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RESEARCH ARTICLE

Dimmuborgir: a rootless shield complex in northern Iceland

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Abstract The origin of Dimmuborgir, a shield-like volcanic structure within the Younger Laxá lava flow field near Lake Mývatn, in northern Iceland, has long been questioned. New airborne laser mapping (light detection and ranging (LiDAR)), combined with ground-penetrating radar results and a detailed field study, suggests that Dimmuborgir is a complex of at least two overlapping rootless shields fed by lava erupting from the nearby Lúdentarborgir crater row. This model builds upon previous explanations for the formation of Dimmuborgir and is consistent with observations of rootless shield development at Kīlauea Volcano, Hawaii. The larger rootless shields at Dimmuborgir, 1–1.5 km in diameter, elliptical in plan view, ~30 m in height, and each with a 500-m-wide summit depression, were capable of storing as much as $2–3 \times 10^6$ m^3 of lava. They were fed by lava which descended 30–60 m in lava tubes along a distance of 3 km from the crater row. The height difference generated pressure sufficient to build rootless shields at Dimmuborgir in a timescale of weeks. The main summit depressions, inferred to be drained lava ponds, could have emptied via a 30-m-wide × 5-m-deep channel, with estimated effusion rates of 0.7–7 m^3 s^{-1} and minimum flow durations of 5–50 days. We argue that the pillars for which Dimmuborgir is famed are remnants of lava pond rims, at various stages of disintegration that formed during pond drainage.

Keywords Dimmuborgir · Iceland · Rootless shields · LiDAR · Younger Laxá Lava

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Introduction

Lava flow hazard assessments rely heavily on estimated local fluxes (e.g., Harris et al. 2007), which are usually assumed to be less than or equal to the effusion rate from the eruptive vent. However, sudden release of lava which has accumulated in transitory structures such as perched lava ponds—lava ponds, enclosed by levees, that form as a lava flow slows down and spreads out radially—or rootless shields—shield-shaped structures that form over lava tubes—can result in local effusion rates far exceeding those from the vent. For example, Patrick and Orr (2012) documented the collapse of rootless shields at Kīlauea Volcano in 2008 that resulted in discharge rates nearly an order of magnitude higher than those from the vent. Anomalously high effusion rates caused by the sudden release of accumulated lava have also been reported from the 1977 eruption of Nyiragongo Volcano in the Democratic Republic of the Congo, when a lava lake drained (Tazieff 1977) and the 2002 eruption of Stromboli Volcano in Italy, when magma drained through flank fractures (Calvari et al. 2005). Thus, identifying the presence of accumulated lava upslope is an important part of fully understanding the downslope hazard of a lava flow.

Here, we show evidence for the ephemeral accumulation of lava along the flow path of the Younger Laxá Lava (YLL) in Iceland, which erupted 2170 ± 38 calendar years BP

(Hauptfleisch and Einarsson 2012). The YLL represents one of the largest post-glacial lava flows in the Northern Volcanic Zone (Thorarinsson 1951, 1979), which marks the mid-Atlantic ridge in northern Iceland.

Our study focuses on Dimmuborgir, a complex of shield-like structures of uncertain origin within the YLL. Based on airborne laser mapping (light detection and ranging (LiDAR)), ground-penetrating radar (GPR) transects and fieldwork, we propose that Dimmuborgir comprises a complex of at least two rootless shields that developed over a lava tube system within the YLL. We provide further support for this interpretation by comparison with rootless shields that formed at Kīlauea Volcano, Hawaii, during 2007–2008.

Geological background

The YLL is an olivine tholeiite (Thorarinsson 1951; Nicholson and Latin 1992). It is mostly rubbly pahoehoe lava, and its estimated volume of 2.5 km^3 (Thorarinsson 1951, 1979) erupted from NNE-striking *en echelon* fissures, now delineated by the Þrengslaborgir and Lúdentarborgir crater rows (Figs. 1 and 2). The combined length of these crater rows, which are situated at an elevation of 410–440 m above sea level (asl), is approximately 10 km. The lava flowed west around the prehistoric Lake Mývatn and then followed the Laxár Valley to the NNW for over 40 km to Skjálfandi Bay on the north coast of Iceland (Sæmundsson et al. 2012). In the vicinity of Dimmuborgir, around Mývatn and along the northern part of the Laxár Valley, there are numerous rootless cones on top of the YLL. These structures, typically 50–200 m in diameter, formed when lava flowed across wetlands, resulting in rootless eruptions driven by explosive water-lava interactions (Thorarinsson 1951, 1953, 1979).

Within the YLL, between the Lúdentarborgir crater row and Mývatn, is Dimmuborgir (Figs. 1 and 2). Barth (1942) described Dimmuborgir as a low, irregular shield-like structure 2 km in diameter; it is topped by two roughly circular 500-m-diameter summit depressions which are partly bounded by 10–15-m-high vertical lava walls. These depressions are surrounded by numerous pillars composed of lava. The tops of these pillars are at the same elevation as the rim of the depression in which they are found. The sides of the pillars show vertical striations that resemble slickensides and horizontal shelves that protrude 10–20 cm which are referred to as "bathtub rings." On the basis of these observations, Barth (1942) proposed that Dimmuborgir was the site of a former lava pond and that the striations and shelves on the sides of lava pillars recorded stepwise subsidence of the solidified crust of this pond as it drained into an underlying reservoir. Bamlett and Potter (1986) and Sæmundsson (1991) further proposed that the pillars were formed by venting of steam

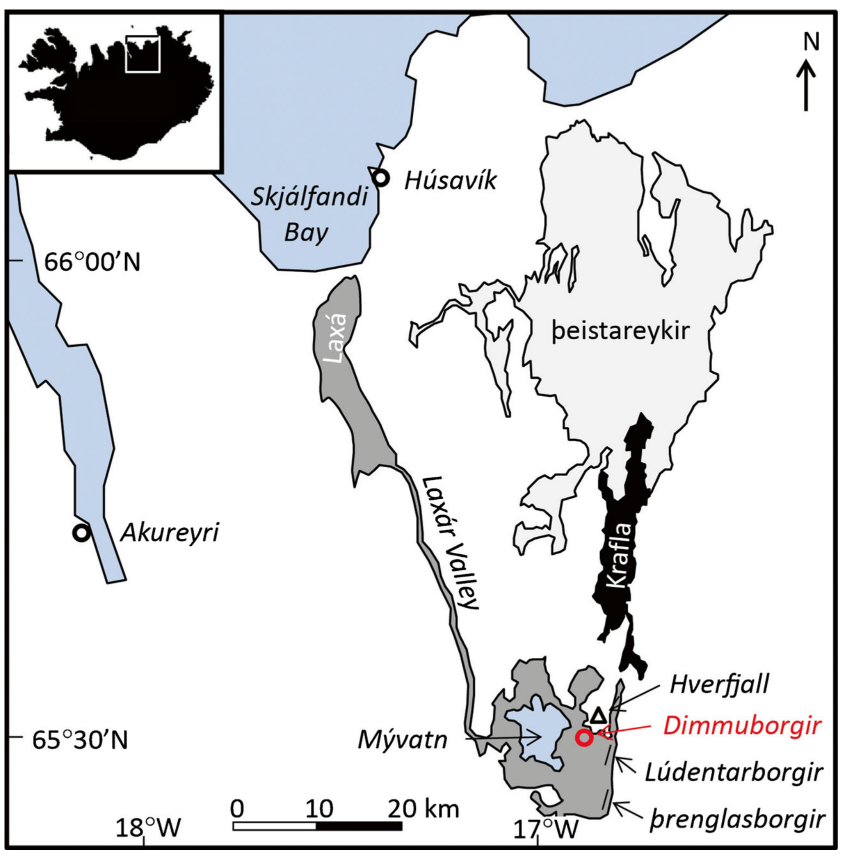

Fig. 1 Simplified map of part of northern Iceland showing Dimmuborgir, the Þeistareykir, Laxá and Krafla lava flow fields, and the Lúdentarborgir and Þrengslaborgir crater rows

