent area (Fig. 1). It also extends through and surrounds the rootless cone of Grámelur. It has a total onshore area of 2.14 km^2. The ‘a‘ā lava was formed later in the eruption than the pāhoehoe; in the channel, it is inset within it; on the shoreline near Eldborg, it overlies it. Where it encircles the eastern side of Eldborg, it can be contrasted with the adjacent pāhoehoe (Fig. 2). The lava has a blocky texture, comprising rough ‘a‘ā clinker. Additionally, it contains clasts of different textures including pāhoehoe slabs, ‘knobbly slabs’ (approximately tabular pieces of irregular, rough, vesicular lava), composite clasts (that comprise numerous other clasts welded together), lava balls (a particular type of clast having concentric shells of lava around a central clast and reaching up to 6 m in diameter) and rafted lava (large blocks consisting of stacked shelly pāhoehoe sheets, still in an approximately horizontal orientation). Where ‘a‘ā lobes overlie pāhoehoe at Eldborg or were measured adjacent to the Hagavíkurhraun, they are ~5 m thick. At the northern end of the ‘a‘ā channel, the lava surface exhibits prominent ogives. Where these ogives have been cut by the road, their clinker-dominated interior is exposed, with no indication of coherent lava in the visible 3-m sections. Enclaves of pāhoehoe lava (<100 m wide) can be found within the ‘a‘ā region of the flow (Fig. 1). Some are rafts of lava within the channel; others form low cliffs on the shoreline. The central channel of Grámelur forms a small headland, which consists of pāhoehoe lava (Fig. 4b).

Where ‘a‘ā flow lobes entered the water, they formed hackly fractured lava bodies (fracture spacing 5–25 cm; Fig. 4a) at the shoreline sometimes with columnar jointing and/or a glassy appearance in the lowest 1.5 m. They are associated with unconsolidated clinkery rubble, which may be oxidised or glassy and which commonly features small, hackly fractures and irregularly shaped intrusions (Fig. 5a).

The cone Grámelur is 600 m wide and 40 m tall. It comprises two kidney-shaped mounds with a lava-filled channel running between them and extending into the lake. Erosion has removed at least 50 m from the lakeward side of the cone. The mounds are made of unconsolidated angular, black, scoriaceous lapilli and ash with occasional small (<10 cm) spatter clasts. Similar material is found in other smaller mounds, to the E of Grámelur (Fig. 5b). Figure 6 shows how the ‘a‘ā lava flows through, to the W of and to the E of Grámelur. A rocky headland just W of Grámelur marks the remains of another, smaller, open-channel cone.

Interpretation

As the ‘a‘ā flows reached the shore, if the mixing ratio was unsuitable to cause explosions (e.g. Wohletz 2002), they were chilled by water and steam, which produced quench hyaloclastite and caused hackly fracture in the cores of the flows (Lescinsky and Fink 2000; Tucker

