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RESEARCH ARTICLE

Widespread inflation and drainage of a pāhoehoe flow field: the Nesjahraun, Þingvellir, Iceland

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Abstract This study describes the emplacement of the Nesjahraun, a basaltic lava flow that entered the lake Þingvallavatn, SW Iceland. High-resolution remotely sensed data were combined with fieldwork to map the flow field. Onshore, the Nesjahraun exhibits a variety of textures related to the widespread inflation and collapse of a pāhoehoe flow field. Its emplacement is interpreted as follows: Initially, the eruption produced sheet pāhoehoe. In the central part of the flow field, the lava has a platy-ridged surface, which is similar to some other lava flows in Iceland and on Mars. Here, the texture is interpreted to have formed by unsteady inflation of the brittle crust of stationary sheet pāhoehoe, causing it to break into separate plates. The ridges of broken pāhoehoe slabs formed as the plates of crust moved vertically past each other in a process similar to the formation of shatter rings. Upstream, fresh lava overflowed repeatedly from channels and tubes, covering the surface with shelly pāhoehoe. Formation of a 250-m-wide open channel through the flow field allowed the inflated central part of the flow to drain rapidly. This phase produced ‘a‘ā lava, which eroded the channel walls, carrying broken pāhoehoe slabs, lava balls and detaching large (>200 m long) rafts of compound shelly pāhoehoe lava. Much of this channelized lava flowed into the lake, leaving a network of drained channels and tubes in the upstream part of the flow. As in other locations, the platy-ridged texture is associated with a low underlying slope and high eruption rate. Here, its formation was possibly enhanced by lateral confinement, hindered entry into the lake and an elevated vent location. We suggest that formation of this type of platy-ridged lava, where the plates are smooth and the ridges are slabs of broken pāhoehoe, can occur without significant horizontal transport, as the surface crust is broken into plates in situ. This reconstruction of the emplacement of the Nesjahraun also demonstrates that high-resolution aerial survey data are extremely useful in the mapping and measurement of lithofacies distributions in large flow fields, but that fieldwork is still necessary to obtain the detailed textural information necessary to interpret them.

Keywords LiDAR · Lava · Iceland · Platy-ridged lava · Inflation · Shelly pāhoehoe

Introduction

Observations of contemporary eruptions (e.g. Hon et al. 1994; Kauahikaua et al. 2003) and analysis of the deposits of past eruptions (e.g. Calvari and Pinkerton 1999; Mattsson and Höskuldsson 2005) improve our understanding of lava flow behavior, allowing us to develop models of flow emplacement and to improve hazard mitigation. Models for the emplacement of the

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largest lava flows on Earth, which were formed during episodes of flood basalt eruptions and have volumes of 20–100× those of the largest historic eruptions, are based on analysis of their deposits (Self et al. 1998). Martian eruptions have produced even larger lava flows, with estimated volumes of over 5,000 km^3 (Jaeger et al. 2010). Our understanding of these flows is based on their surface textures and geomorphology, as measured by remote sensing (e.g. Jaeger et al. 2007; Keszthelyi et al. 2010) and compared to analogous flows on Earth (e.g. Keszthelyi et al. 2000, 2004).

This study combines high-resolution light detection and ranging (LiDAR) data and aerial photos with field mapping to investigate the emplacement of the Nesjahraun, a relatively young, but prehistoric, basaltic lava flow in Iceland. Through description and mapping of a number of flow facies, it reveals that the flow field underwent a period of inflation, during which platy-ridged lava was formed. This was followed by rapid drainage, as a consequence of the formation of an ‘a‘ā channel through the flow field. It is found that large horizontal translations of solidified lava crust are not always necessary for the formation of platy-ridged lavas. This has important implications for the interpretation of such features elsewhere in Iceland and on Mars.

Background

Inflation of lava flows

Inflation is the mechanism whereby lavas increase in thickness by the emplacement of fluid lava beneath a solidified skin or crust. It is most commonly associated with pāhoehoe lavas, which have a smooth or ropey (folded) surface (Hon et al. 1994), but has also been reported during emplacement of rubble-covered ‘a‘ā flows (Geist et al. 2008). During inflation, small pāhoehoe lobes coalesce into larger lobes. Where supply rates are low, lava delivery to the flow front is focused along preferred lava pathways, the localized inflation of which produces tumuli (Hon et al. 1994). Depressions between these inflated pathways are known as lava rise pits (Walker 1991), and variations in the flux within the tubes may cause sections of the roof to rise and fall, generating shatter rings (Kauahikaua et al. 2003; Orr 2010). If the effusion rate is high, large lobes can coalesce into a single sheet with a continuous upper crust (Self et al. 1998); this is a sheet flow. Such flows are usually found in areas with low topographic slopes (e.g. Rossi 1997; Solana et al. 2004), and this emplacement mechanism may predominate during flood basalt eruptions (Self et al. 1998).

Platy-ridged lavas and rubbly pāhoehoe

The identification of platy-ridged lava flows on Mars prompted a search for analogues on Earth (Keszthelyi et al. 2000, 2004; Haack et al. 2006). Keszthelyi et al. (2004) describe two platy-ridged lava morphologies on Mars. In the first, the plates have smooth surfaces and are defined by narrow, elevated ridges, which they refer to as ‘pressure ridges’. In the second type, the plate surface has sub-parallel, arcuate ridges like those found on a terrestrial silicic lava flow. Plates of this type are defined by topographically lower channels with a smooth surface that is interpreted to have formed from fluid lava when the plates were ‘rafted apart’. The Martian plates are typically 1 km in diameter, with ridges ~10 m high (Keszthelyi et al. 2004). Features identified as ‘pressure ridges’ or resulting from ‘rafting apart’ have been identified on lava flows on Earth, especially in Iceland. On both Earth and Mars, examples are found of long grooves, often >1 km long, formed where lava has flowed past obstacles (Keszthelyi et al. 2004).

Field investigations of Icelandic platy-ridged flows allow close examination of the lava textures, which are usually dominated by rubbly pāhoehoe. This type of lava is characterized by an extensive cover of loose blocks of pāhoehoe lava crust, generally <10 cm in size, which are commonly piled up into elongate ridges (Guilbaud et al. 2005). This ridged texture is similar to the surfaces of Martian plates which have ‘rafted apart’ (Keszthelyi et al. 2004). Other clast types include large (>1 m) tabular slabs of pāhoehoe crust, compound clasts of reworked pāhoehoe crust and irregular vesicular clasts welded together, and the breccia of pāhoehoe blocks has sometimes been intruded by liquid lava (Keszthelyi et al. 2004; Guilbaud et al. 2005). Both platy-ridged lava and rubbly pāhoehoe lavas are interpreted to be formed by the disruption of the crust of an inflated pāhoehoe lava, usually due to a pulse in lava supply or continued movement of the flow down slope (Keszthelyi et al. 2004; Guilbaud et al. 2005).

Geological setting

The Nesjahraun is located in Iceland’s Western Volcanic Zone (Fig. 1), 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