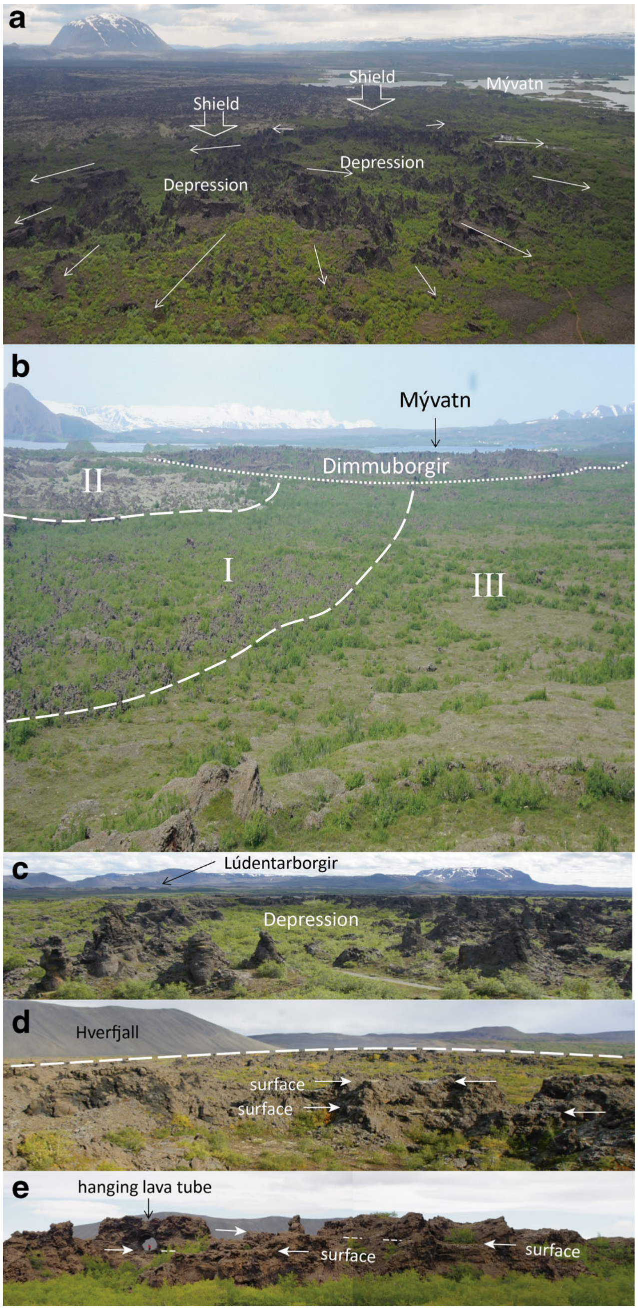

Fig. 2 Overview photographs of Dimmuborgir **a** looking southwest from Hverfjall to Dimmuborgir and Mývatn (vertical exaggeration ×2.5) showing summit depressions atop two overlapping shield-like structures with *arrows* denoting slope directions, **b** looking west from Lúdentarborgir to Dimmuborgir and Mývatn (vertical exaggeration ×2.5) showing areas covered by rubbly pahoehoe lava (*I*), windblown basaltic sand (*II*), and pahoehoe lava (*III*), **c** looking southeast from the rim of the western summit depression, **d** looking east from the same viewpoint showing the eastern shield-like structure (surface delineated by *dashed line*) and two underlying laterally extensive flat pahoehoe surfaces (marked by *arrows*), and **e** looking north across the western summit depression at two of these flat pahoehoe surfaces (marked by *arrows*), one at the same level as the floor of a remnant stranded lava tube

produced from the mingling of lava with lake water. They suggested that the lava pond drained along a lava channel, visible on the western side of Dimmuborgir, before the steam vents had completely solidified. It has further been suggested that the lava pond was perched behind an area of rootless cones, also visible to the west of Dimmuborgir. Other proposed origins for Dimmuborgir are as a primary eruption center (Rittman 1938) or as a result of eddying in a turbulent lava flow (van Bemmelen and Rutten 1955).

Methods

To help unravel the origin of Dimmuborgir, airborne laser mapping (LiDAR) with a mean density of 7.6 points per square meter was used to construct a digital terrain model (DTM) of Dimmuborgir and Lúdentarborgir with a 1-m-grid cell size on a Lambert Conic Conformal projection with parameters set for Iceland's geodetic reference system ISN93. The projection parameters are standard parallels at 64.25° and 64.75° N; central meridian at 19° W; false easting of 500, 000 m; and false northing of 500,000 m. DTM heights refer to mean sea level (MSL) derived using the geoid separation model in the vertical reference system for Iceland ISH2004. All LiDAR data were initially collected with respect to the GRS80 ellipsoid. The average height difference in the surveyed area between ISH2004 and GRS80 is ~65.6 m. LiDAR is a largely automated topographic land surveying method. It is performed by an aircraft-mounted ranging laser that fires a stream of laser pulses that are reflected by the ground. The distance between the laser and the terrain surface is given by the return time of a series of pulses. The first of these pulses records vegetation whereas the last pulse records the position of the ground surface and is used to construct the DTM (Fig. 3a). The detected difference in time between the first and last return of a pulse provides a measure of vegetation height in time that may be converted to meters by multiplication with the speed of light. The difference between the return times of the first and last pulses can be used to calculate vegetation height (Fig. 3b). The coordinates of the laser spots are computed on the basis of position, direction and distance, measured using a Global Positioning System (GPS) receiver, an Inertial Navigation System, and the ranging laser, respectively. Dimmuborgir was mapped using an Airborne laser scanner ALTM 3100 mounted to a Twin Otter aircraft operated by Norlandair flying at an altitude of 800 m and speed of 60 m s^{-1}. The laser scan rate was 100,000 Hz. The maximum scan angle was 14°, and the scan frequency was 61 Hz. The reference area chosen for verification of system calibration was a nearby runway. Height resolution is better than 8 cm. Data were visualized using the computer program Fledermaus version 7.

Ground-penetrating radar (GPR) was used to search for shallow (ceiling <20 m) open lava tubes in the Younger Laxá lava capable of transporting lava from Lúdentarborgir