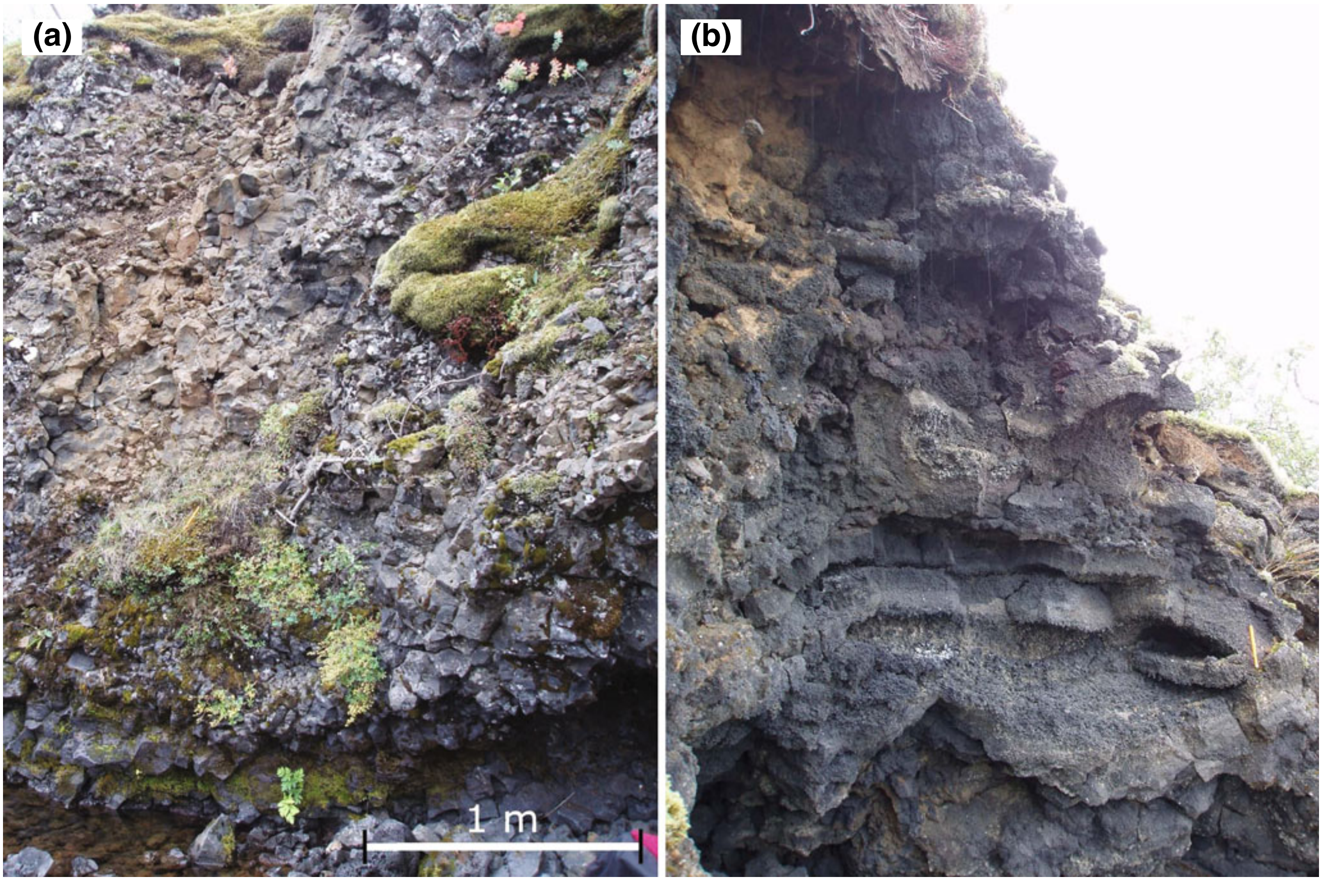

Fig. 4 Lava textures at the shoreline. **a** Larger lava bodies of coherent ‘a‘ā lava are fractured into small, angular blocks (*hackly fracture*). This is a result of quenching by water and/or steam, demonstrating that the lava interacted with significant amounts of water on the lake shore. Location 491640, 7113240. **b** The pāhoehoe lava region at the tip of the Grámelur lava channel consists of stacks of thin, vesicular pāhoehoe sheets with large void spaces. *Orange* pencil (*lower right*) for scale. Location 491750, 7112910

