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Abstract

To examine whether there was any physical or thermal interaction between trees and lava when a lava flow inundates a forest we studied the Kīlauea's July 1974 lava flow. We mapped the location of ~600 lava-trees and the lava type (pāhoehoe versus ʻaʻā), and sampled an additional ten lava-trees for chemical and textural analysis to infer flow viscosity and dynamics. The emplacement event lasted 3.5 hours and markers on the outer surface of the lava-trees allowed us to define initial high effusion rate and velocity (~400 m^3/s and 5–10 m/s) that then declined to 9 m^3/s and 4 m/s during a waning phase. We find that lava passing through the forest underwent an initial cooling rate of 4 °C/km which increased to 10 °C/km late in the eruption. This is no different to cooling rates recorded at Kīlauea for tree-free cases. There thus appears to be no effect on cooling for this case. The lava-trees did, though, form a network of vertical cylinders obstacles and evidence for local diversion of flow lines are noticed. However, this varies with lava type, as almost no lava-trees form in ʻaʻā. We find a relation between the percentage of ʻaʻā and the number of lava-trees per hectare. The pāhoehoe–ʻaʻā transition for this flow occurs at a viscosity of 10^3 Pa s and this appears to be a threshold below which lava-trees can form so as to behave as a network of obstacles, and above which they cannot.

Keywords: Lava-tree, lava channel, cooling rate, viscosity, pāhoehoe–ʻaʻā transition

Introduction

Lava flow emplacement dynamics are controlled by extrinsic parameters (topography, nature of the substrate, effusion rate, total volume emitted) and intrinsic properties (composition, temperature, vesicularity, cooling rate) which together control the viscosity and velocity of the lava (e.g., Chevrel et al. 2013; Harris and Rowland, 2015; Kolzenburg et al. 2017; Rumpf et al. 2018). Under cooling-limited conditions (Pinkerton and Wilson 1988; Wilson and Head 1994), the run-out distance of a lava flow (i.e., the maximum length that can be reached at a given effusion rate) has typically been related to the rate of effusion (Walker 1973), to the total volume of material erupted (Malin 1980) and to rheological changes due to the heat loss (Pinkerton and Wilson 1994). The evolution of the surface morphology of a channel-fed lava flow system commonly changes from a pāhoehoe-dominated proximal zone, to a medial transition zone with the formation of lava channels, to a distal zone of ‘a‘ā (Lipman and Banks 1987). The transition between pāhoehoe and a’ā has been the focus of many studies and is thought to be caused by an increase in strain rate or by a change in lava rheological properties including higher viscosity, development of yield strength and disruption of the cooled surface (e.g., Peterson and Tilling 1980; Cashman et al. 1999; Sehlke et al. 2014). To characterise the changing properties that control lava down-flow behaviour, several techniques have been used. If the flow is active, lava properties may be directly measured in the field (Lipman and Banks 1987; Moore 1987; Crisp et al. 1994; James et al. 2007; Belousov and Belousova 2018). In the case of solidified flows, several studies have analysed the textural and chemical evolution of samples collected between the vent and the flow front to obtain down-flow thermal, textural and rheological evolution (e.g., (Soule et al. 2004; Riker et al. 2009; Chevrel et al. 2013; Robert et al. 2014; Castruccio and Contreras 2016). Other studies have modelled lava flows as function of cooling either with analogue materials (e.g., Hulme 1974; Sakimoto

and Gregg 2001; Garel et al. 2014) or via numerical models (e.g., Crisp and Baloga 1994; Dragoni and Tallarico 1994; Harris and Rowland 2001; Bernabeu et al. 2016; Kelfoun and Vargas 2016).

The lava flow emplacement is also highly dependent on ground topography, substrate roughness (Rumpf et al. 2018) and encountered obstacles (Dietterich and Cashman 2014). Dietterich et al. (2015) examined how lava, using small basaltic flows created in the laboratory—effectively pouring molten basalt onto a synthetic topography— can be diverted by obstacles. Using the same method, Rumpf et al. (2018) showed that the higher the ground roughness the lower the flow front velocity. Computational simulations were also used by Chirico et al. (2009) and Scifoni et al. (2010) to examine the effect of barriers on flow paths.

However, the dynamics of lava moving through forested areas remains rather unknown. Recently, Bernabeu et al. (2018) showed that a fluid moving through a grid of vertical cylindrical obstacles, as analogue for a lava flow inundating a dense forest, would form a wider and thicker flow than expected. Besides when the lava enter in contact with trees, energy will also be required to heat, dry and combust wood (e.g., Van Wagner 1967; Babrauskas 2002). These studies suggest that the presence of cold, combustible obstacles in the flow may be added to the list of extrinsic parameters that potentially affect lava flows. Trees may thus play a role in both thermally and mechanically interacting with the flowing lava to exert a control on lava flow rheology, and thus also dynamics and morphology, as well as path and dimensions. However, although several studies exist that describe the morphology of casts left by trees due to the quenching effect on lava flowing around them, i.e., lava-trees (e.g., Finch 1931; Moore and Richter 1962; Lockwood and Williams 1978; Carveni et al. 2011; Parcheta et al. 2012), no data are available on the effects of vegetation on lava flow propagation. There therefore remains an outstanding question: can trees cause enhanced lava cooling and mechanically interact with an advancing flow, thereby playing a role in changing flow dynamics

and morphology (pāhoehoe versus ʻaʻā) as compared with a forest-free scenario? To answer this question our study focuses on the July 19–22, 1974 lava flow of Kīlauea (Hawaii), a flow well-known for its abundance of standing lava-trees (Hazlett 1993). We carried out detailed mapping and analysis of glassy samples collected from the inside and outside surfaces of the lava-tree casts and extracted flow temperature, plus crystal and bubble concentrations at each sampled site. These results were then used to estimate down-flow cooling and infer the corresponding increase in viscosity, which—for this case—appears no different to a tree-free emplacement case. Our analysis does, however, imply that some local mechanical interactions do occur with lava-trees, and allows us to propose a conceptual model and a viscosity threshold at which a tree may or may not turn into a lava-tree, and hence can or cannot interact. This point corresponds with, but does not cause, the pāhoehoe–ʻaʻā transition.