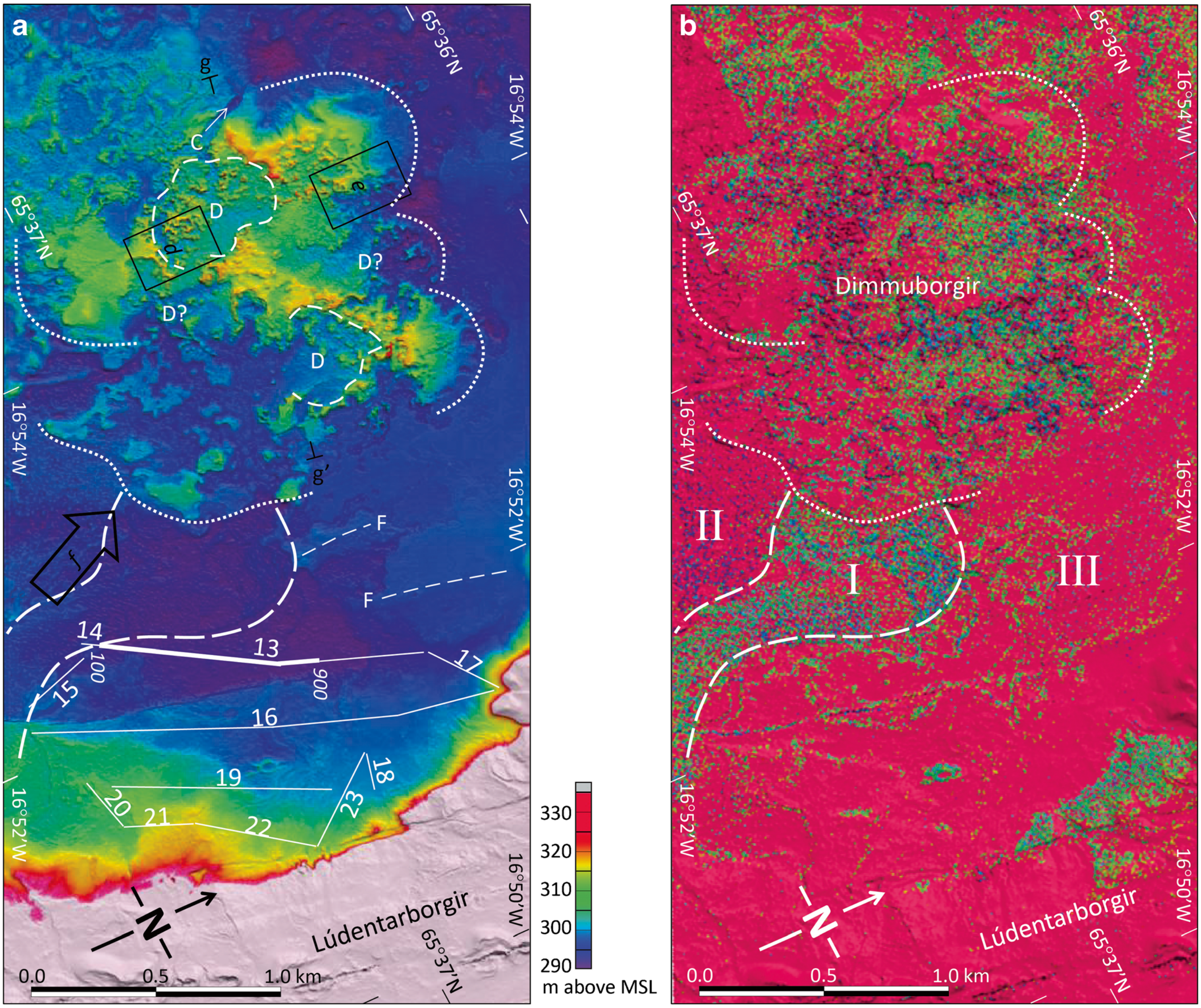

Fig. 3 **a** DTM of Dimmuborgir and Lúdentarborgir showing approximate outline of the overlapping shield-like structures (*dotted lines*), summit depressions (*dashed lines*, labeled *D*), a channel descending north before veering west towards Mývatn (*arrow*, labeled *C*), faults (*thin dashed lines*, labeled *F*), location of the GPR survey lines (*numbered lines*) with the section of survey line 13 (from 100 to 900 m) shown in Fig. 4 highlighted, locations of panels d, e and the view direction of panel f. **b** Areas of different vegetation types (*I*, *II*, and *III*) classified based on their height above ground, derived by the time difference between first and last LiDAR pulses returns (*magenta* denotes groundcover vegetation only, whereas *blue* and *green* denote bushes and small trees. **c** Satellite image from Google Earth of the same area showing areas of different vegetation types as well as an areas of rootless cones (shown in Fig. 15) and stump-like protrusions (shown in Fig. 7e). **d** A close-up DTM showing various stage of pillar formation (*I–III*, see text for details). **e** A close-up DTM showing alignment of rootless eruptive sites (marked by *arrows*) along the NNE-striking Grjótagjá Fault. **f** Oblique DTM showing overlapping shield-like structures (*top* marked with *dotted lines*) each with a central depression (labeled *D*) forming the main part of Dimmuborgir, viewed obliquely from the southeast in the direction of the *arrow* (**a**). **g** A profile along line *g–g* (**a**) showing the shield-like shape of Dimmuborgir, two summit depressions (labeled *D*) and the channel at its western margin (labeled *C*)

fissure to Dimmuborgir. GPR uses high-frequency electromagnetic waves to produce high-resolution images of the shallow subsurface. The GPR system used consisted of a GroundExplorer (GX) controller and a 50 MHz Rough Terrain Antenna (RTA), giving a penetration depth of ~30 m in our study. GPR surveys made after several days of dry weather across the low-lying area between Lúdentarborgir and Dimmuborgir were used to construct four profiles. These surveys were oriented approximately perpendicular to collapsed lava tubes observed at the surface and covered a rectangular 2 × 1 km area of the flow field (Fig. 3). The topsoil was thin, so the transmitter/receiver was run over the basalt surface. Processing of GPR data was accomplished using the program ReflexW using topographic data from the LiDAR survey. Previous GPR surveys of young volcanic rocks yield velocities of 0.09 (Russell and Stasiuk 1997) and 0.07 m/ns (Miyamoto et al. 2005). In our study, we used a value of 0.1 m/ns, noting that our primary purpose is to confirm the presence

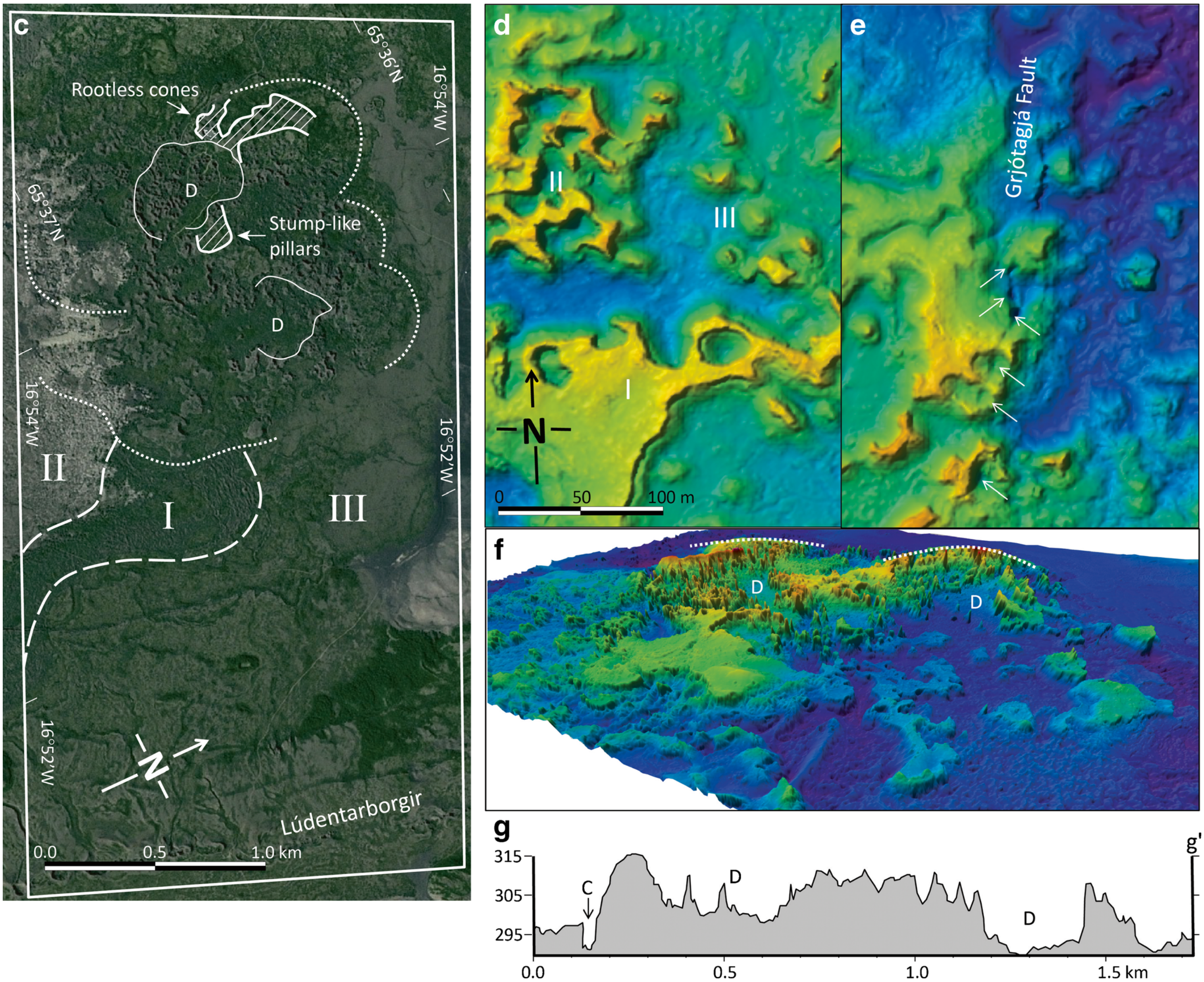

Fig. 3 (continued)

of lava tubes in the uppermost 20 m of the Younger Laxá lava rather than to accurately determine their depth and size. Previous work (Miyamoto et al. 2005) has shown that lava tubes are seen as hyperbolae on GPR sections. In some cases, a double hyperbolae indicates both upper lava/air and lower air/lava boundaries.

Results

Younger Laxá Lava

The lava flow field of the YLL between Lúdentsborgir, Þrengslaborgir, and Dimmuborgir comprises two or three flows which can be distinguished on the basis of vegetation height (Figs. 2b and 3b). The most recent flow (area I) is composed texturally of rubbly pahoehoe lava. It fills a 0.4–0.5-km-wide channel in the mapped area which widens at the base of Dimmuborgir. This flow was fed from multiple smaller flows from Lúdentsborgir and Þrengslaborgir which were first mapped by Rittman (1938). The area SW of this flow and S of Dimmuborgir (area II) is covered by windblown basaltic sand which partly obscures the southern flank of Dimmuborgir. This area was mapped as part of the YLL by Thorarinsson (1951, 1979) and Sæmundsson et al. (2012). The area NE of this flow and E of Dimmuborgir (area III) is composed texturally of pahoehoe lava. This is atypical for the YLL which is otherwise dominated by rubbly pahoehoe lava (Thorarinsson 1951, 1979). This area is probably a sheet flow as described by Self et al. (1998). Its probably thickness, based on the GPR profile (Fig. 4), is 15–20 m. This flow was fed with lava from the Lúdentsborgir crater row. It bulges upwards along two N–S trending faults (*F* on Fig. 3a) and there is no definitive break between this flow and the eastern flank of Dimmuborgir.