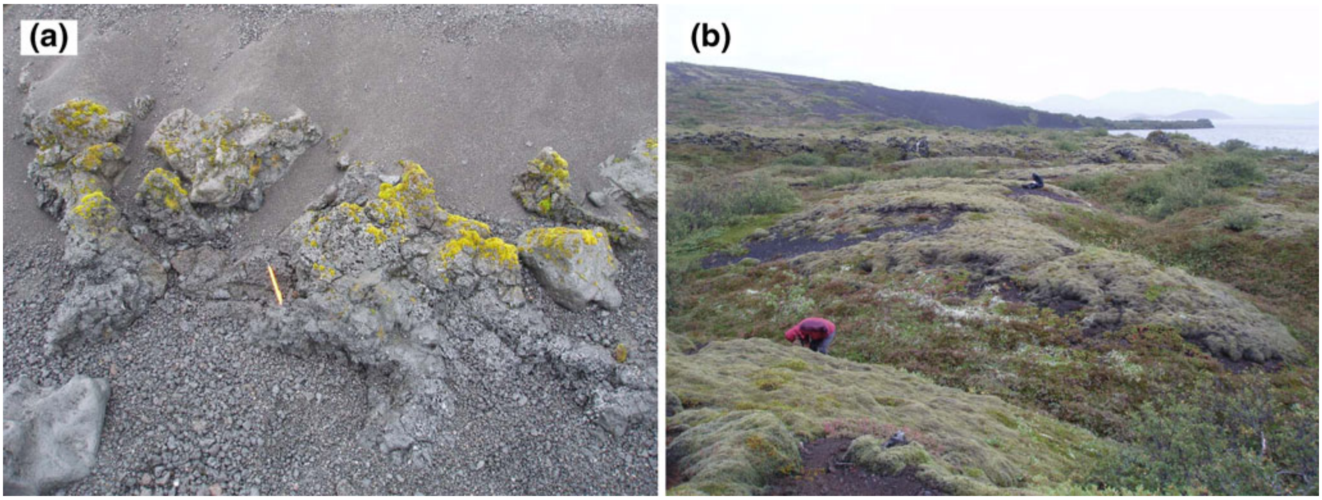

Fig. 5 Characteristics of ‘a‘ā lava on the lake shore. **a** Irregularly shaped bodies of glassy and fractured basalt lava were intruded into a matrix of wet, unconsolidated hyaloclastite. Pencil for scale. Location 491830, 7112300. **b** Mounds of scoria lapilli along the ‘a‘ā shoreline. In the background, a lobe of ‘a‘ā lava can be seen, with Grámelur beyond. Location 491715, 7112320