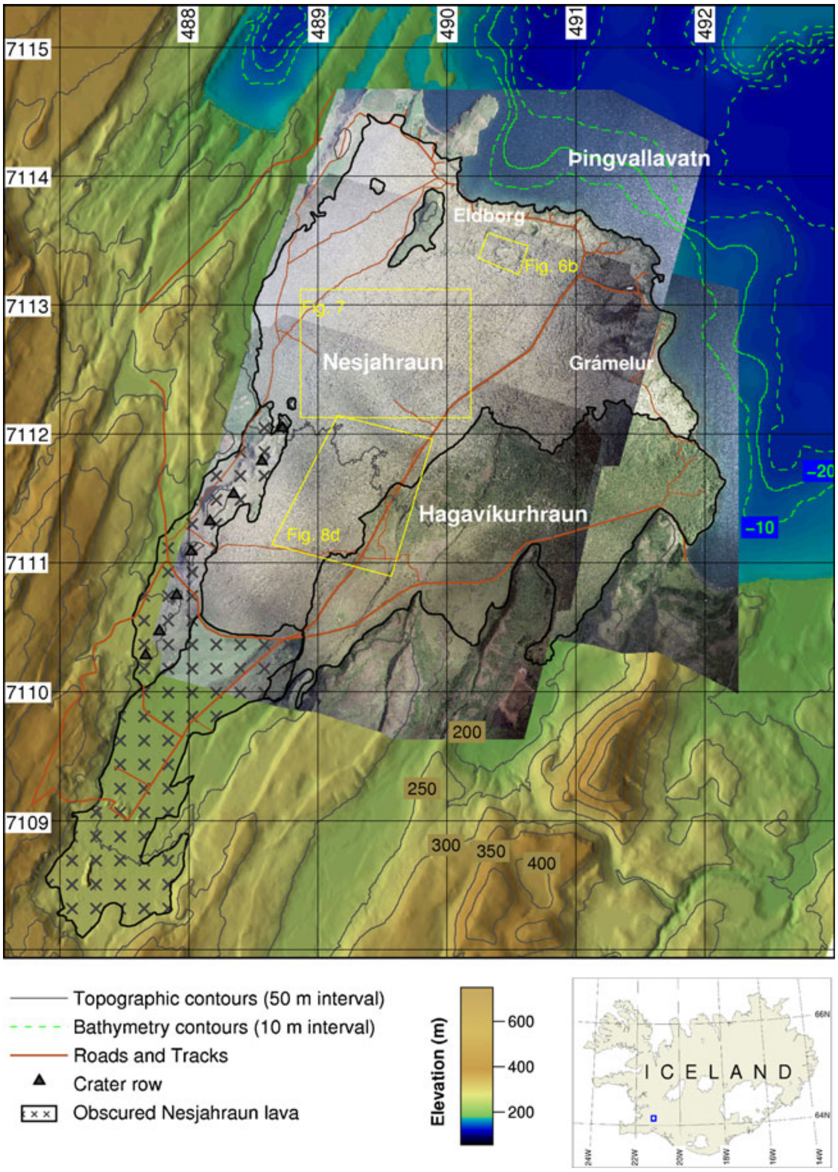

Fig. 1 Mosaic of orthorectified aerial photos of the Nesjahraun. The flow is coated with a layer of green moss. The row of source craters, the rootless cones of Grámelur and Eldborg and the platy-ridged texture are all visible. The SSW–NNE structural trend is the topographic expression of the mid-Atlantic ridge and is produced by parallel hyaloclastite ridges and fault scarps. *Yellow boxes* indicate the locations of aerial photographs used in other figures. The coordinate system is UTM Zone 27, WGS84 datum, 1 km grid squares. Coordinate labels are abbreviated, e.g. 488$_{000}$, 7114$_{000}$. A larger version of this map, and of Fig. 4, is available as online Supplementary Material. *Inset*: Map of Iceland. The *blue box* marks the location of the study area

Ridge. Postglacial volcanic activity in the region has erupted 110 km^3 of magma since 12,000 B.P., with 64% of this material being erupted as 11 shield volcanoes in the first 3,000 years since deglaciation (Sinton et al. 2005).

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); this article concentrates on the northern one. The fissure extended into the lake, producing two tuff cones, which deposited tephra within the lake and along the eastern shore (<40 cm thick). Lava from the on-shore vents formed the Nesjahraun, adjacent to the Hagavíkurhraun, between Hengill and the southern shore of Þingvallavatn (Fig. 1). 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). The lava–water interaction as the Nesjahraun entered the lake was investigated by Stevenson et al. (2011), who found that phreatomagmatic explosions were common, generating the rootless cones of Eldborg and Grámelur (Fig. 1) and that the bulk of the lava beneath the lake was emplaced during the ‘a‘ā phase of the eruption.

Methods

On 1st August 2007, the UK’s Natural Environment Research Council’s Airborne Research and Survey Facility flew 14 NE–SW-trending survey lines over the

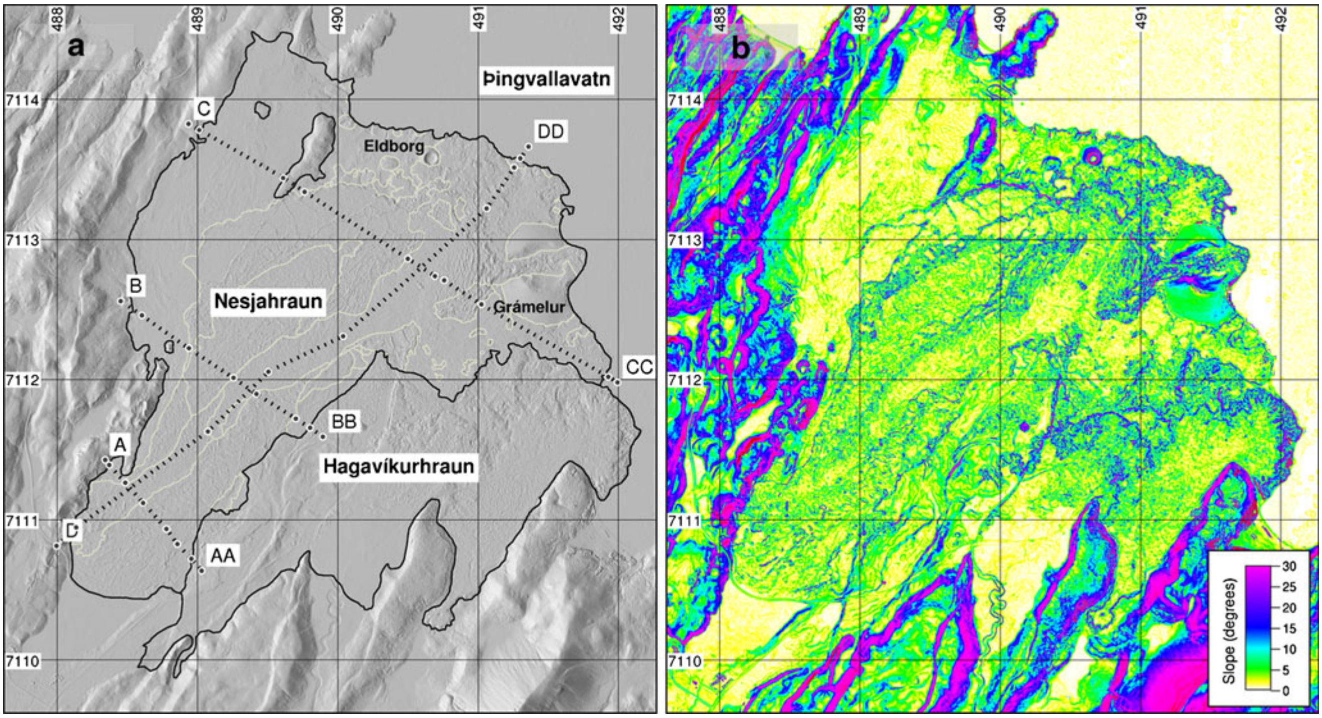

Fig. 2 Regional geomorphology. Note the complex surface texture of the central part of the Nesjahraun lying in the floor of the Þingvallavatn graben. **a** Shaded relief map of the Nesjahraun. *Black dotted lines* mark topographic profiles (Fig. 3). *Pale lines* are lithofacies boundaries, see Fig. 4 for details. The *circles* correspond to changes in slope or lithofacies marked on the profiles. **b** Slope map generated from the denoised LiDAR data. The overall slope of the flow field is low, but local variations can be used to map different textural regions

Nesjahraun at an altitude of approximately 2,200 m and covering an area ~250 km^2. An ALTM-3033 LiDAR system scanning at 33.3 kHz registered the first and last return and intensity of ~70 million points with a mean spacing of 1.9 m. Fifty-three aerial photos were taken concurrently with an RC-10 Aviphoto aerial camera system. The last-return data points from all 14 overlapping survey lines were combined into a single point cloud, with a mean density of 3.7 points m^{-2}. This was interpolated by local kriging, using the *gstat* (Pebesma and Wesseling 1998) and *GRASS GIS* (GRASS Development Team 2009) software packages, to create a 1-m resolution digital elevation model (DEM). All data and processing used Universal Transverse Mercator (UTM) coordinates, in UTM Zone 27W with the WGS84 datum. In the figures, these are truncated to kilometres for brevity, e.g. 490000 becomes 490.

Selected aerial photos were orthorectified, using topography from the LiDAR DEM, tie points selected from a shaded relief map generated from the LiDAR DEM and the camera calibration information provided with the data. The orthorectified photos were combined to create a mosaic (Fig. 1). Mismatches in the navigational data between different LiDAR flight lines introduced noise into the combined data point cloud, so the DEM was denoised with Sun et al.'s 2007 denoising algorithm (see Stevenson et al. 2010, for details of denoising topographic data), which improved clarity in the derived maps. A shaded relief map (Fig. 2a), a slope map (Fig. 2b), topographic profiles (Fig. 3) and 'local relief' maps ("Flow facies" section) were also generated from the DEM. To generate the 'local relief' maps, a trend surface was created by interpolating through the median elevation points of the DEM on a 25-m grid (using a regularized spline with tension algorithm, tension = 40, smoothing = 0.1; GRASS Development Team 2009). This surface preserves local trends, but does not resolve the plates or ridges. It was subtracted from the DEM, leaving a map showing which areas are higher or lower than their immediate surroundings.