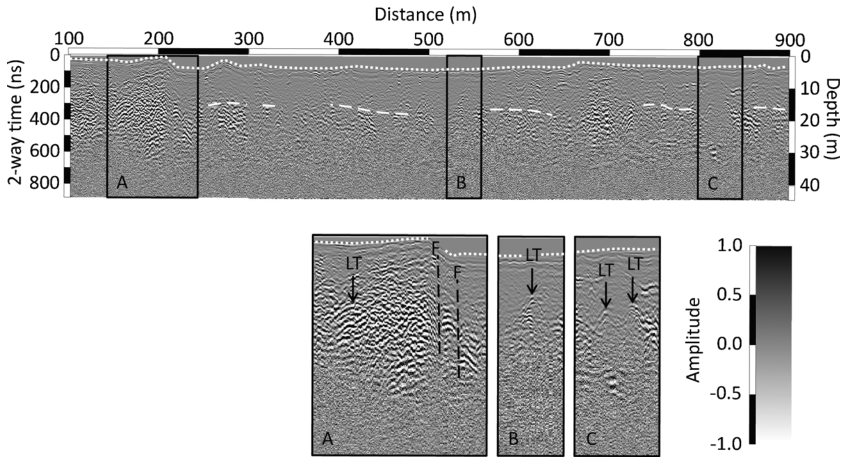

Fig. 4 Section of GPR profile 13 (located on Fig. 3a). This profile was mapped on to the topographic surface (*dotted line*) from the LiDAR survey. It shows a change of reflection amplitude (*dashed line*) at an approximate depth of 15 to 20 m which may correspond to a boundary between the YLL and older lava flows. The profile also shows reflections suggestive of faulting (labeled *F*) and lava tubes (labeled *LT*). Lava tubes are seen as single or multiple hyperboles; these were seen on most of the GPR profiles. Examples of hyperboles interpreted as lava tubes are shown in *insets A*, *B*, and *C*. These are at calculated depths ranging from 15 to 20 m. Faults, which are associated with surface displacements, can be distinguished from lava tubes because they produce partial rather than full hyperboles. Examples of faults are shown (*inset A*). It was not possible to extrapolate lava tubes between the GPR profiles. However, based on these profiles, we can confirm the presence of lava tubes at a range of depths beneath the lava flow surface between Dimmuborgir and Lúdentarborgir

Dimmuborgir

Dimmuborgir is a volcanic structure composed texturally of pahoehoe lava and dominated by at least two partly overlapping and variably collapsed shields, each with a depression at its top (Fig. 2a). These shields, apparent on the DTM (Fig. 3a) and satellite imagery (Fig. 3b), are elliptical, 1–1.5 km in diameter and about 30 m higher than the surface of the surrounding lava. This gives an approximate volume (calculated as an elliptical cone) of 1.2×10^7 m^3 for each shield. The flanks of Dimmuborgir slope outwards at an angle of 2.3°–3.4°, which is consistent with classifying the structure as a lava shield, i.e., within the range for tholeiitic shield volcanoes on Iceland 0.03°–7° (Rossi 1996). The summit of Dimmuborgir (317 m asl) is about 30 m lower than the lowest point along the Lúdentsborgir crater row (~350 m asl).

Summit depressions

The summit depressions (*D* on Fig. 3a, c and g) are irregular in shape, about 500 m across and 10–15 m deep, each equating to an approximate volume of $2–3 \times 10^6$ m^3 (calculated as a cylinder). They are floored by tilted, meter-wide, and 2–3-dm-thick plates of pahoehoe lava (Fig. 5). If these are remnants of a crust on top of originally ponded lava, we can estimate that it stagnated for 7–15 h based on the empirical relationship of Hon et al. (1994). In addition, two well-defined, laterally extensive pahoehoe surfaces are identifiable within the summit depressions (Fig. 2d, e). These surfaces are of similar thickness to the plates of pahoehoe lava found on the floor of each depression. They extend from the base of, or terminate at, stranded lava tubes exposed in the walls of the crater (Fig. 2d) and are inferred to be bathtub rings, recording former pond levels. We thus infer that the summit depressions were filled with lava which ponded at different levels for time periods ranging from several hours to 1 day.

Skylights, semi-circular depressions, and pillars

The summit depressions are fringed by circular skylights—openings formed by collapse of the roof of a lava tube—5 to 20 m in diameter (Fig. 6a) and semi-circular depressions, 10 to 50 m in diameter (Fig. 6b). A low-roofed and gently sloping lava tube can be seen at the base of most of these depressions (Fig. 6b). The DTM (Fig. 3d) shows that circular skylights (area I) and semi-circular depressions (II) transition into the pillar-like features, for which Dimmuborgir is renowned (area III). Some of these pillars as well as the sides of the semi-circular depressions have relatively smooth walls with vertical grooves resembling slickensides, and multiple horizontal lava bathtub marks that protrude horizontally for a few decimeters (Fig. 7a). This relatively smooth surface is a 10–50-cm-thick hard veneer that encases the central part of the pillars and the sides of the depressions. Where the veneer is broken and missing, the pillars and depression walls are composed of thin pahoehoe layers (Fig. 7f). Some pillars further from the sides of the summit depressions tend to have complex shapes controlled by the degree to which they have collapsed (Fig. 7b, c) and are, in some cases, tilted (Fig. 7d). Finally, some lava flows on the flanks of Dimmuborgir appear to drape stump-like protrusions (Fig. 7e), which we infer to be

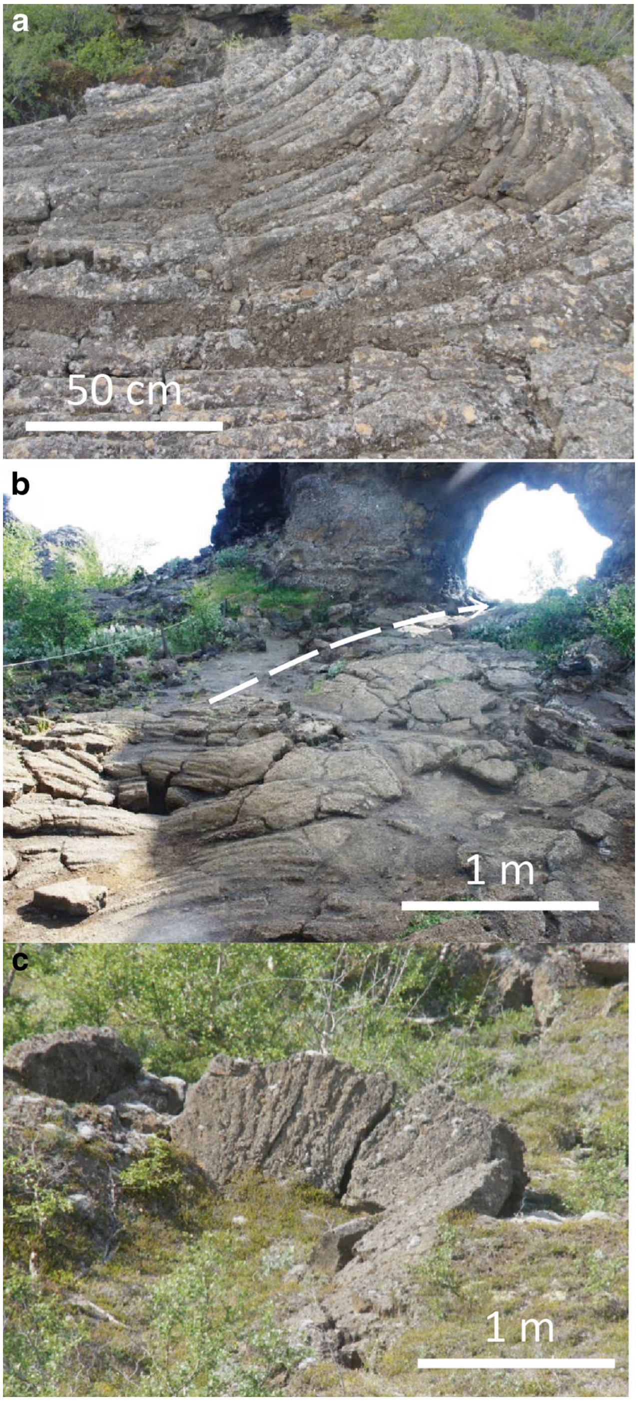

Fig. 5 Pahoehoe lava **a** on the flank of Dimmuborgir, **b** on one of the flat surfaces seen in Fig. 2d indicating flow towards the rear side of the stranded lava tube seen in the upper right corner, and **c** on the floor of one of the summit depressions as tilted meter-size pieces

buried pillars. We infer that the progression from skylights and semi-circular depressions to upright pillars to collapsed and tilted pillars, seen on the DTM (Fig. 3d) and in the field (Figs. 6 and 7), reflects collapse of the sidewalls of the summit depression during drainage of ponded lava.