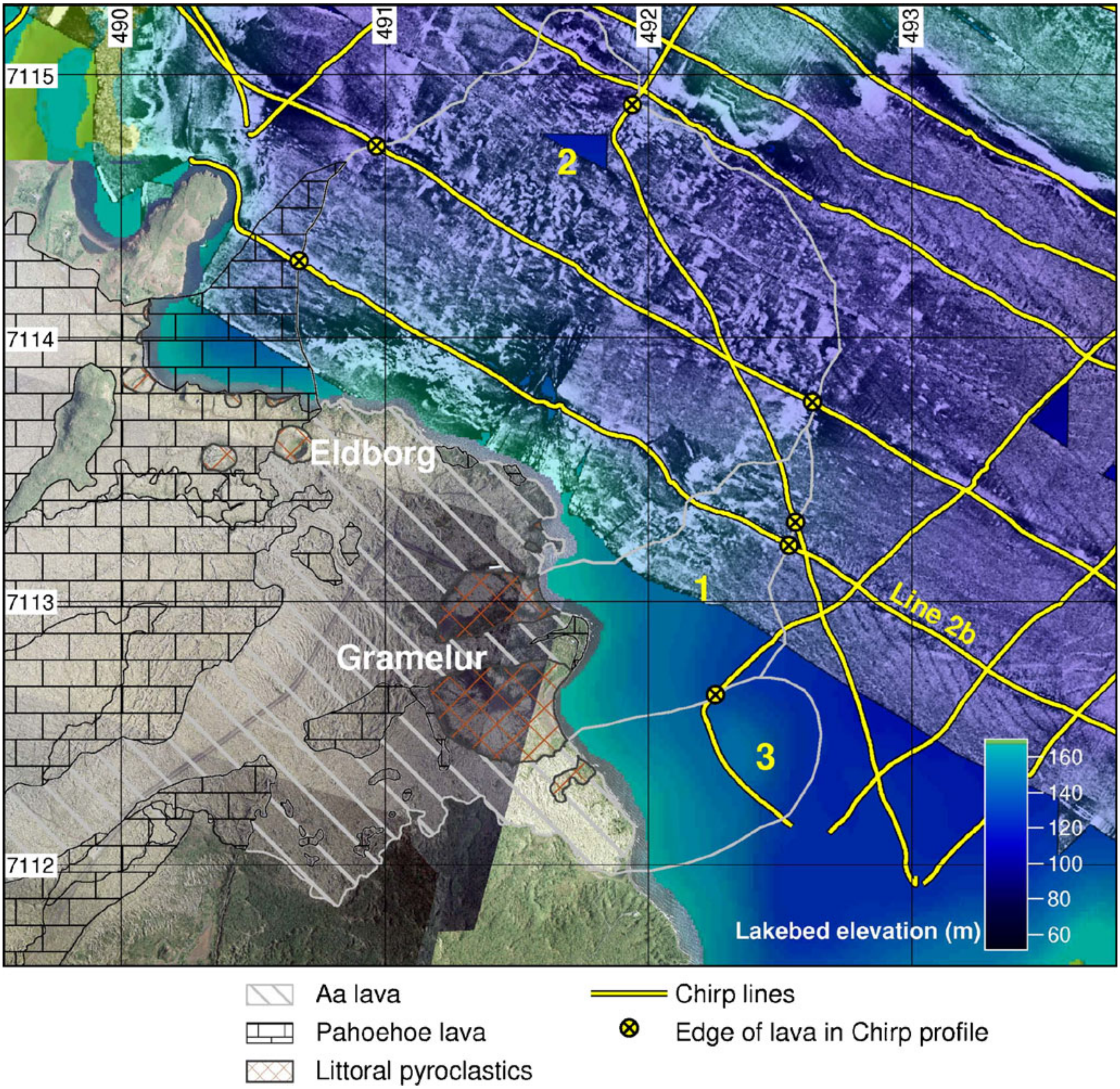

Fig. 6 Subaqueous extent of the Nesjahraun (coordinates in UTM Zone 27, WGS84 datum, grid size 1 km). The sidescan sonar map shows the presence of rocky lava (high acoustic backscatter; *light colour*) on the lake bed. The flow can be traced in the sidescan for 1.5 km offshore, coinciding with where the lake is shallowest. The flow has been divided into three sections: The first (*1*) was emplaced through the cone at Gramelur; the second and largest (*2*) flowed northward from the main ‘a‘ā channel; the third (*3*) was emplaced last when the flow diverted to the southern side of Gramelur. NNE-trending flow lobes, 50–200 m wide, are visible near *2*

and Scott 2009). The restriction of the greatest chilling to the base of the flows is consistent with the water level being relatively unchanged since the eruption (Saemundsson 1992). The pāhoehoe regions within the ‘a‘ā channel are interpreted as rafts dislodged by the flowing ‘a‘ā lava, while outcrops along the coastline may be small areas that were not covered by the ‘a‘ā flow, or small breakouts from the flow front. In particular, the headland at Grámelur may have formed from the last lava draining from the channel through the cone.

Grámelur, far from the source fissure, is also interpreted as a rootless cone, in agreement with Saemundsson (1992). It is unlike typical Icelandic rootless cones, but paired half-cones of unconsolidated scoria lapilli and ash are similar to littoral cones formed by ‘a‘ā lava entering the ocean in Hawaii (Fisher 1968). The tephra were produced by tephra-jet explosions resulting from open-mixing between lava and lake–water (Mattox and Mangan 1997), and the large size is interpreted as a result of sustained explosive activity and a high lava flux. Saemundsson (1992) associated the cone with a previous eruption, as surfaces of the surrounding ‘a‘ā lavas are free from tephra, but aerial photos (Fig. 6) show that all lobes of the ‘a‘ā lava form the same flow; this includes the channel through the half cones. The lobes to the W and E are therefore interpreted to have formed after the explosions at Grámelur had ended (see also “Interpretation: pāhoehoe or ‘a‘ā?” section). Shorter-lived explosion sequences, or less-explosive lava–water mixing (Wohletz 2002), are interpreted to have generated the smaller scoria mounds.

Offshore geology

Geophysical data

The Nesjahraun can be traced offshore in the bathymetry, sidescan and Chirp data. The bathymetry data show that Þingvallavatn is shallower offshore from areas where ‘a‘ā lava reaches the shoreline. The bathymetric contours (particularly 20 and 30 m depth) suggest the presence of three main subaqueous lobes (Figs. 1 and 6). The sidescan data show patches of rocky lava as regions of high backscatter (white, with a speckled, irregular texture) amongst the sediments covering much of the lake floor (grey, with a more uniform texture). A speckled, white texture can be seen over a large region 1.5–2 km wide extending NNE-wards offshore from between Eldborg and Grámelur. It extends up to 1.5 km from the shoreline beneath the water, reaching the submerged flow front of Þingvallahraun. Notable features within the region include a bright fringe running parallel to the coastline about 200 m offshore north of Eldborg in water 10–20 m deep, which may represent a flow front, and a series of NNE-trending ‘lobes’ located about 1 km NE of Eldborg, which are 50–200 m wide.