Fieldwork in August 2008, informed by the remote sensing data, was carried out to examine field relationships and small-scale structures and textures. The Nesjahraun was divided into a number of lithofacies, and their extents were digitized in GRASS GIS using a combination of the aerial photo mosaic, the slope map, scanned fieldslips and field notes to create a lithofacies map of the flow field (Fig. 4). High-resolution versions

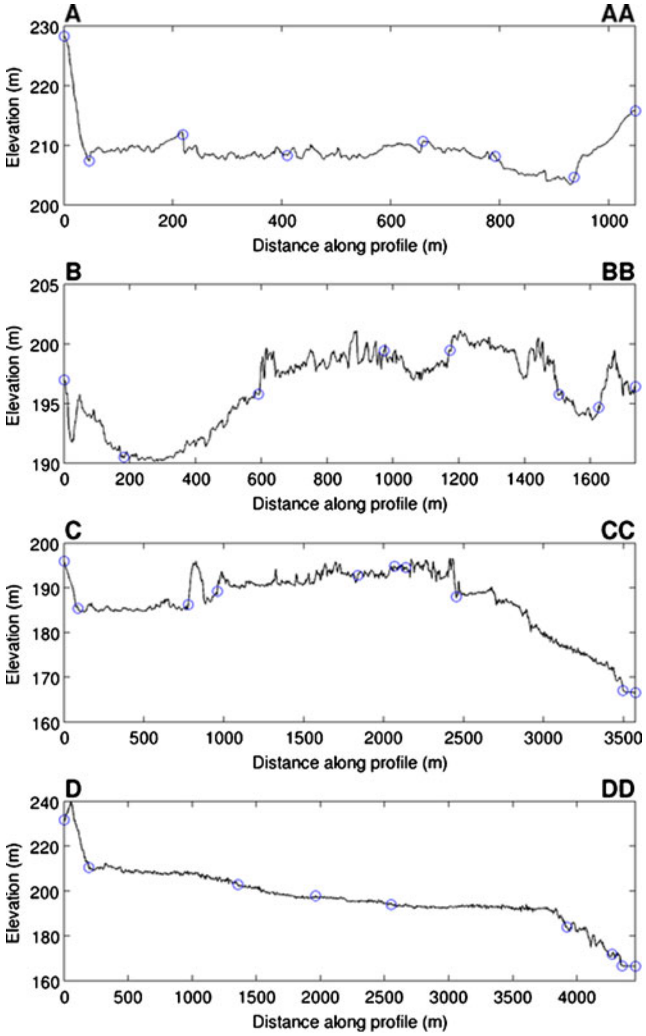

Fig. 3 Topographic profiles across the Nesjahraun. **a** *A* to *AA*. **b** *B* to *BB*. **c** *C* to *CC*. **d** *D* to *DD*. The *circles* correspond to changes of slope or lithofacies. See Fig. 2 for profile locations and Extent and geomorphology of the Nesjahraun for discussion of the profiles. The edges of the ʻaʻā channel are marked in each of the figures **a**–**c**. The vertical exaggerations are large (**a** = 11×, **b** = 36×, **c** = 28×, **d** = 17×)

of the aerial photo mosaic, slope map and lithofacies map are provided in the online Supplementary Material.

Extent and geomorphology of the Nesjahraun

The Nesjahraun lies at the south shore of Þingvallavatn, in the centre of a NNE–SSW-trending graben (Fig. 1). Topographically, the region is dominated by a series of parallel ridges, which are either fault scarps or hyaloclastite ridges erupted subglacially along tectonically controlled fissures. The Nesjahraun was erupted from one such fissure, extending beyond the limits of the map in Fig. 1 and into Þingvallavatn itself. The fissure is preserved as a row of poorly defined spatter cones that run along the crest of the ridge, some of which have channels that run down to the main flow field to their E. Traces of other fault lines running through the Hagavíkurhraun can be seen in the aerial photo mosaic to the east of the road (e.g. 490400, 7111500; Fig. 1).

The total area of the Nesjahraun that was erupted from the fissure north of Hengill is 13.8×10^6 m^2. Of this area, 4.0×10^6 m^2 is beneath the waters of Þingvallavatn. The part of the Nesjahraun that fills the southern part of the graben comprises sheet pāhoehoe and has an area of 2.7×10^6 m^2. It is largely covered in grass and alluvium and is not discussed further in this study (Fig. 1).

The middle part of the Nesjahraun is elevated relative to its margins. This is demonstrated in the topographic profiles (Figs. 2a and 3). In profile A, the flow surface in the western 800 m is 5 m higher than in the eastern 150 m. The elevation of the central part is the clearest in profiles B and C. Profile D is a longitudinal profile along the ʻaʻā channel and shows the low gradient of the flow, including a narrow step at the southern edge and a steepening close to the lake. Some of these features are also visible on the slope map (Fig. 2b). Surface textures of the lava flows are clear in the slope map (Fig. 2b, c.f. Fig. 4), particularly the smooth pāhoehoe sheet to the NW, the ridges of the platy-ridged flow in the centre and the ʻaʻā channel.

Flow facies

The division of the flow field into lithofacies is shown in Fig. 4. Each is described and interpreted in this section, and the information is summarized in Table 1.

Pāhoehoe sheet flow

Description

The pāhoehoe sheet flow crops out mainly to the western edge of the flow field (Fig. 4) and covers an area of 1.86×10^6 m^2 (including the obscured southern part). It is also found by a roadside on the eastern part of the lava flow field (489800, 7111800) and forming the tip of the headland extending from Grámelur. It consists of flat, smooth pāhoehoe with very little relief (which takes the form of slightly domed polygonal slabs 2–5 m in diameter). The lack of relief is clear in Fig. 5a and in the slope map and cross sections (Figs. 2 and 3). In some locations, especially towards the platy-ridged lava, the

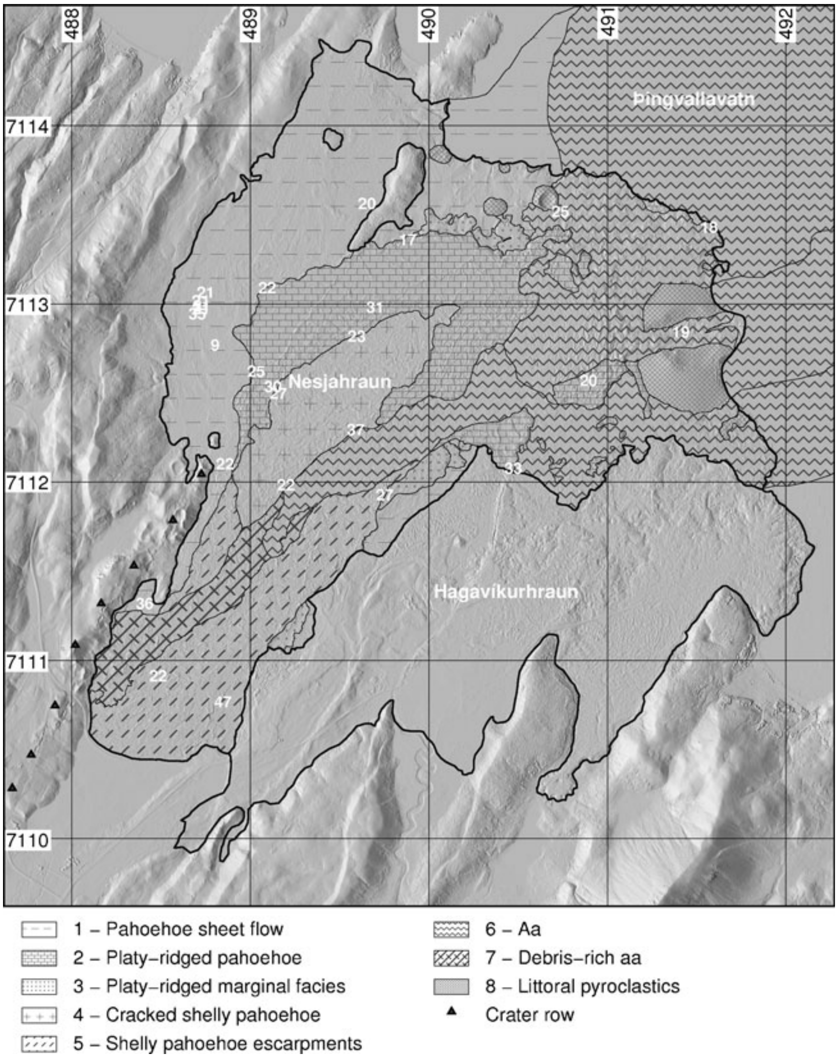

Fig. 4 The different lithofacies of the Nesjahraun. *White numbers* give the thickness of pāhoehoe slabs (centimetres) at locations where measurements were made. Those measurements plotted in areas of ‘a‘ā lava were made on slabby clasts carried by the flow

surface has been pushed up as slabs 20–50 cm thick, 1.5–3.5 m in diameter to form ridges up to 10 m wide and 100 m long. At one incipient ridge, there was a trench running beneath the lava slabs, some of which had tilted down into it (488720, 7113010; Fig. 5a). The mean ratio of the total slab length to the current trench width for the blocks in the figure is 1.27, indicating localized shortening. Here, the bases of the slabs have stalactites of lava that are perpendicular to the orientations of the slabs. The pāhoehoe sheet flow entered the lake along a length of shoreline west of the Eldborg rootless cone (Fig. 4; see Stevenson et al. 2011).

Interpretation

The low relief of the surface and lack of tumuli and channel features suggest that the lava was fed endogenously, with a sufficiently high supply rate to allow individual flow lobes to coalesce into a single sheet (Hon et al. 1994; Self et al. 1998). The tilted slabs have been lifted by compressive forces. The linear ridges, localized downward tilting and perpendicular drip orientations (indicating that the lava was frozen at the time of movement) suggest that in some locations the deformation was focused along old lava tubes or other preferred lava pathways that had since drained.