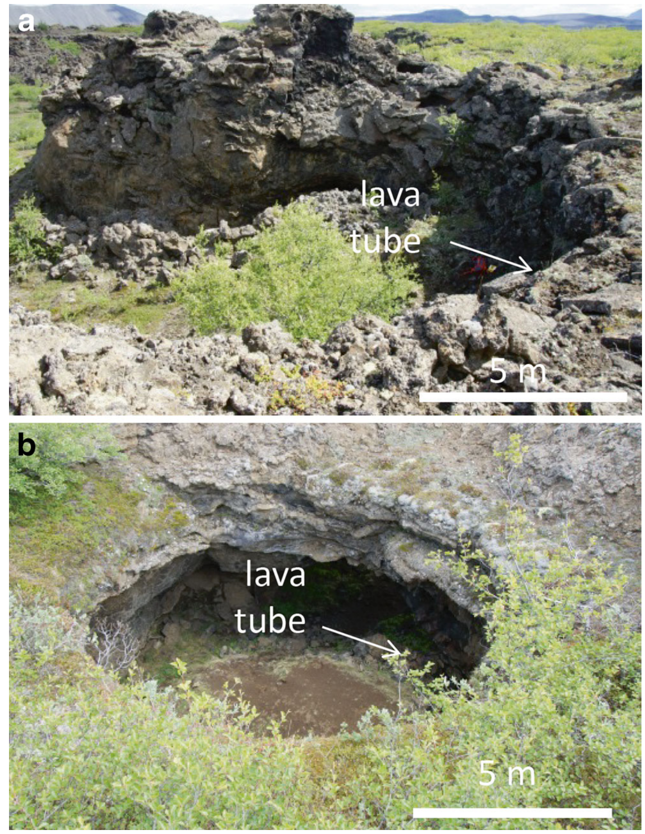

Fig. 6 Representative examples of skylights and semi-circular depressions. **a** Semi-circular depression at the rim of a summit depression. **b** Circular skylight set back from this rim revealing a gently sloping, low-roofed, lava tube

Rootless eruption sites

A second type of circular feature can be seen on the DTM (Fig. 3e). These are steep-sided pits, 5–50-m in diameter. Each pit is located over a vertical conduit-like opening, which is partly wholly filled with debris (Fig. 8). The pit walls and rims are coated with locally derived spatter (Fig. 8). In some cases, remnants of a vertical pipe-like shaft can be seen on the pit wall (Fig. 8). These features are most common at the NW margin of Dimmuborgir. Here, a string of pits follows the present-day Grjótagjá Fault (Fig. 3e). The fault can be seen at the base of each pit, both on the DTM and in the field. We infer that these are rootless eruption sites and note a spatial association with faults.

Lava channels and lava tubes

Lava channels were observed on the DTM (Fig. 3) and in the field (Fig. 9), whereas lava tubes were inferred using GPR (Fig. 4) and observed in the field (Fig. 10). Lava channels were distinguished from lava tubes based on size and morphology. Lava channels at Dimmuborgir were 20–30-m wide with 3–5-m high vertical and overhanging and sometimes

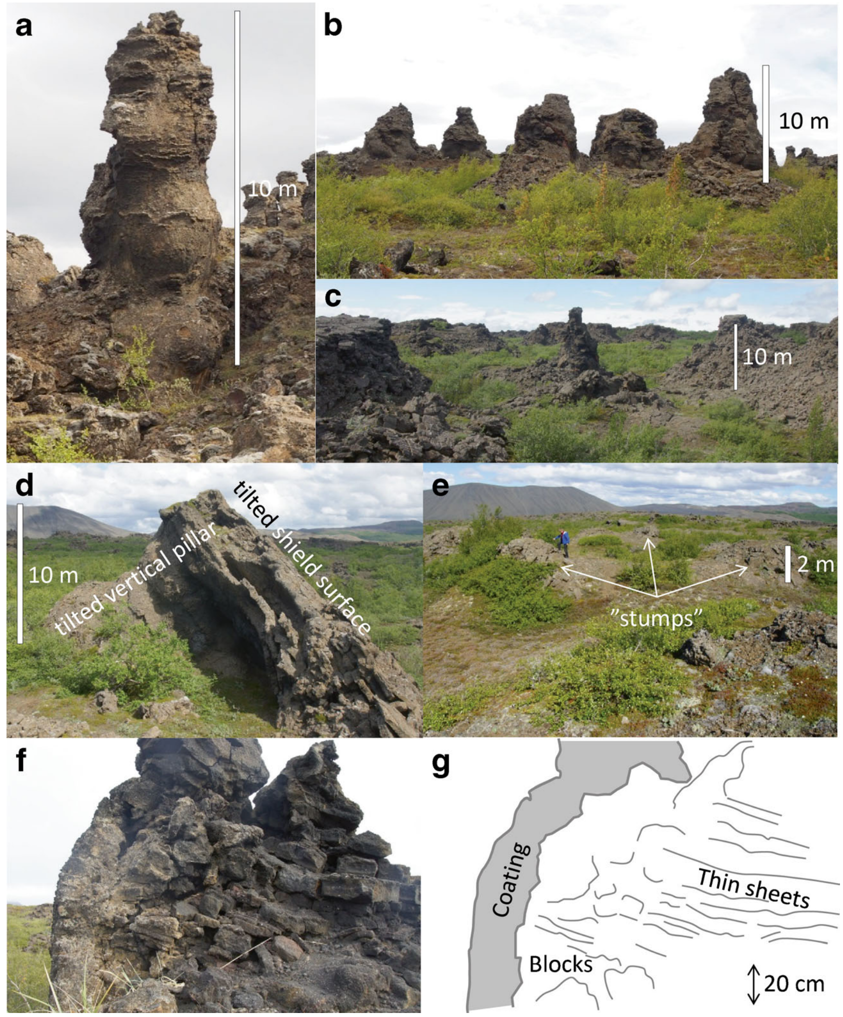

Fig. 7 Examples of pillars at Dimmuborgir. **a** Smooth-sided pillar with vertical striations resembling slickensides and multiple horizontal lava shelves marking different pond levels. **b, c** Pillars at differing stages of collapse. **d** Tilted pillar with part of shield surface attached. **e** Stump-like protrusions from the area shown in Fig. 3c, which could reflect an early stage of lowering of the rim as lava drained from the summit depression. **f** Side view of a partly collapsed pillar showing veneer encasing thin layers and randomly oriented blocks of lava. **g** Interpretative sketch (**f**)

elevated walls (Fig. 9). In contrast, lava tubes were mostly less than 5-m wide with circular or arched profiles (Fig. 10). The most prominent channel seen on the DTM (Fig. 3a, g) is the channel along which Bamlett and Potter (1986) proposed that Dimmuborgir emptied. This channel extends north from the western side of Dimmuborgir before curving west towards Mývatn. It is ~30-m wide with partly overhanging walls ~5-m high (Fig. 9a), and its floor is strewn with large, occasionally tilted meter-size plates of pahoehoe lava (Fig. 9b). The sides of the channels are coated in places with a hard veneer (Fig. 9b), which we infer solidified while the lava level in the channels dropped. Where this veneer is absent, the channel walls are seen to be composed of thin layers of lava (Fig. 9c, d). Also apparent on the DTM (Fig. 3a) and in the field (Fig. 9b) are channels that descend west from Lúdentsborgir towards Dimmuborgir. These channels were not traceable across the lava flow between Lúdentarborgir and Dimmuborgir either on the DTM or in the field. However, hyperbolae and double hyperbolae from which we infer the presence of subterranean lava tubes are seen along all GPR sections (Fig. 4; Supplementary data). In some cases, multiple small hyperbolae are seen in the GPR sections, and we infer that these are ≥1-m-diameter collapsed lava tubes, with hyperbolae representing fallen blocks. There are also numerous lava tubes exposed within the floor, at floor level, and stranded at various heights above the floor (Fig. 10) of the summit depressions at Dimmuborgir. The lava tubes have a 10–50-cm-thick hard veneer coating their walls and roof (Fig. 10a), similar in appearance to that of the pillars' and channels' coating. Some of the tubes contain several lava bathtub marks (Fig. 10b), showing that they were most likely drained in stages. In one example, a frozen cascade is preserved at the mouth of a hanging lava tube (Fig. 10c).

Discussion

In the first part of our discussion, we present a case for classifying Dimmuborgir as a rootless shield complex. We propose a model for its formation, which explains how Dimmuborgir was supplied with lava, why the flow of lava slowed or halted thereby allowing rootless shield formation to

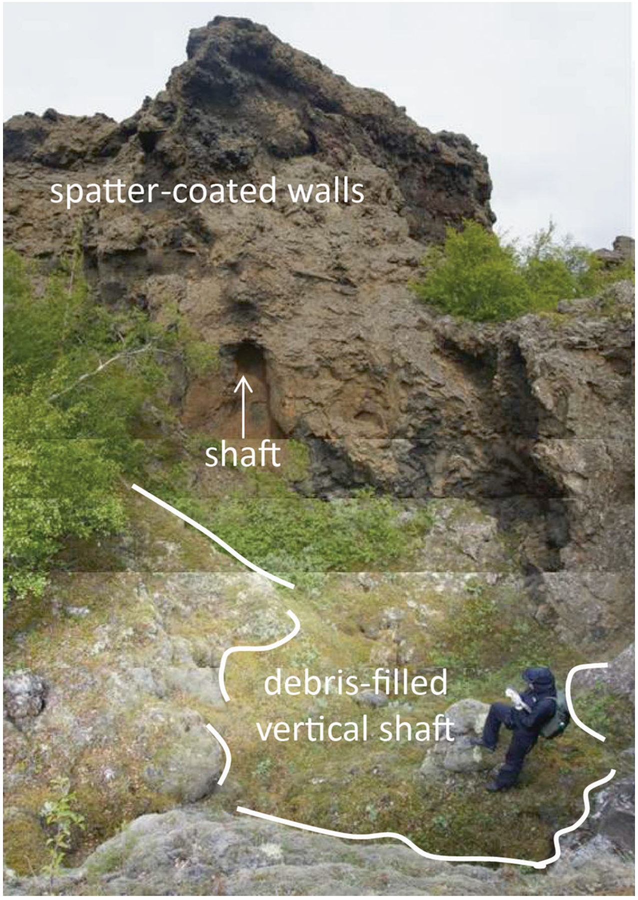

Fig. 8 Representative example of a rootless eruptive site showing a steep-sided pit above a debris-filled vertical conduit-like opening, remnants of a vertical shaft and spatter-coated walls and rim. Note that this image is a vertical panorama and the debris-filled vertical conduit is directly beneath the section of shaft seen on the side of the pit

commence, and how Dimmuborgir was drained of lava. We also propose a mechanism of formation for the enigmatic pillars for which Dimmuborgir is famed. We conclude this part of our discussion by comparing our model with previous models for the formation of Dimmuborgir. In the second part of our discussion, we compare Dimmuborgir with rootless shields at Kīlauea.