Chirp data (Fig. 7) show the stratigraphy of the lake bed, allowing determination of areas of sediment, areas of lava and the boundaries between the two. The edges of the lava flow extracted from the Chirp data show good agreement with those determined from the sidescan imagery. Generally, the western margins of the flow on the Chirp profiles is sharper, with lava (~15 m thick) sitting clearly on the lake bed; on the eastern margins, the top of the lava is unclear and Thors (1992) interpreted the disruption to the sediment in this region as a result of penetration by the lava.

Interpretation: pāhoehoe or ‘a‘ā?

The majority of offshore Nesjahraun is interpreted as having been emplaced during the ‘a‘ā phase of the eruption. Shallow water, lobe axes and the highest backscatter in the sidescan data are all found offshore from the ‘a‘ā part of the subaerial flow, especially between Eldborg and Grámelur. Based on bathymetry, orientation of ogives and the presence of ‘rafted’ sheets of pāhoehoe lava, three phases of emplacement during the ‘a‘ā phase are postulated (Fig. 6). The first phase generated the cone of Grámelur, as lava flowed through

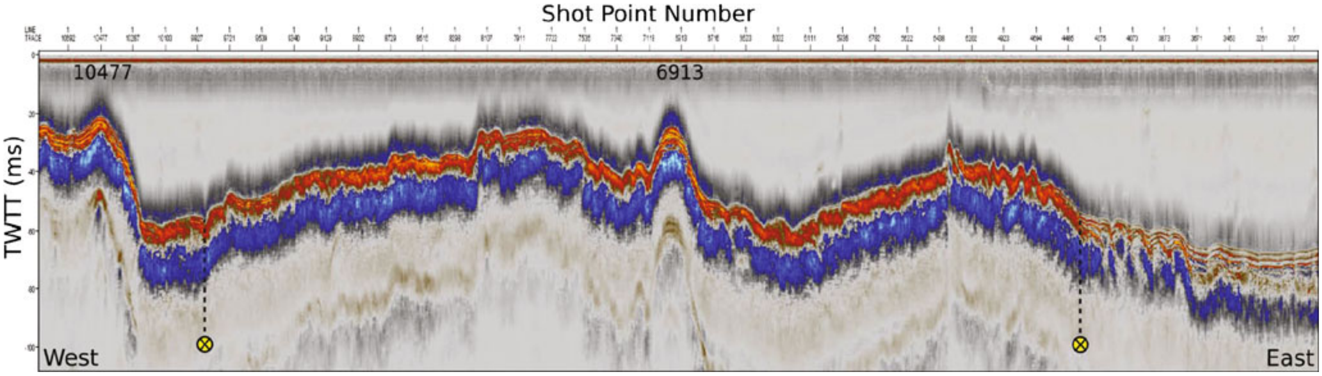

Fig. 7 An example Chirp profile (line 2b). The line section shown is 3.3 km long; 20 ms TWTT corresponds to ~15 m water depth. The rocky lava (in the west) can be distinguished from the smooth sediments (in the east). The sharp peaks at shot points 6913 and 10477 are pre-existing hyaloclastite features related to faulting. The edges of the ‘a‘ā flow identified in the Chirp data (*yellow circles* with *diagonal crosses*) coincide with the boundaries seen in the sidescan image. The flat region immediately west of the western margin of the ‘a‘ā flow is interpreted as pāhoehoe or pāhoehoe rubble