Platy-ridged lava

Description

Platy-ridged lava is found in the centre of the Nesjahraun flow field and consists of flat plates of pāhoehoe separated by ridges made of slabby blocks formed from broken pāhoehoe slabs (Fig. 5b, c). The plates are very flat and have similar relief to the pāhoehoe sheet flow, although deep, narrow cracks

Table 1 Lava flow facies summary

Facies	Description	Interpretation	Area ($\times 10^6$ m^2)
Pāhoehoe sheet flow	Flat, low relief pāhoehoe	Rapid emplacement on flat ground at high effusion rate allowing lobes to coalesce into a sheet	3.86
Platy-ridged lava	Polygonal, flat, low-relief pāhoehoe plates, 30–100 m in diameter, separated by ridges composed of piles of tabular slabs 20–30 cm thick	Uneven inflation of pāhoehoe sheet flow caused crust to break into plates. Ridges form from blocks broken from plate margins in a similar fashion to the formation of shatter rings	1.32
Platy-ridged marginal facies	Elevated plateaux of pāhoehoe sheet lava or small lobes of cauliflower ‘a‘ā found on the edges of the platy-ridged lava	Injection of lava from platy-ridged flow interior beneath plateaux lifts them up while breakouts of viscous lava produce cauliflower ‘a‘ā lobes	
Cracked shelly pāhoehoe	Undulating surface of raised plates and sunken channels with occasional higher tilted blocks. The surface lavas are shelly pāhoehoe	Separation of plates of sheet pāhoehoe crust forms plates and channels. Frequent overflows of channels form shelly pāhoehoe. Lava movement tilts some blocks that were underlain by fluid lava	0.56
‘A‘ā	Channel ~200–350 m wide of predominantly ‘a‘ā clinker also contains other clasts including pāhoehoe slabs, lava balls, composite clasts and large rafts of compound pāhoehoe lava	Open channel flow carries lava directly from the vent area to the lake, draining the lava pond. Mixing of clasts and rafts suggests rapid flow and erosion of channel walls The majority of the underwater part of the flow was emplaced during this phase of the eruption	5.92
Shelly pāhoehoe escarpments	Elevated islands of often tilted compound shelly pāhoehoe lava, whose orientation suggests that they have been rotated. The walls are often overhanging and are plastered by a layer of striated lava	Rafts of shelly pāhoehoe formed like the cracked shelly pāhoehoe lithofacies. Drainage of lava from channels leaves isolated islands. Rotation of islands suggests that they are still underlain by molten material	0.93
Debris-rich ‘a‘ā	‘A‘ā lava containing many fragments of pāhoehoe and rafted material. Found in depression near vent area. Pāhoehoe lava and spatter are also present	Lava emplaced during final stages of eruption. The drainage of the perched lava pond left behind the depression, and the last lava was emplaced as pāhoehoe	

The area of the pāhoehoe sheet flow includes material south of the study area (see “Extent and geomorphology of the Nesjahraun” section). The area of ‘a‘ā lava includes the subaqueous part of the flow (Stevenson et al. 2011)

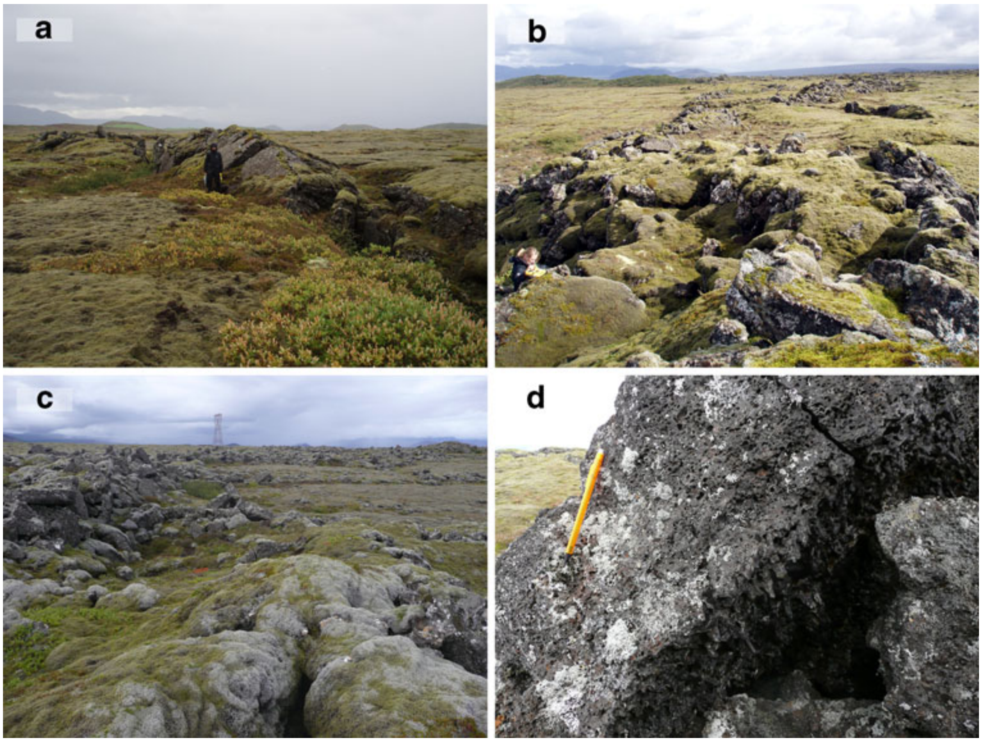

Fig. 5 Pāhoehoe sheet flow and platy-ridged lava textures. **a** Pāhoehoe sheet flow (488750, 7113000). Note the generally flat topography. An isolated ridge of uplifted blocks runs through the image. In the foreground, some of the blocks have tilted down into a trench, indicating that lava had drained from beneath prior to the deformation. **b** Simple ridge caused by compression of the pāhoehoe sheet surface. This is the westernmost ridge in the platy-ridged facies. To the west (*left side of the image*) lies flat pāhoehoe sheet flow. **c** Platy-ridged lava from within the centre of the lithofacies. The *flat area on the right* is a plate, with a surface like pāhoehoe sheet lava. Blocks of tabular pāhoehoe slabs (*left*) form the ridges. **d** Close-up of slab with drips on base. In this case, the drips have a perpendicular orientation to the slab, implying that fluid lava had drained from beneath it before the deformation occurred

are commonly found. The ridges are 7–12 m wide and 2–5 m tall and have divided the plates into areas of 1,000–7,000 m^2. The blocks are similar to the tilted pāhoehoe slabs described in "Pāhoehoe sheet flow" section. They generally range in thickness from 20 to 30 cm. Their bases are covered in drips that may be smooth or rough and orientated vertically (implying that they were molten when the slabs were tilted) or perpendicular to the block (Fig. 5d). The blocks of slab material are stacked haphazardly within the ridges, which contain a significant proportion ($<\sim 40\%$) of void space.

The southern, eastern and northern margins of the platy-ridged lava are separated from the rest of the flow by these ridges of blocks. This part of the flow is elevated with respect to its surroundings (Figs. 1, 2, 3 and 4). The northern margin stands ~10 m above the pāhoehoe sheet flow that it contacts. In the NE corner, nearest the channel, the ridges are wide and the plates are less well-defined. At the north end of the western margin, the contact with the pāhoehoe sheet flow is gradational as the plates increase in size and the ridges of blocks extend partway into the adjacent undisturbed sheet lavas (Fig. 1 and Supplementary Material).

Interpretation

The similarity of the plates to the pāhoehoe sheet flow, along with the gradational boundary on the western margin, suggests that the platy-ridged lava was also emplaced originally as a series of pāhoehoe lobes that coalesced into a sheet flow. The blocks that make up the ridges formed from broken tilted slabs, just like those described in "Pāhoehoe sheet flow" section. In Hawaiian lava flows, ridges of large blocks are produced when slabs of pāhoehoe are repeatedly lifted and lowered due to changes in the lava pressure in tubes beneath them producing features known as 'shatter rings' (Kauahikaua et al. 2003; Orr 2010). In a similar fashion, differential rates of vertical motion between the slabs as they were jacked upwards may have caused the breaking off of the blocks.

Compression may also have played a role. A section of triangular ridge measuring 10 m wide and 5 m high with 25% void space contains the same material as a single slab 50 cm thick and 40 m wide, representing 30 m of compression (e.g. a 75% reduction in length). The wider ridges in the NE, near the ‘a‘ā channel suggest greater disruption here (Fig. 1), and it appears that some of the plates were beginning to be rafted away. A large connected body of fluid lava beneath the plates would act like a well-insulated perched lava pond (Swanson 1973), with the plates floating on top.

Platy-ridged marginal facies

Description

The southern end of the western margin ranges from a deep gouge, 1 km long, in the far south (Fig. 6a) up to a single ridge of blocks further north. Two facies are occasionally found between the platy-ridged lava and the pāhoehoe sheet flow. These are the *uplifted pāhoehoe* and the *cauliflower ‘a‘ā* facies (Fig. 4) and are collectively referred to as the *platy-ridged marginal facies*. The uplifted pāhoehoe facies is found along the north and east of the platy-ridged lava flow facies. Wide, flat regions of the pāhoehoe have been uplifted, in some places by up to 8 m, to form a single, coherent platform (Fig. 6b). The uplifted region can extend for up to 500 m along the facies boundary and reach up to 200 m away from it. The surface may be undulating and drop gradually to the lower level over ~50 m, or it may be flat, with a sharp boundary just a few metres wide. Where the boundary is sharp, it may be straight and marked by tilted pāhoehoe slabs, or it may be dendritic and marked by irregular, angular blocks with a rough-textured surface. These blocks are cauliflower ‘a‘ā facies (Fig. 6c). In some locations, small lobes 100 m long of cauliflower ‘a‘ā have squeezed out from the base of the platy-ridged lava.