Dimmuborgir as a rootless shield complex

On the basis of the DTM constructed from the LiDAR survey, the GPR survey, and our field observations, we propose that Dimmuborgir is a complex of at least two overlapping rootless shields that formed over lava tubes, fed from Lúdentarborgir, within the YLL flow field (Fig. 11).

This classification is supported by the following observations:

- The main part of Dimmuborgir consists of at least two partly overlapping 1–1.5 km × 30 m shield-like structures (Fig. 3a).
- Dimmuborgir is located downslope of Lúdentarborgir, which we infer to be the source of the lava that built the shields (Fig. 3a).
- Numerous lava tubes were detected by GPR in the low-lying area between (and which we infer to connect) Lúdentarborgir and Dimmuborgir (Figs. 4 and 9).
- Each shield is topped by a ~500-m-wide summit depression floored with plates of pahoehoe lava, that we infer to be a drained lava pond (Fig. 3a).

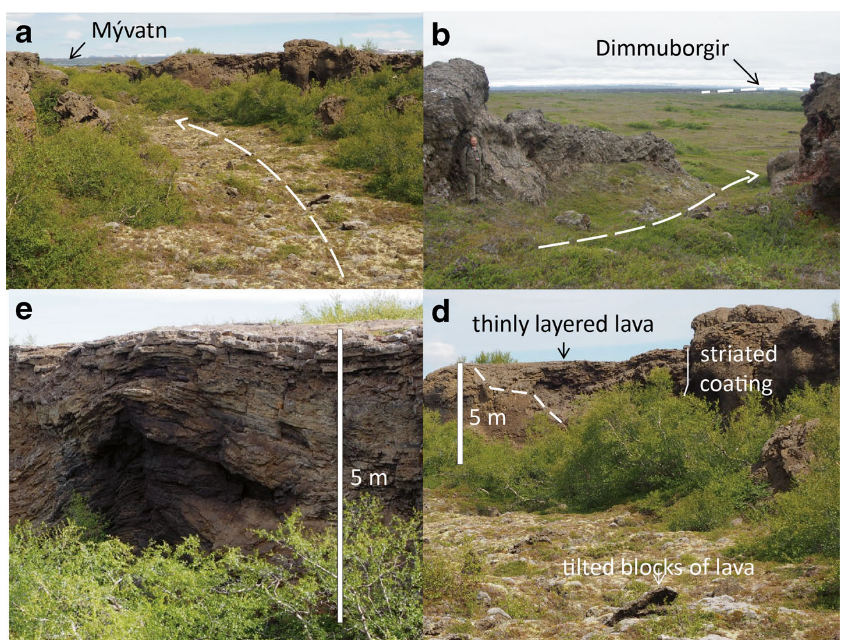

Fig. 9 Channels along which lava descended **a** north from Dimmuborgir towards Mývatn and **b** northwest from Lúdentarborgir towards Dimmuborgir. **a**, **b** *Dashed lines* show general flow direction. **c, d** The east side of the channel (**a**) is seen to be made of thin layers of lava which are held together by a veneer of lava on which downslope-curving striations can be seen. **d** The floor of the channel is strewn with occasionally tilted meter-size pieces of lava

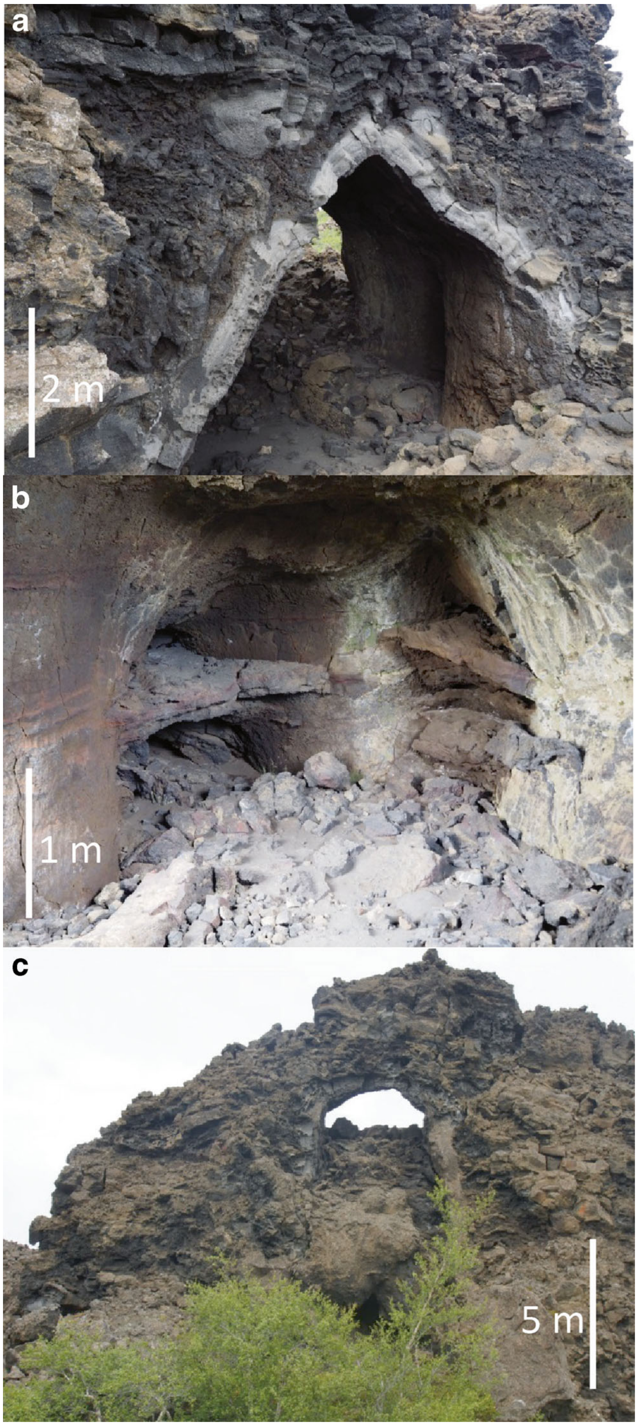

Fig. 10 Examples of lava tubes at Dimmuborgir. **a** Part of a lava tube on the flat area south of the western summit depression. Lava tube ceiling and wall coated with ~30-cm-thick veneer. **b** Lava shelves inside this lava tube. **c** Lava that solidified while pouring out from a stranded lava tube, i.e., towards the observer southeast of the western summit depression

- A progression from skylights and semi-circular depressions to upright, collapsed, and tilted pillars was observed at the fringes of each summit depression (Figs. 3d, 6, and 7), which we infer to have formed as its walls collapsed during drainage of the lava pond.
- A lava channel along which we infer Dimmuborgir was drained descends from its western margin towards Mývatn (Figs. 3a, g and 9a). Also, laterally extensive pahoehoe surfaces which we infer to mark former pond levels terminate at stranded lava tubes (Figs. 2e, 5b and 10c) along which we infer drainage of lava also occurred.

Supply of lava to Dimmuborgir

We propose that Dimmuborgir grew to its current height partly as a consequence of the 30-m height difference between Lúdentarborgir and Dimmuborgir. This produced a "lava-static" pressure sufficient to drive lava upward from the underlying lava tubes so as to build the complex of shields (Fig. 11). The minimum lava-static pressure, P_l can be calculated from the equation:

$$P_l = h\rho g \tag{1}$$

where h is the minimum height difference, ρ is the density of the lava, and g is gravitational acceleration (9.81 m s^{-2}). With $h = 30$ m, $\rho = 2600$–2700 kg m^{-3} (Murase and McBirney 1973), and $P_l = 0.77$–0.79 MPa. This value can be used to calculate the discharge rate, Q at which lava would enter Dimmuborgir using the following equation, which considers a cylindrical conduit (lava tube) of radius R and length L:

$$Q = \frac{\pi R^4 P_l}{8\eta L} \tag{2}$$

where η is the viscosity of the lava. The calculated value of Q is strongly dependent on conduit radius, R. Figure 12 shows that for a minimum length $L = 3$ km (straight line distance from Lúdentarborgir and Dimmuborgir) and with $\eta = 10^2$–10^3 Pas (Murase and McBirney 1973), Q ~1–10 m^{3}s^{-1} with R ~2 m. At this flow rate, one of the two rootless shields at Dimmuborgir (approximate volume = 1.2×10^7 m^3) could be built in 10–100 days, or less if Dimmuborgir was fed by more than one lava tube simultaneously. From this simple calculation, we conclude that lava-static pressure generated by a height difference of 30 m is sufficient to force lava upward from lava tubes and build rootless shields at Dimmuborgir over a timescale of weeks to months.