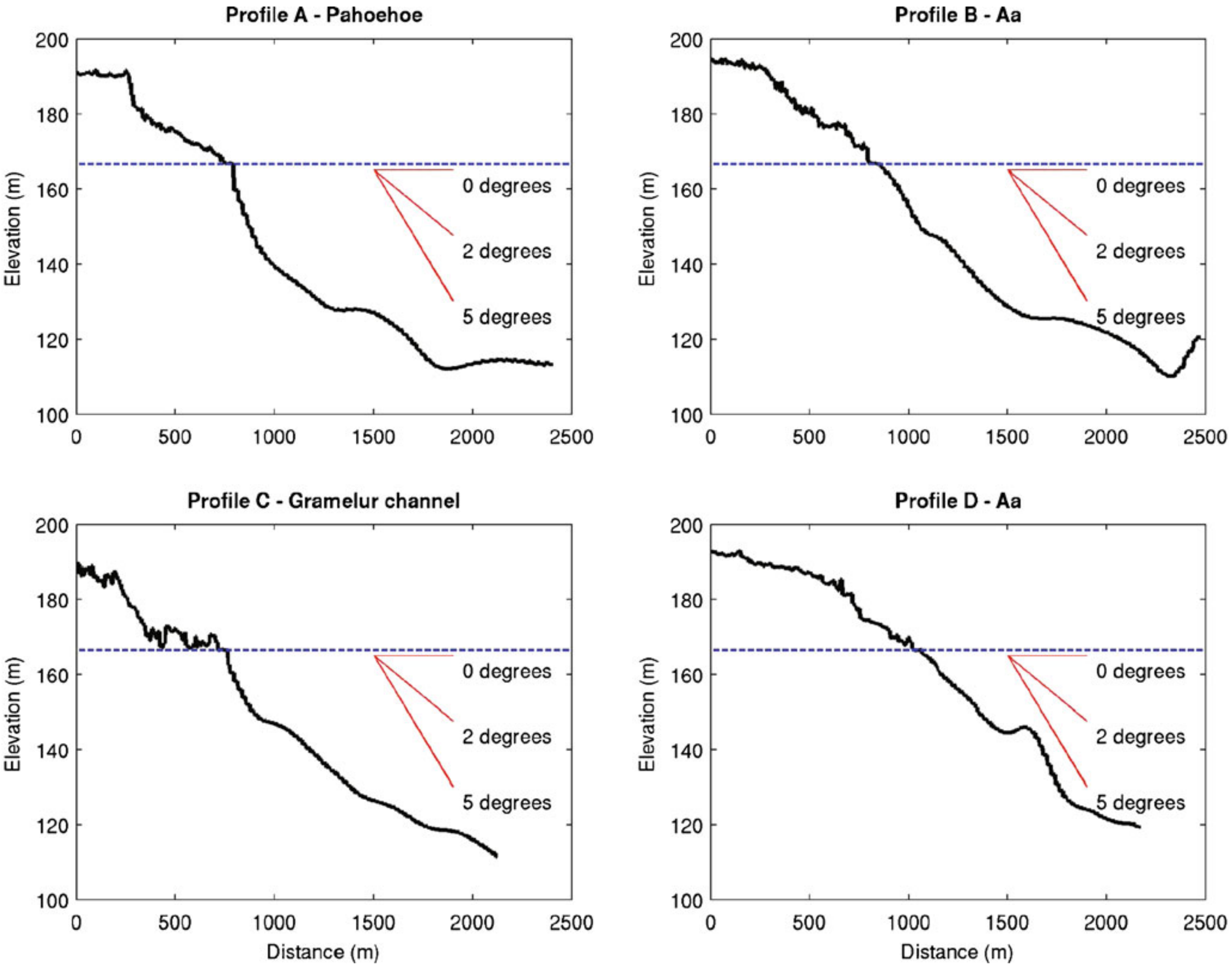

Fig. 8 Topographic profiles along lines in Fig. 1, through pāhoehoe and ‘a‘ā lava, respectively. Note the large vertical exaggeration. There is a significant break in slope at the shoreline in the pāhoehoe, while the surface gradient of the ‘a‘ā flow is relatively unchanged on entering the lake