Interpretation

The deep gouge in the southern end of the western margin was caused by movement of the platy-ridged

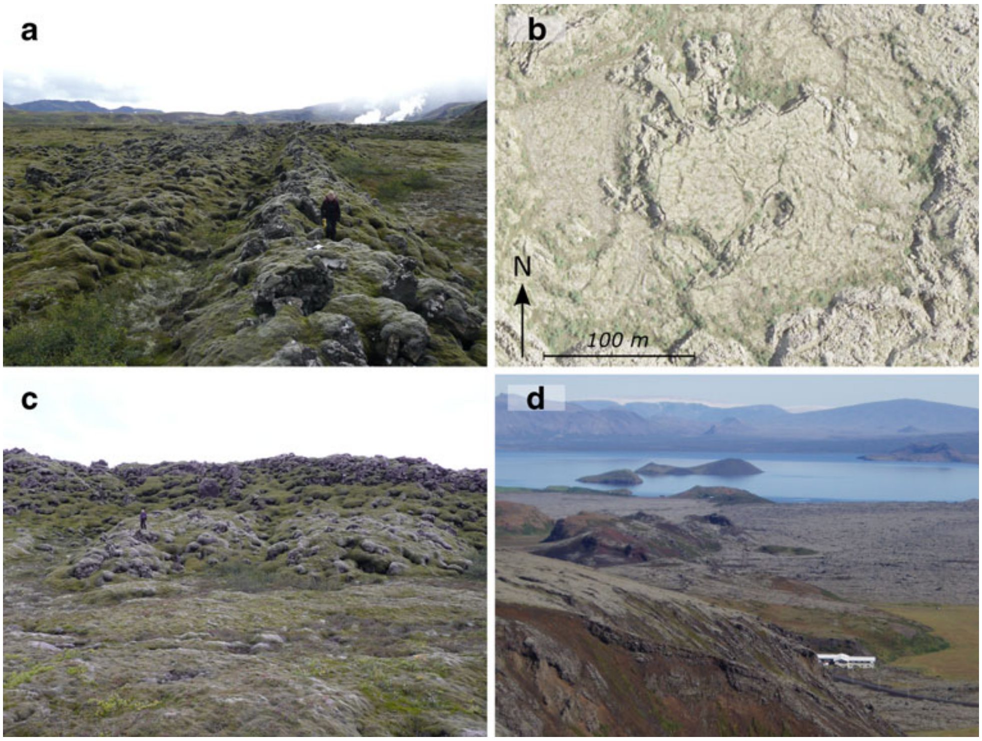

Fig. 6 Marginal textures of the platy-ridged lava lithofacies. **a** The SW margin of the platy-ridged lava is defined by a deep gouge separating it from the pāhoehoe sheet lava. It was formed by horizontal movement of the platy-ridged flow. The displacement is unknown, but was probably only tens of metres. The gouge is also visible of Figs. 1 and 2. **b** Aerial photo of uplifted pāhoehoe (490500, 7113400). The uplifted part has a flat surface like the adjacent pāhoehoe sheet flow. In some places, the margin takes the form of a monoclinal fold. At the N end, breakouts of cauliflower ‘a‘ā are developed. The rough material to the south is the edge of the platy-ridged lava. **c** Two cauliflower ‘a‘ā breakout lobes at the front of platy-ridged lava (490100, 7113500). The blocks are irregularly shaped with rough surfaces. Note different texture to platy-ridged lava behind. **d** Looking NNE along the Nesjahraun fissure. The row of cones extends into the lake. All of the flat-lying lava is part of the Nesjahraun flow field, which is at an elevation of 50–100 m lower than the vents

flow relative to the sheet flow. It is similar to the long grooves described in other platy-ridged flows on Earth and Mars (Guilbaud et al. 2005; Jaeger et al. 2007; Keszthelyi et al. 2010), many of which are interpreted as ‘wakes’ caused by lava flowing past an obstacle. In this case, however, the close fit of the plates, the continuity of some cracks across plate boundaries and the gradational western contact imply that lateral movements and consequent compression were minor. The length of the gouge does not represent the distance moved, but the length of the interface between the crust that moved and that which did not.

The uplifted pāhoehoe facies has been pushed up by lava flowing beneath it from the platy-ridged lava, as it is only present along its margins, and the elevation decreases with distance from the contact. The coherent uplift of large slabs over 100 m wide suggests that they possessed significant strength, and it is likely that the whole of the platy-ridged part of the flow was raised in this manner. The cauliflower ‘a‘ā blocks are clearly different to the pāhoehoe slabs around them. Their form implies that they were created from relatively viscous lava that may have been stagnating beneath the crust for some time (Rossi 1997). This suggests that the breakouts or uplift took place many hours after the platy-ridged flow was originally emplaced. Toothpaste pāhoehoe has also been associated with late-stage breakouts from sheet flow margins (Self et al. 1998; Kauahikaua et al. 2003) and is also likely to be a component of the platy-ridged marginal facies. Injection of fluid lava beneath the stagnating regions with a thick crust would likely require a relatively high hydrostatic head (where the fluid in this case is lava). This may have been supplied by the ponded lava, or possibly by the elevated position of the vents (Fig. 6d).

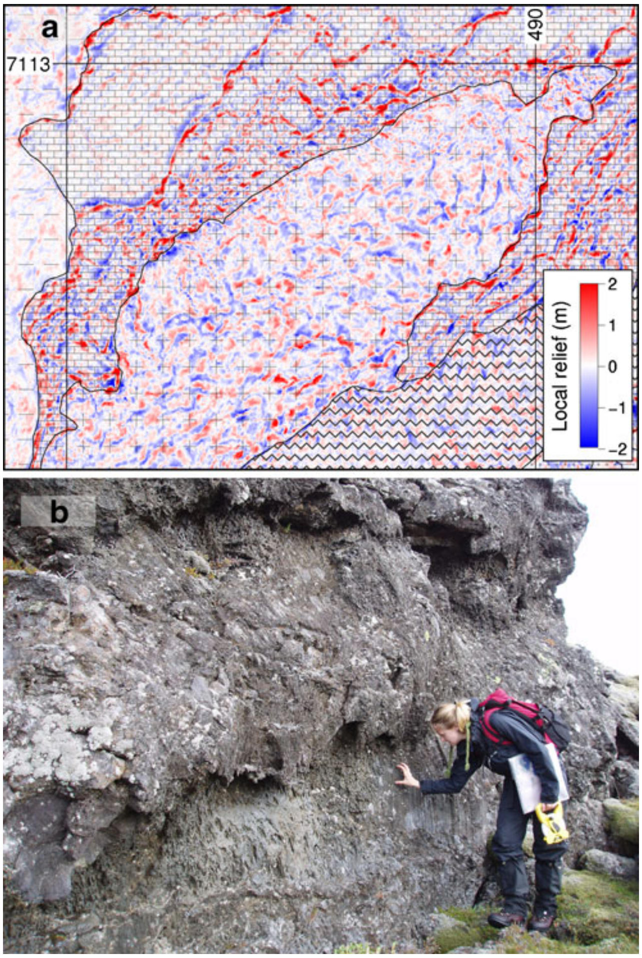

Fig. 7 Shelly pāhoehoe textures. **a** Local relief map of cracked shelly pāhoehoe. The facies decorations are the same as for Fig. 4. Organization of the surface relief into plates and channels is visible. The low-lying channels form a *blue* network between plates. By contrast, in the platy-ridged lava facies, the network of elevated ridges is *red*. **b** Small ridge on cracked shelly pāhoehoe with plastered surface. Vertical striae are visible, formed when the block was tilted upwards or when the lava level in the adjacent channel fell

Cracked shelly pāhoehoe

Description

The cracked shelly pāhoehoe is found in the centre of the flow field, where it is bordered by platy-ridged lava to the north and west and the ‘a‘ā channel to the east (Fig. 4). The surface is uneven, with irregular ridges and troughs (generally with an amplitude of <1 m) in various orientations. The undulations are the clearest on the local topography map, which highlights the presence of elevated polygonal ‘islands’ between shallow channels (Fig. 7a). The lava forms many thin vesicular flows (<20 cm thick) which have cavities beneath, giving the whole outcrop a hollow sound, e.g. shelly pāhoehoe (Swanson 1973; Rossi 1996). Some larger escarpments (<5 m tall, <50 m long) can also be found. A cross section through one such ridge revealed multiple flow units, all of which were tilted, plastered with a vertical skin (Fig. 7b). The plastering lava is often striated. Deep (<3 m) sharply defined fractures, trending dominantly in a NW–SE direction, run through the upper surfaces of the ‘islands’.

Interpretation

Shelly pāhoehoe is associated with overflows from channels, lava lakes and perched lava ponds (Swanson 1973). The polygonal ‘islands’ highlighted in the local topography map are similar in size and shape to the plates of the platy-ridged lava. The ‘channels’ between them suggest that they have moved apart and may be like those observed on Mars (Keszthelyi et al. 2004), which have a floor of smooth lava. The vertical skin on the wall of the ridge suggests that it was once the side of a channel or tube, and the 'islands' were perhaps originally large compound lava plates. Thus, the cracked shelly pāhoehoe formed with lava flowing between and inside a network of lava plates, frequently overflowing and coating them with thin flows. The tilting of large blocks suggests that they were supported by liquid lava beneath them. The deep fractures formed as tension cracks once the surface lavas had solidified, and their consistent orientation implies that they formed in a single event.