Commencement of rootless shield formation at Dimmuborgir

There are several factors which could have slowed or halted the flow of lava and thereby allowed rootless shield formation to commence. These include surges in lava supply, constrictions in the tube system, and/or a different barrier to flow. In our model, we propose that rootless eruptive activity caused by mixing of lava and water created deposits that acted as

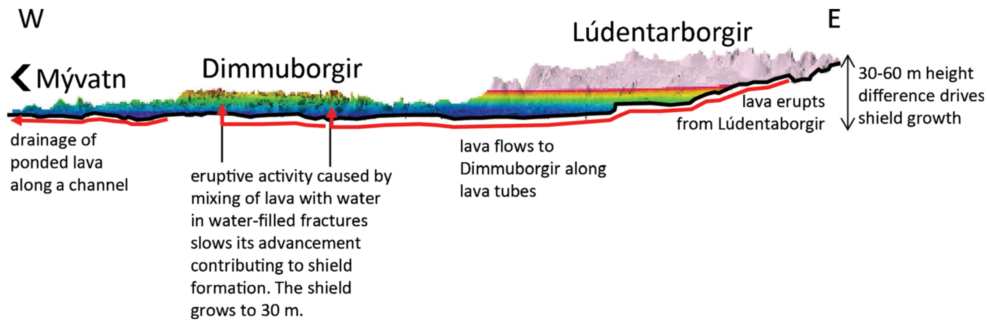

Fig. 11 DTM profile showing the stages of rootless shield formation at Dimmuborgir. The *red line* shows the pathway of the Younger Laxá Lava. The *color scale* for altitude is the same as in Fig. 3

barriers to flow. Clustering of rootless eruptive sites has previously been shown to be controlled by supply of lava and water in a geospatial analysis of the Laki lava flow (Hamilton et al. 2010). We infer that clusters of rootless eruptive sites at Dimmuborgir developed where the lava flow crossed open fractures because these provided a steady supply of groundwater. We base this model on finding rootless eruptive sites, i.e., pits with vertical conduits and spatter-coated walls (Fig. 8), clustered along the present day Grjótagjá Fault. We argue that spatter-coated walls and rims of these pits (Fig. 8) reflect spattering caused by lava-water interactions where lava poured into water-filled fractures. Intense spattering has been documented in Hawaii where lava poured into water-filled cracks on lava deltas (Orr 2011). The present-day Grjótagjá Fault is water-filled and was used in the past for bathing (Fig. 13). We are aware that the Grjótagjá Fault is younger than Dimmuborgir. In our model, we infer that a water-filled open fracture was also present at this location at the time Dimmuborgir was formed. We argue that shield formation commenced upstream of clusters of eruptive sites. This may have begun with local inflation and breakouts associated with pooling of lava in the transport system in a similar manner to that observed during the 1963–1967 Surtsey eruption (Thordarson and Sigmarsson 2009).

Drainage of Dimmuborgir

In our model, we further propose that lava ponds atop Dimmuborgir drained along the 30-m-wide channel identified by Bamlett and Potter (1986) which runs northwards before veering westwards towards Mývatn, as well as along (presently stranded) lava tubes. It is possible that the channel was fed with lava which escaped from Dimmuborgir via lava tubes. The effusion rate (E_r) for lava in such a wide channel is given by (Jeffreys 1925; Booth and Self 1973; Harris et al. 2007):

$$E_r = w\rho g \sin(\alpha) d^3 / 3\eta \quad (3)$$

where w is channel width and d is lava depth. For $\rho = 2600$–2700 kg m^{-3} and $\eta = 10^2$–10^3 Pas (Murase and McBirney 1973) and for lava drainage along a channel with average width 30 m, depth 5 m, and $\alpha = 1.7°$, we calculate a maximum E_r of 0.7–7 m^3 s^{-1}, consistent with observed rubbly pahoehoe lava downslope of Dimmuborgir towards Mývatn. Given this effusion rate and assuming that the channel remained filled, complete drainage of one of the lava ponds atop Dimmuborgir (approximate volume = 2–3×10^6 m^3) along this channel would have taken 5–50 days. If the pond was simultaneously recharged, drainage would have taken longer.

We concur with Bamlett and Potter (1986) that drainage of ponded lava at Dimmuborgir occurred along this channel which forms an outlet in one of the summit depressions. Although the layers of lava that compose the channel walls (Fig. 9c) are consistent with channel down-cutting through layered lava flows on the flanks of the shields, we feel that they are more likely representative of repeated channel overflows, particularly given a tendency for levees to stand higher than the shield surface. The downslope-curving striations that mar the veneer coating the sides of these channels were probably formed as the last lava in the channel drained.

Formation of the pillars

We infer that the drainage of ponded lava from each summit depression led to the progressive formation of skylights, semicircular depressions, and ultimately the pillars, as the walls of the depression collapsed into the slowly emptying pond. We envisage the following progression:

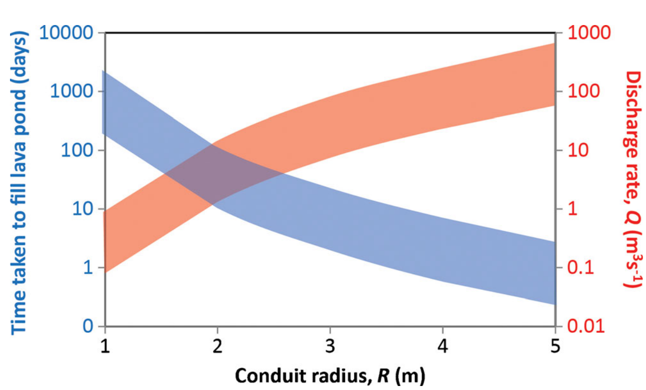

Fig. 12 Plot showing discharge rate, Q, and time taken to build the rootless shield for different conduit radii, R, calculated using Eq. (2)

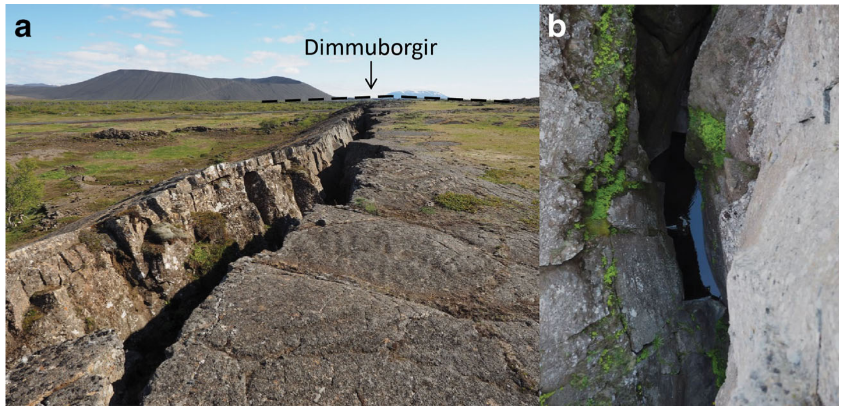

Fig. 13 The Grjótagjá Fault which **a** extends south towards Dimmuborgir and is **b** water-filled

- As the lava pond at the summit of Dimmuborgir drained, the rim of the summit crater slowly widened via collapse, producing skylights and semi-circular satellitic depressions at or close to the rim (area I in Fig. 3d).
- Continued drainage and collapse created more depressions which intersected with one another, producing first a network of sinuous ridges between them (area II in Fig. 3d).
- Continued drainage and collapse of ponded lava left only pillars marking intersections between three or more depressions (area III in Fig. 3d). We envisage that presently tilted pillars were carried away from the depression wall by lava as it drained away.

The pillars comprise thinly bedded lava fragments (Fig. 7f), which supports our model that they were formed from the overflow levees of a former lava pond. Protruding shelves (Fig. 14a) and inclined striations (Fig. 14b) on the sides of the pillars at Dimmuborgir support our model that they were formed when ponded lava drained, probably in an episodic fashion, forming the summit depression. Our model differs from the classical view (Bamlett and Potter 1986; Sæmundsson 1991) that the pillars were formed by venting of steam produced from the mingling of lava with lake water in a manner similar to that cited by Gregg and Christle (2013) for pillars associated with the 1783–1784 Laki fissure eruption. Those pillars also have vertical striations and multiple horizontal shelves, but most have vertical conduits within them, unlike all of the pillars we observed at Dimmuborgir. The absence of this conduit as well as the uneven shelf spacing distinguishes the pillars at Dimmuborgir from submarine lava pillars (Chadwick 2003).