it generating the two half cones as the moving flow carried away any tephra landing upon it. The orientation of the ogives suggests that the flow then switched to the west of the cone. The bulk of the ‘a‘ā was emplaced in this phase, at high local flux rates sufficient to displace large rafts of pāhoehoe and translate them downstream. Finally, the third lobe was emplaced, breaking through a barrier of pāhoehoe lava south of Grámelur and flowing to the east of the cone. Thus, the shoreline east of Eldborg was produced. To the west, the subaqueous geology is interpreted to relate to the emplacement of pāhoehoe lava prior to the ‘a‘ā phase, but there are no direct observations as the sidescan and Chirp data are only available 300 and 700 m offshore, respectively. This area coincides with the sub-horizontal deposits visible in Chirp line 2b (Fig. 7). Figure 8 shows four bathymetric profiles, two through each lava type (see Fig. 1 for associated profile locations). All show relatively shallow gradients (<5°), but profiles A and C (which pass through pāhoehoe lava regions) both show a pronounced break-in-slope at the waters edge, with a steeper surface offshore, whereas profiles B and D (‘a‘ā) show a more modest change in gradient on entering the water. This indicates that a change in flow regime on entering the water occurred only in the pāhoehoe phase.

Discussion

Shoreline processes

The most obvious manifestation of shoreline processes are the rootless cones of Eldborg and Grámelur, formed by pāhoehoe and ʻaʻā lava, respectively. The finer-grained deposits of Grámelur suggest more violent explosions in this case. Littoral cones are best known in the literature from examples in Hawaii (Moore and Ault 1965; Mattox and Mangan 1997). There, deposits of spatter and coarse pyroclastic rocks are associated with littoral lava-fountaining and bubble-burst type explosions, which are the product of confined mixing between water and lava, often when seawater penetrates a lava tube (Mattox and Mangan 1997). These are equivalent to the explosions that generated Eldborg, whose base is lower than and hydraulically connected to the waters of Þingvallavatn and the unconsolidated spatter that underlies the lavas exposed in the bays. Mattox and Mangan (1997) suggested that a magma flux of >4 m^3 s^{-1} is required to produce such deposits. A high magma supply rate (compared with other Hawaiian eruptions) here is also implied by the lack of tumuli (Hon et al. 1994), widespread shelly pāhoehoe (Swanson 1973) and wide channels. Rootless cones have the same shape as Eldborg and are also typically associated with tube-fed pāhoehoe flows, but in their case, water is supplied from the wet substrate beneath (Fagents and Thordarson 2007).

Flow in the pāhoehoe channels may have been open during overflows; however, Hawaiian examples of open mixing between lava and seawater, which result in tephra jets and lithic blast explosions, produced finer-grained deposits (e.g. ash) than those most apparently associated with the pāhoehoe deposits of the Nesjahraun. Mattox and Mangan (1997) describe how collapse of lava benches or wave action could be triggers for open-mixing explosions in pāhoehoe lava by promoting the mixing of lava and water. Neither factor is likely to have been significant during the Nesjahraun eruption, as the slope of the lake bed is very shallow and the sheltered lacustrine environment has smaller waves than the ocean. A lack of waves may have allowed preservation of the unconsolidated scoria deposits found in the bays along the pāhoehoe shoreline; these light, loose clasts would be expected to be washed away were they to be inundated by ocean waves (c.f. Umino et al. 2006).

In contrast, the pyroclastic deposits associated with the ʻaʻā parts of the flow are similar to those produced by open mixing. These include the double cone of Grámelur and some of the low mounds beside it. This suggests that waves are not necessary to cause explosions when channelized ʻaʻā flows into water. The dimensions of Grámelur are similar to the Sand Hills (80 m high) and Puu Hou (80 m high, 500 m wide) littoral cones in Hawaii, which were formed in eruptions with mean lava fluxes of 80–90 m^3 s^{-1} (Mattox and Mangan 1997) and which also consist of ash to lapilli-size tephra with little spatter. Later stages of the flow diverted round the original Puʻu Hou cone, Hawaii (Fisher 1968), as is also seen at Grámelur. The high lava flux during the ʻaʻā phase of the Nesjahraun is also reflected in the rafting of plates of pāhoehoe lava. The explosions at Grámelur stopped when the lava flow diverted to the west (Fig. 6) and cut off the supply through the cone. Drainage of the final lava likely produced the small pāhoehoe region at the mouth of the channel.