ʻAʻā lava

Description

The ʻaʻā lava forms a channel 200–350 m wide that runs from near the vents down to the coast to the east of Eldborg, including through the middle of the cone of Grámelur. The margins of the channel are associated with deep trenches, and its surface has a lower elevation than the surrounding lithofacies. Near the coast, the ʻaʻā lava widens into a number of lobes flowing down to the water. These can be seen to overlie the pāhoehoe sheet lava and is most apparent where the ʻaʻā lobe partly surrounds Eldborg (Fig. 1; Supplementary Material). The lava has a blocky texture and is predominantly made of clasts of rough-surfaced ʻaʻā clinker. In addition to this, it carries large (>50 cm) clasts of different textures (Fig. 8a) including pāhoehoe slabs, 'knobbly slabs' (approximately tabular pieces of irregular, rough, vesicular lava), composite clasts (that contain numerous other clasts welded together), lava balls (which have concentric shells of lava around a central clast and may reach 6 m in diameter) and rafted lava (large blocks consisting of stacked pāhoehoe sheets, still in an approximately horizontal orientation). At the northeast tip of the platy-ridged lava, some large rafts of lava have been displaced (Fig. 4; 490700, 7113200). Towards Grámelur, the surface of the lava has developed ogive-like undulations. These have an approximate wavelength of ~10–20 m and an amplitude of <3 m, but no dominant wavelength can be identified by Fourier analysis (c.f. Pyle and Elliott 2006). Where the undulations have been excavated during road building, their interior is seen to consist of ʻaʻā clinker with some of the other blocks and no indication of coherent lava near the surface (Fig. 8b). In the main channel and to the east of Grámelur, the ʻaʻā lava has much more subdued topography although small, shallow ogives can still be identified. In the east, the channelized ʻaʻā contains a number of very large rafted clasts composed of multiple thin layers of stacked shelly pāhoehoe with small (<30 cm) pāhoehoe lobes intruded between the sheets (Figs. 4 and 8; 490800, 7112100), but smaller pāhoehoe slabs or composite clasts are rarer.

Interpretation

The ʻaʻā lava was formed in a period of high lava flux focused through the central channel. This led to sustained high strain rates, which prevented formation of a surface crust (Kilburn 2000) and allowed large clasts to be carried on the flow, in particular, lava balls and rafted lava. The varied clasts in the flow suggest that it eroded material from the channel walls (Rossi 1997) with the deep trough forming on the contact. The presence of broken and jumbled pāhoehoe slabs is a defining feature of rubbly pāhoehoe (e.g. Keszthelyi et al. 2004; Guilbaud et al. 2005), but here the overall abundance of clinker, whose rough surface texture implies ductile fragmentation, as demonstrated in the road cuttings, leads to its classification as ʻaʻā. The initial channel flowed through Grámelur, which was generated by phreatomagmatic explosions. When flow through Grámelur was blocked, the flow direction moved to the west and emplaced most of the subaqueous lava (Stevenson et al. 2011). The piling up of large ogives may occur during decelerating flow, while the subdued topography of the channel ʻaʻā represents more steady conditions. The rafted clasts to the east also indicate a further period of rapid flow. It is likely that this occurred when the lava burst through the eastern margin of the flow field, sweeping the platy-ridged lava away and opening a clear, direct path down to the lake to the east (Fig. 1 and Supplementary Material).

Shelly pāhoehoe escarpments

Description

The shelly pāhoehoe escarpments lithofacies is found at the south of the flow field (Fig. 4), particularly on the eastern side of the channel. It is most similar to the cracked shelly pāhoehoe lithofacies, particularly on the western side of the channel where the main difference is a network of deep, parallel tension cracks. In the shelly pāhoehoe escarpments facies, these cracks have widened sufficiently to break the gently undulating surface into a series of raised plateaus or 'islands'. In the east, the cracks run NNE–SSW and form a series of raised escarpments 50–150 m long and 2–5 m high. The escarpments are vertical to overhanging on the eastern

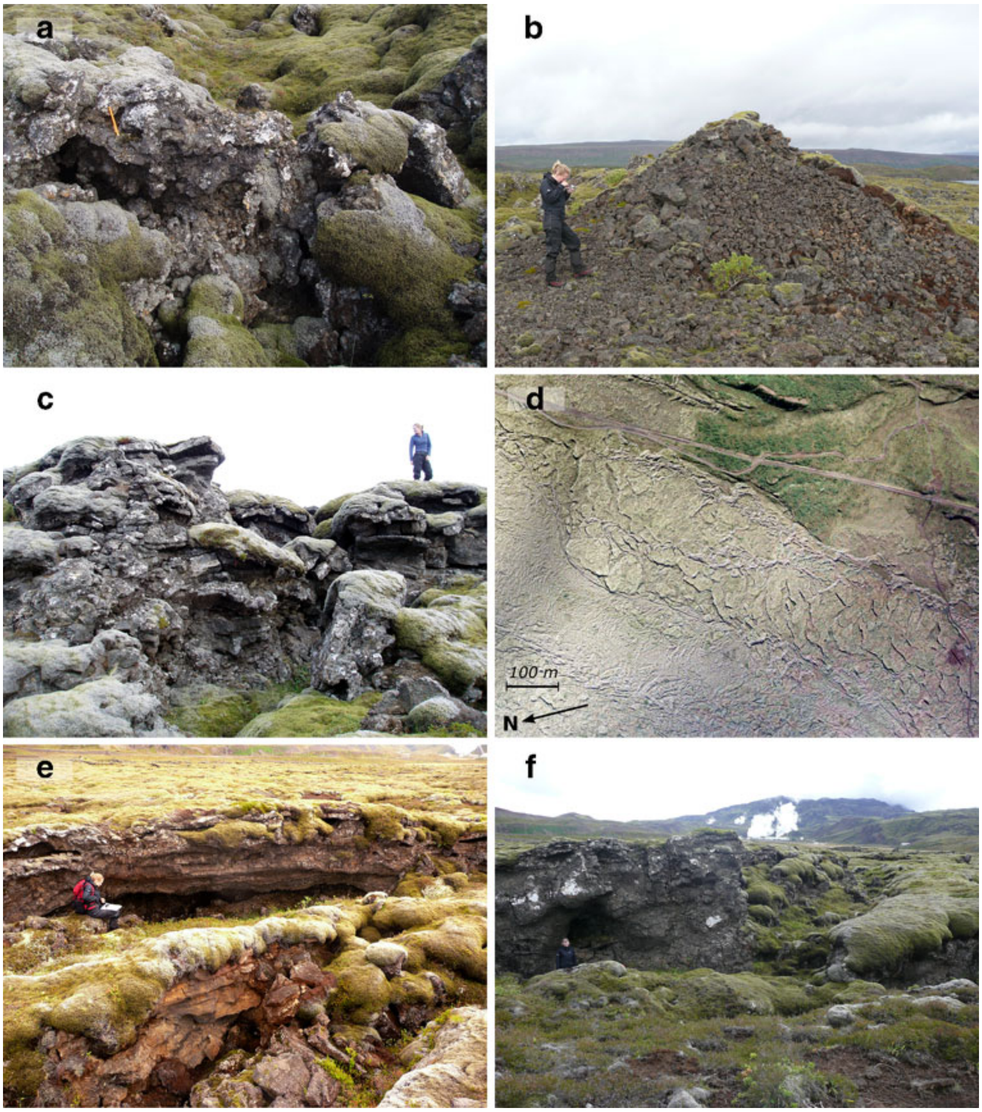

Fig. 8 Features of the drainage phase of the eruption. **a** Surface of ‘a‘ā lava, displaying extremely uneven surface covered by large clasts including broken pāhoehoe slabs (*right side of the image*), and composite clasts (*left side of the image*). This combination of clasts is also found in rubbly pāhoehoe flows, which lack ‘a‘ā clinker. **b** Road cutting through an ogive in the ‘a‘ā channel, revealing that it consists entirely of loose material. This material is dominated by clasts of ‘a‘ā clinker, with characteristically rough surfaces. **c** Rafted block in ‘a‘ā lava. It comprises stacked shelly pāhoehoe with small lava lobes (<30 cm diameter) intruded between some of the slabs. **d** Aerial photograph shows separated rafts in shelly pāhoehoe escarpments. **e** An escarpment in the shelly pāhoehoe escarpments. Note the strongly overhanging roof. This suggest that the plate has broken along a preferred lava pathway or lava tube. Shelly pāhoehoe layers are visible in the *upper part*. **f** Escarpment in shelly pāhoehoe with overhanging wall, upper shelly pāhoehoe layers, skin with columnar joints and typical size. The figure also shows rubble-filled trench, backwards dip, a lava tube and other escarpments in the background

side and dipping steadily down away from the channel on the western side (Fig. 8d). Towards the northern end of the eastern region, they change into an approximately E–W orientation and often occur in pairs that converge giving the impression that the high ground outside them is being unzipped. Further north still, rafts of lava appear to be separating and rotating clockwise.

The escarpments themselves are typically plastered with a skin of lava <30 cm thick, which sometimes exhibits striae along the exposed surface, sloping downwards in the downstream direction (Fig. 8e, f). The upper 1–2 m of the escarpment consist of stacked layers of shelly pāhoehoe, and where the walls are not plastered, it is clear that the raised slopes or islands are made of multiple stacked thin pāhoehoe flows. At the base of the escarpments, especially in the narrow channels between two ‘islands’, rubble is often present. The escarpment walls are generally overhanging, sometimes dramatically so (Fig. 8e, f). Lava tubes are occasionally found, with flattened oval cross sections, plastered walls and locally exhibiting false floors or shelves on the walls.