Comparison with previous models

Our model brings together, rather than directly contradicts, previous models for the formation of Dimmuborgir, which consider it to be an eruption center (Rittman 1938), a lava pond (Barth 1942) perched behind a row of scoria cones and/or a result of eddying in a turbulent lava flow (van Bemmelen and Rutten 1955). In our model, mixing of flowing lava with water in open fractures led to local explosive eruptive activity (cf. Rittman 1938). This may have slowed advancement of the YLL, causing eddying (cf. van Bemmelen and Rutten 1955) and the formation of rootless shields (cf. Barth 1942). It is unclear if the presence of rootless cones (Fig. 3c) contributed to shield formation. This is because the cones might be younger than Dimmuborgir. We found scoria on top of the uppermost lava surface (Fig. 15a), implying that the scoria cones are younger than the lava. Although the scoria could have been moved there later by slope processes or wind transportation, we found mounds of scoria on the summit of one pillar that was separated by 20 m from the scoria cones (Fig. 15b, c), a relationship less easily attributed to slope processes or wind transportation. Regardless, the blocking effect

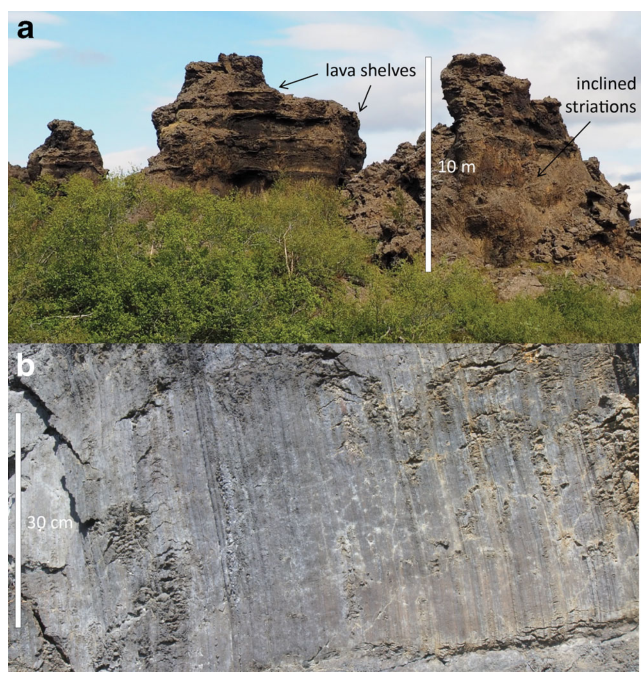

Fig. 14 Striations and lava shelves. **a** Close-up of the pillars shown in Fig. 10b showing striations and lava shelves. **b** Close-up of striations

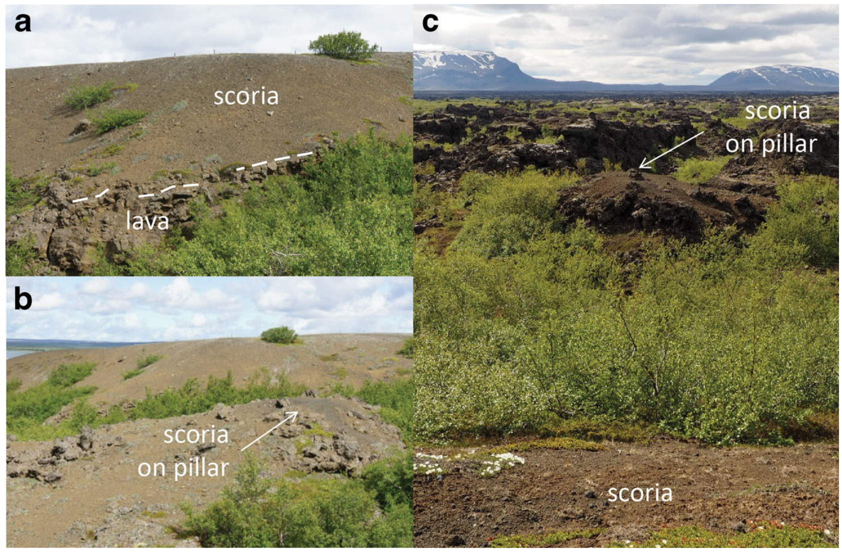

Fig. 15 Scoria resting on **a** the lava composing the flank of Dimmuborgir, and **b, c** on top of an adjacent pillar from the area shown in Fig. 3c

of the scoria cones is not necessary, as is evident for rootless shields in Hawaii (Patrick and Orr 2012).

Comparison with rootless shields at Kīlauea

From December 2007 to February 2008, a lava flow, erupting from Kīlauea's East Rift Zone at an inferred effusion rate of 6 ±2 m^3 s^{-1} sequentially constructed a series of overlapping rootless shields, some topped by perched lava ponds, along a developing lava tube (Patrick and Orr 2012). Patrick and Orr (2012) documented vertical accumulation rates of ~1 m day^{-1}, to maximum shield heights of 20–30 m and diameters of 400–700 m. Invariably, once a shield reached these approximate dimensions, a breakout occurred near its downslope base and the next shield in the series would begin to grow. The collapse of one of these shields was captured on a series of time-lapse camera images (Orr 2011). This collapse released 'a'ā lava with an estimated peak effusion rate of ~46 m^3 s^{-1}. During this collapse, isolated pieces of the partly disintegrated shield flanks remained standing, some of which collapsed thereafter (Fig. 16). We speculate that the pillars at Dimmuborgir may have formed in a similar manner, though not necessarily through catastrophic collapse as in the example from Kīlauea.

There are some striking similarities between rootless shields formed during 2007–2008 at Kīlauea and at Dimmuborgir. Dimmuborgir comprises two overlapping shields which are 1–1.5 km in diameter and ~30 m in height, each with a central depression which is ~500 m in diameter. This is broadly similar to rootless shields on Kīlauea. For example, 2–3 km ridges of overlapping shields, up to 20-m high and 500 m in diameter, with summit ponds up to 175 m in diameter were formed in 1999, 2001, and 2003 during the Pu u Ō ō-Kūpaianaha eruption (Kauahikaua et al. 2003; Orr et al. 2015). These shields were built in periods of weeks, similar to that we infer for Dimmuborgir. The Dimmuborgir shields were constructed by lava fed through a tube system inferred to extend from Lúdentarborgir, and the ponds that topped the shields had a storage capacity of 2–3 × 10^6 m^3, of the same order of magnitude as ponds on rootless shields at Kīlauea. However, barriers formed by mixing of lava and water along open fractures and possibly a line of scoria cones may have been contributory factors that led to shield formation at Dimmuborgir but did not happen at Kīlauea. Also, because Dimmuborgir's final drainage was not via catastrophic collapse, the calculated effusion rate during its drainage (0.7–7 $m^3 s^{-1}$) was slower than at Kīlauea.

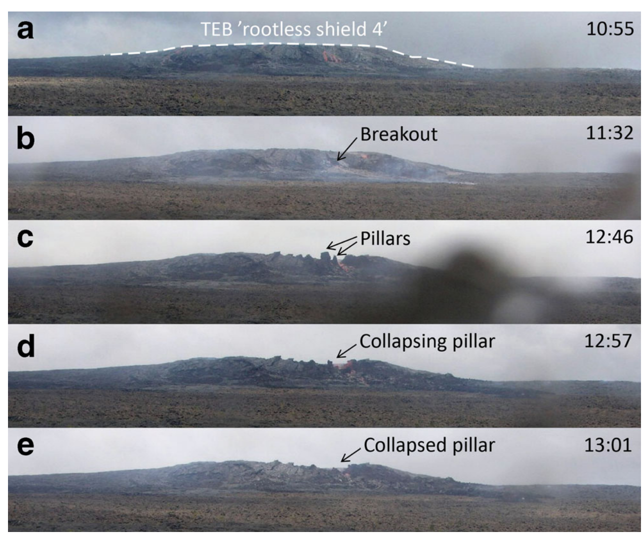

Fig. 16 Time-lapse camera images showing the collapse of a rootless shield (Thanksgiving Eve Breakout, *TEB 'rootless shield 4'*) at Kīlauea Volcano, Hawaii, on January 26, 2008. Pillars, similar to those seen at Dimmuborgir (Fig. 5) remain after the lava breakout, some of which collapse thereafter

Conclusions

Based on airborne laser mapping, surveying with ground-penetrating radar, and new field observations of Dimmuborgir, we conclude the following:

- Dimmuborgir comprises at least two overlapping rootless shields along the flow path of the YLL fed from the Lúdentarborgir crater row. The larger shields are approximately elliptical and 1–1.5 km in diameter.
- Lava erupting from the Lúdentarborgir crater row descended along lava tubes to the site where Dimmuborgir grew. This elevation difference was sufficient to support growth of the shields to a height of ~30 m.
- Rootless eruptive sites, often formed where the lava flow crossed water-filled fractures, may have created barriers to flow, contributing to the onset of shield formation.
- Lava ponds atop the shields were 0.5 km in diameter and 10–15-m deep and drained along open channels north towards Mývatn and south and southeast towards the flat lying area between Dimmuborgir, Lúdentarborgir, and Þrengslaborgir.
- The pillars for which Dimmuborgir is famed may be remnants following disintegration of the rims of these lava ponds as they drained, probably as the eruption waned.

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