Subaqueous flow

There is no direct evidence of the subaqueous extent of the pāhoehoe part of the Nesjahraun, and it has been mapped based on an absence of ʻaʻā lava. It is also not known whether the pāhoehoe lava, fed by the channels, continued to flow underwater or if it broke up on quenching to form a lava delta. Typically, a lava delta has a slope of 25–35°, i.e. the angle of repose (Skilling 2002). In Þingvallavatn, the slope is $\sim 5°$. Similar slopes (4–7°) have been measured on the upper surfaces of lava deltas of the Azores that have been modified by wave action (Mitchell et al. 2008). As the wave energy of the lacustrine environment is less, it is speculated that the break in slope results from a change in flow regime of the pāhoehoe lava and generation of unconsolidated material as it enters the water. However, it is far less pronounced than the scarp around the front of the pāhoehoe flow of the Þingvallahraun in the north of the lake (Fig. 1), which is interpreted as a true lava delta. The difference may be related to a low lake-bed gradient or high lava flux decreasing the fragmentation of the lava.

Penetration of the water by the ʻaʻā flow is consistent with reports from elsewhere (Moore et al. 1973; Mitchell et al. 2008). Deposits of hackly jointed lava and hyaloclastite along the shoreline are similar to the sub-lacustrine flow described by Tucker and Scott (2009). Chilling of lava in contact with ice or snow produces similar textures (Lescinsky and Fink 2000; Mee et al. 2005), which are interpreted to form by steam penetrating the lava along cracks and joint planes. The deposits described here were never submerged so cooling was probably enhanced by steam generated from the lake water rising through the lava. The indistinct eastern margin of the flow, observed in the sidescan and Chirp data, may record where the lava intruded the sediments, possibly generating peperite. This would be consistent with other examples of wet sediment–lava interaction (Skilling et al. 2002; Wohletz 2002) and also with the disruption of the sediments interpreted as liquefaction by Thors (1992). The visible structures within the flow, especially the lobes, which have similar dimensions to those on land, imply that the flow remained coherent on entering the lake. This is consistent with direct observations of subaqueous ‘a‘ā flows (Moore et al. 1973) and sonar surveys of ocean islands (Mitchell et al. 2008). The minimal change in gradient on entering the lake also suggests that the water had only a minor effect on the flow.

Estimates of flow thickness onshore (~5 m, "‘A‘ā" section) and offshore (~15 m, "Geophysical data" section) suggest that the lava flow is thicker underwater. This may be a result of the reduced density contrast between the flow and its surroundings as it enters the water, or of resistance to flow by a rind of chilled lava. These limited observations do not allow distinction between these two hypothesis. The formation of a passage zone (Jones 1970; Skilling 2002) seems to be more likely with pāhoehoe lavas and low lava fluxes, as ‘a‘ā lavas appear to remain coherent on entering water, both at the Nesjahraun, and elsewhere (at least on gradients <17°; Mitchell et al. 2008).

Conclusion

The Nesjahraun was emplaced in two phases, first pāhoehoe, then ‘a‘ā. Both phases entered the waters of Þingvallavatn, providing an opportunity to contrast the behaviours of the two lava types as they enter water, independent of complicating factors such as variations in composition. The results are consistent with studies previously described in the literature, namely that rootless explosions are common and that ‘a‘ā flows are able to remain coherent on penetrating water. The lack of significant wave action meant that explosions in the pāhoehoe part of the flow were restricted to those caused by closed mixing, as occurs when water infiltrates lava tubes, and that unconsolidated material was not washed away and consequently formed a large proportion of the deposits. ‘A‘ā flows generated tephras similar to those in an oceanic setting, and wave action is therefore not necessarily a requirement for open-mixing explosions in these flows. The most important factor in determining the behaviour of lava entering water is the lava flux. The results of this study agree with others in that passage zones are only found associated with pāhoehoe eruptions, at least where the topographic gradient is low. The lack of a true, angle-of-repose lava delta at the Nesjahraun may also result from a low lake-floor topographic gradient. This distinction is important in reconstruction of paleoenvironments and eruptions, for example at tuya-forming subglacial volcanoes.

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