Interpretation

Like the cracked shelly pāhoehoe, the shelly pāhoehoe escarpments must have formed from repeated overflows of lava, but in the latter case, the cracks have been 'torn' open into trenches or channels. The common elevation of the 'islands' and of the surface away from the cracks suggests that the level of the lava was previously higher. It is possible that these features were lifted up above their surroundings, but the near-constant elevation of all the escarpments makes it more likely that their relative high elevation is due to the drainage of lava from around them. The plastering of the escarpment bases suggests that lava flowed through the channels between the raised 'islands'. The overhanging wall morphology is consistent with both tubes or channels that were in the process of crusting over. The rubble on the floor may result from the collapse of the complete or partial roof. The rotation of the crack orientation in the northern part reflects the drag of the moving channel ʻaʻā, and these islands may detach to be carried along as rafts in the ʻaʻā channel. Their ability to rotate and be moved suggests that they were at least partially underlain by molten material. It is unclear why the escarpments to the south are back-tilted away from the channel. They may have been built up that way by repeated overflows (like channel levees; Rossi 1997), or uplifted at one side by lava flowing in tubes beneath them (like tumuli; Hon et al. 1994; Mattsson and Höskuldsson 2005), or have rotated like fault blocks in a graben. Their appearance from above is superficially similar to features on Mars interpreted by Jaeger et al. (2007) as lava-draped dunes, but whose shape may also indicate tearing and rotation.

Debris-rich ʻaʻā (and pāhoehoe)

Description

This complex region is the continuation of the ʻaʻā channel back up to the vent region and contains a number of sub-regions with different textures. At the northern end, it consists of channel ʻaʻā, but with a high proportion of raised 'islands' with escarpments and also ridges of pāhoehoe slab blocks between flat pāhoehoe plates. The margins are defined by a trough, as with the channel ʻaʻā. At the southern end of the mapped extent, this lithofacies is partly floored by shelly pāhoehoe. The most distinctive feature is a sharp cliff ~4 m high that defines the southern margin and separates this region from the higher pāhoehoe sheet flow and vents above it. A mound of spatter is found at the southern end of the region.

Interpretation

The complicated facies distribution results from drainage of the inflated flow field combined with the final effusion from the vent. The prominent scarp to the south and the trough along the channel margins define this region as the source of much of the lava that flowed downstream. The low elevation of the southern part records the draining of lava from this area at the end of the eruption. The higher pāhoehoe sheet flow forming the cliff marks the maximum level reached by the lava prior to drainage. It is unclear if the scoria is primary, represents material from the vents above or was produced in some localized phreatomagmatic (rootless) eruption (Hamilton et al. 2010). The shelly pāhoehoe flooring the southernmost part of the flow field was the last material erupted as the effusion ended.

Discussion

Emplacement of the flow

The following scenario for the emplacement of the Nesjahraun in three phases is proposed to explain the different lithofacies and their distribution:

1. The eruption began with the emplacement of the pāhoehoe sheet flow, which covered the graben floor from the vents to the lake shore. A relatively high effusion rate and low slope allowed individual flow lobes to coalesce into a sheet with a continuous crust (e.g. Rossi 1997; Solana et al. 2004). The lava entering the lake as pāhoehoe generated phreatomagmatic explosions and spatter deposits (Stevenson et al. 2011) that may have hindered advance of the flow front.
2. Confined by Hagavíkurhraun to the east and perhaps by a small fault scarp, now buried, along the line of the crater row to the west (Fig. 2b, 489200, 7112800), the flow began to thicken. The thickening is the greatest in the middle of the graben, leading to an inversion of the topography (e.g. Self et al. 1998, see also Fig. 3). New lava was added either to the base of the flow, lifting it up (forming platy-ridged lava, see also "Platy-ridged lava" section) or by overflows from a network of channels and or shallow tubes (forming shelly pāhoehoe,

“Description” section). High hydrostatic pressure (where, in this case, the fluid is molten lava) at the base of the platy-ridged lava led to the escape of small volumes of lava around the margins, either by intruding beneath large sheets, lifting them up, or by small breakouts of cauliflower ‘a‘ā and possibly toothpaste pāhoehoe. The whole central part of the lava flow, 1 km wide and 4 km long, was then effectively acting as a perched lava pond (c.f. Haack et al. 2006).

3. Formation of the ‘a‘ā channel allowed lava to drain into Þingvallavatn from the northeast corner of the flow field. Approximately 6 × 10^7 m^3 (30–50% of the total flow volume) flowed into the lake, firstly through Grámelur, then to the north, then finally to the east (Stevenson et al. 2011). There is abundant evidence that the lava flux at this stage was very high, including the variety of clasts incorporated, the translation of rafts of lava and the large ogive-like undulations formed in the ‘a‘ā flow. This open-channel ‘a‘ā flow widened by erosion of the margins (e.g. Rossi 1997). The drainage of the flow pulled apart blocks of lava to the south of the flow field, generating deep cracks in the cracked shelly pāhoehoe and forming ‘islands’ in the shelly pāhoehoe escarpments. The draining lava plastered the walls of these blocks, like channel walls, and striated their plastic

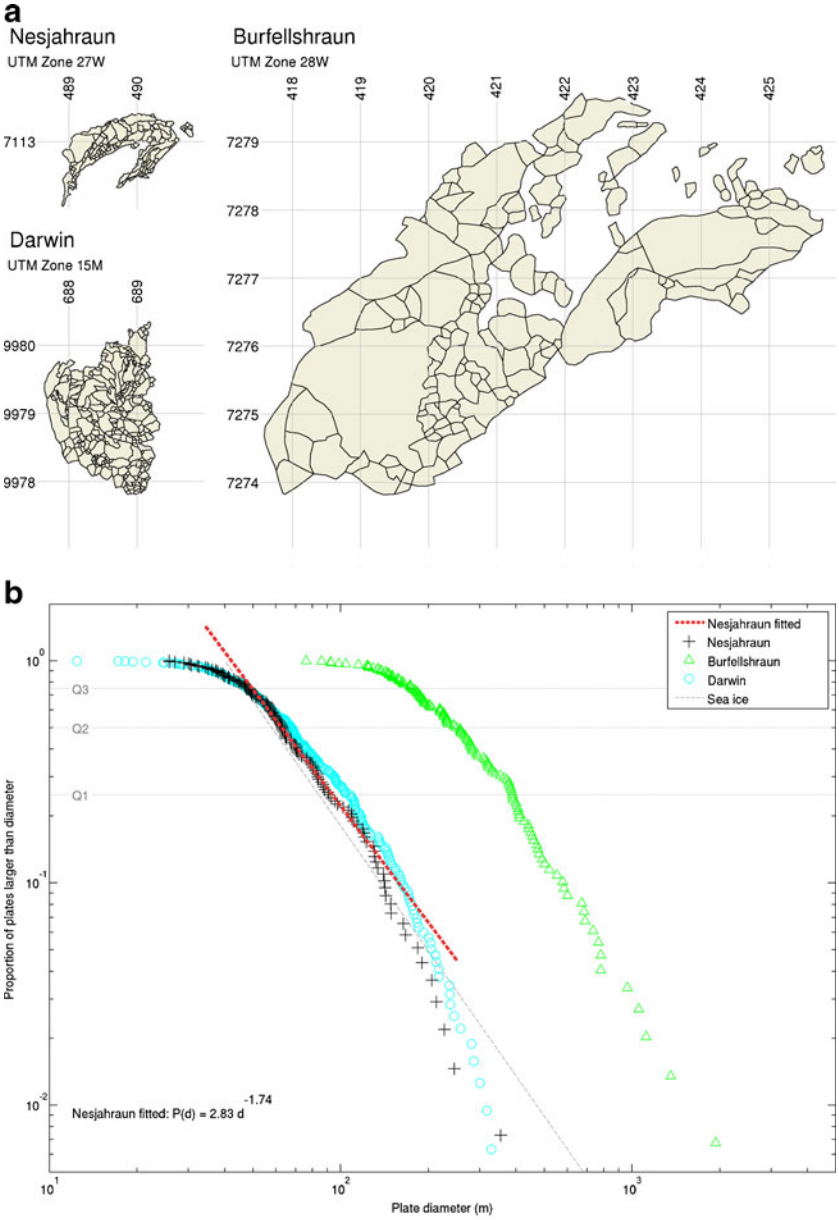

Fig. 9 Size distribution of plates on platy ridged lava flows. **a** Digitized plate outlines from Nesjahraun, Darwin volcano (Galapagos, 91.29° W, 0.19° S) and Burfellshraun (Iceland, 16.58° W, 65.61° N), all shown at the same scale. The grid numbers in each map are truncated UTM coordinates within the given UTM zone, and grid lines are 1,000 m apart. **b** Size distribution of plates. The curves can be approximated in the inter-quartile range by a power-law distribution. The curves tail off at small plate sizes, which may be due to limitations of the resolution of the data

> surfaces as it flowed past. Diagonal striae suggest that the lava was draining as it flowed. Some pāhoehoe lava was emplaced at the southern end of the channel during the final stages of the eruption. The preservation of the drainage scarp along the southern margin suggests that the drainage occurred near the end of the eruption.

The combination of ʻaʻā-filled channels surrounded by sheet pāhoehoe could have been formed more simply by repeated overflows from an open channel. This explanation is rejected because of the large distances at which the pāhoehoe has been emplaced from the channel (up to 2 km), the absence of shelly pāhoehoe in these locations (slabs here are much thicker) and the flow of ʻaʻā lava over the sheet pāhoehoe at the N end of the flow. Furthermore, the cross sections show that the whole central part of the flow field has inflated and that it lacks levee structures sloping outwards from the channel (Fig. 3). The development of an ʻaʻā channel in what began as a pāhoehoe-sheet-flow-producing eruption, as at the Nesjahraun, has been observed elsewhere in Iceland, during the Krafla 1984 eruption (Rossi 1997). Overflows from the Krafla lava produced wedge-shaped levees of shelly pāhoehoe along the channel margins, which were distinct from the initial pāhoehoe sheet flows. Such features are absent at the Nesjahraun because the formation of the ʻaʻā channel allowed the ponded lava to drain, resulting in a lowering of the level.

Platy-ridged lava

Size distribution of plates

The size distribution of the plates was calculated by manually digitizing their outlines with GIS software and calculating an equivalent diameter from their area ($d = \sqrt{4 \times A/\pi}$). This method was used by Toyota et al. (2006) to characterize the size distribution of ice floes in the northern Pacific ocean. For comparison, platy-ridged lava from the Burfellshraun, Iceland, and within the caldera of Darwin island, in the Galapagos, were digitized from Google Earth imagery (Fig. 9a). The plates at both Darwin and Burfellshraun were found to be larger than those of the Nesjahraun. The central part of the distribution can be approximated by a power-law distribution of the form ($P(d) \propto d^{-\beta}$, where P is the proportion of plates with diameter > d), but the relative numbers of the smallest and largest plates are overestimated (Fig. 9b). The best fit for the Nesjahraun data is achieved where $\beta = 1.74$. This exponent is similar to value found by Toyota et al. (2006) for sea ice ($\beta = 1.7$–2.9). The distribution tails off at small plate sizes ($d = 30$ m) for Nesjahraun and Darwin, which were digitized from aerial photo data (resolution 1 m) and at $d = 150$ m for Burfellshraun, which was digitized from satellite data (resolution 8 m). This may indicate that image resolution is an important factor in the size of plates that can be digitized.

It is likely that the diameter of the plates is related to the thickness of their crust, with larger plates being formed of thicker, stronger, crust. Observations that slabs within the ridges of the Burfellshraun are 50–80 cm thick (and in some locations 1.5–2 m thick; Keszthelyi et al. 2004) would be consistent with their greater size. The relatively narrow range of plate thicknesses measured at the Nesjahraun is surprising (Fig. 4), as it suggests that most slabs were tilted between 16 and 24 h following initial formation of the crust (based on Eq. 2 of Hon et al. 1994). It seems unlikely, therefore, that they were all tilted in a single event because the crust in different areas would be expected to be of different ages. Also, the brittle nature of their formation, that some slabs were pushed downwards and that sometimes drips are frozen perpendicular to the slab surface all suggest that in some cases the lava may have drained from beneath the slabs before they were tilted. This drainage would prevent further slab thickening and is also an important factor in the formation of shelly pāhoehoe. The narrow range of sizes may also reflect an optimum slab thickness for ridge formation: too thin and the slab breaks or deforms, too thick and it would not be lifted. Alternatively, it may indicate some sort of sampling bias; perhaps slabs of 20–30 cm thickness conform best to the image of an ‘ideal’ slab.

Formation of ridges

The two Martian lava morphologies of Keszthelyi et al. (2004) are flat plates separated by narrow ‘pressure ridges’ and ridged plates separated by low, smooth, channel-like areas where they have ‘rafted apart’. The platy-ridged lava lithofacies of the Nesjahraun is most like the former type. Its ridges are also similar to shatter rings: concentric elliptical rings of broken rubble <4 m tall and >50 m in diameter, which form above wide lava tubes in response to the repeated uplift and subsidence of part of the tube roof as the lava-level changes beneath it (Kauahikaua et al. 2003; Orr 2010). Keszthelyi et al. (2004) proposed that the ‘pressure ridge’-type platy-ridged texture forms by compression of lava crust during flow to form ridges, with growth of new crust forming the plates. It seems likely, however, that compression would lead to parallel ridges, arranged perpendicular to the direction of compression. Instead, the proposed method of formation here is by inflation/deflation as lava moves beneath, either through preferred lava pathways or, more likely, as a continuous body acting as a perched lava pond. Thus, the slabs within the ridges form by the same mechanism as a shatter ring. The plates must only have been subjected to a few cycles of uplift and subsidence in order to preserve their interiors. Lateral translation is therefore unnecessary for ridge formation, and at the Nesjahraun, significant movement did not take place (see "Description" section). Evidence from Mars, such as 'pressure ridge'-type platy-ridged texture on lava that flowed into an impact crater through an entrance narrower than the diameter of the plates (Keszthelyi et al. 2004), points to the formation of at least some of the Martian ridges in situ. Ice floes are another example of fracturing by vertical motions of underlying fluid (in this case seawater; Toyota et al. 2006).

It is noted that at the Nesjahraun and Darwin volcano, as well as at Sierra Negra, Galapagos, where inflated 'a'ā was described by Geist et al. (2008), that the lava flows were topographically confined and that the vents feeding them were located in elevated positions (e.g. on a hyaloclastite ridge or caldera rim). Similarly, rubbly pāhoehoe flows formed at Laki, Iceland, in response to the flow advance being blocked by a group of rootless cones (Hamilton et al. 2010). Thus, flow confinement and an elevated vent location may contribute to the buildup of hydrostatic head and consequently promote inflation. The margins of the Nesjahraun are unlike platy-ridged flows elsewhere, which typically have a zone of hummocky pāhoehoe at the leading edge of the flow (Keszthelyi et al. 2004; Guilbaud et al. 2005). The absence of this hummocky pāhoehoe may also be a result of confinement.

A single phase of disruption?

The Nesjahraun lacks true ridged plates separated by smooth lava channels, although the flat areas between 'islands' of cracked shelly pāhoehoe are similar to these channels and the ogives in the 'a'ā channel resemble the ridges of the plates in both their overall form and the types of clasts that they contain. Broken pāhoehoe slabs, composite clasts and rafts of shelly pāhoehoe cover the surface of rubbly pāhoehoe, which is interpreted to form by a series of inflation and disruption events as a flow advances (Guilbaud et al. 2005). Each cycle generates more pāhoehoe crust, more fragmentation and more mixing of surface clasts with underlying fluid lava. The Nesjahraun is interpreted to result from just a single inflation event, which was disrupted by the formation of the 'a'ā channel. This explains the simple, pāhoehoe-slab-derived ridges around the flat plates, which have not undergone significant translation and the dilution of rubbly pāhoehoe components by 'a'ā clinker during the sustained draining of the flow field through the channel.

Conclusion

In our reconstruction of the emplacement of the Nesjahraun, it was emplaced in three main phases. Firstly, a pāhoehoe sheet flow was emplaced over the whole graben floor. Secondly, as lava was erupted from the vent faster than it could flow away, the central part of the flow field inflated, producing platy-ridged lava. Where the lava was injected beneath a brittle crust it inflated, breaking into plates and forming ridges of pāhoehoe slabs as the plates moved vertically past each other. Where lava overflowed from channels and tubes between moving plates, shelly pāhoehoe was formed. The flow then essentially formed a large perched lava pond, 1 × 4 km in size. Thirdly, following establishment of an open channel though the flow field, the lava drained rapidly into the lake, Þingvallavatn, as 'a'ā, carrying large rafts of compound shelly pāhoehoe and lava balls along with it. This left a network of elevated 'islands' and drained channels and tubes near the vent region.

The platy-ridged lava is interpreted to have formed by the inflation and uplift of pāhoehoe sheet lava once it had formed a brittle crust. The gradational margin with pāhoehoe sheet lava on the NW and the presence of large uplifted sheets on the margin to the NE demonstrate how this happens with little or no lateral movement. The generation of the broken slabs that comprise the ridges is interpreted to be by differential uplift and is the same mechanism by which shatter rings form. The cumulative size distribution of the plates can be approximated by a power-law of the form $P(d) \propto d^{-\beta}$ where $\beta \sim 1.74$ for the Nesjahraun and is similar to that of Darwin volcano, Galapagos. In addition to low slope and high discharge being factors favoring platy-ridged lava flows, lateral confinement and an elevated vent location may also have played an important role.

High-resolution aerial survey data are excellent for the identification and outlining of different lava lithofacies in large or complicated flow fields and to identify interesting areas for targeted field work. In particular, LiDAR data allow removal of distortion from aerial photos by orthorectification, generation of slope and local topography maps to highlight boundaries and subtle features and measurement of gradients and profiles. However, fieldwork was still required to determine that the ridges were formed from tabular broken pāhoehoe slabs and to measure their thickness, to identify shelly pāhoehoe, lava tubes, ‘a‘ā lava and the clasts rafted within it. The best results are obtained when both techniques are used in a complementary fashion.

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