Lava-trees and tree-molds

It is well known that when low viscosity pāhoehoe invades a forest, often the lava does not topple the trees but rather cools rapidly against the cold, damp bark to form a cast of the tree (Finch 1931; Jaggar 1945; MacDonald et al. 1983). Following Finch (1931), a tree inundated by lava will form a quenched cast of lava around it. The tree will then heat to combustion and burn slowly as the lava continues to flow around it (Honda 1998). If the lava level remains constant then, once the tree has burnt away, a "hollow cylinder" (Moore and Richter 1962) or "hole" (Finch 1931) will be left in the lava flow with the same size and form as the tree root, trunk and branch system. The texture of the bark is often imprinted onto the interior of the cast surrounding the hole, so this is termed a "tree-mold" (Finch 1931; Lockwood and Williams 1978). If the lava level subsequently drops, then the tree cast will instead be left standing as a column (Fig.1); this is a "lava-tree" (Finch 1931; MacDonald et al. 1983; Lockwood and Hazlett 2010). In this case, rapid lowering of the lava level may cause the crust to scrape across the plastic outer surface of the cast to cause striations and tension-

102 produced gash fractures (Moore and Richter 1962). In some cases, the lava may entirely over-
103 come the height of the tree to form a closed lava-tree (Moore and Richter 1962). Where the
104 lava did not reach the top of the tree, the hole left by the consumed trunk is exposed forming
105 an open lava-tree. In such a case, one can have access to pre-lava inundation ground surface
106 through the shaft (Fig. 1). In some places, tree trunks inside the cast may not burn completely,
107 indicating that the lava inundation and drainage must have taken place in a short time (Fiske
108 and Koyanagi 1968); in others, the tree may be toppled and ingested horizontally into the lava
109 or its crusts (basal or surface) to form horizontal, tubular molds (MacDonald et al. 1983;
110 Carveni et al. 2011).

111 Lava-trees have been used in various ways, such as to estimate maximum thicknesses
112 reached by a lava flow (Moore and Richter 1962; Moore and Kachadoorian 1980), to retrieve
113 flow direction (Lockwood and Williams 1978), or to reconstruct the pre-eruption topography
114 of the ground surface (Jones et al. 2017; Parcheta et al. 2012). Lava-trees have also been de-
115 scribed as tools for "public educational purposes" (Carveni et al. 2011) and, given their nar-
116 row cave-like properties, been the focus of speleological studies (Bella and Gaál 2007). Addi-
117 tionally, charcoal left beneath a flow or in the tree molds (Searle 1958) can be analysed by C^{14}
118 for dating lava flow emplacement (Kuntz et al. 1986).

119 All of these studies have described the tree-lava contact and the formation or structure
120 of tree molds and lava-trees. However, no in-depth study exists on under which conditions
121 lava-trees form and whether and how a forest might influence the emplacement dynamics and
122 final form of a lava flow. Guest et al. (1987), Harris et al. (2017) and Bernabeu et al. (2018)
123 have suggested that trees can act to, or at least participate in, slowing down the advance of a
124 lava flow. In addition, Lockwood and Williams (1978) have shown that if two trees are suffi-
125 ciently close, a chilled crust may form between the trunks to form a wall or barrier of solid
126 lava

The July 19, 1974 lava flow

Around 12:30 (Hawaiian Standard Time) on July 19, 1974, lava fountaining began from a small fissure at the base of the south wall of Keanakāko‘i pit crater; with a second fissure opening a few minutes later north of Keanakāko‘i (Lockwood et al. 1999). Shortly thereafter, two en-echelon fissures appeared on the south-eastern sector of the caldera floor, feeding a pāhoehoe sheet flow eastward and northward across the caldera floor (Lockwood et al. 1999). Around the same time, the fissures extended through the Ōhi‘a forest to the west of Keanakāko‘i to feed “a fast-moving fluid flow consisting of slabby pāhoehoe and ‘a‘ā that travelled quickly to the south and southeast” for a distance of 2 km (Lockwood et al. 1999). By 13:00, lava from these fissures began to cascade into Keanakāko‘i to the north and Lua Manu craters to the east, forming a second, eastern, lava flow unit and cutting the chain of craters road (Fig. 2). Although the eruption continued until July 22, activity along the fissures to the east of Keanakāko‘i ceased by 16:15 on July 19 (Lockwood et al. 1999), having lasted around three and a half hours. Soule et al. (2004) gives a volume for the south-eastern unit of 3.5×10^6 m^3, for a mean output rate (given a 3–5 hour eruption duration) of 195–325 m^3/s (280 m^3/s for a 3.5 hour duration). It is the southeast lava flow of this fissure system on which we focus (Fig. 2).

This south-eastern lava flow formed a “field of lava-trees” (Lockwood et al. 1999), and Glatzer (1974) reports forest fires ignited by the passage of the lava, although these were “well under control by nightfall” on July 19. Instead, the “biggest headache” was “illegal parking (by sightseers) in the fire lanes”, where “every possible place to park” was filled (Glatzer 1974). The damage caused to forest in this region due to the 1959 eruption of Kīlauea Iki and the 1974 eruption, as well as subsequent regeneration, has since been studied by Smathers and Mueller-Dombois (2007). The south-eastern lava flow is also the same flow as the one studied by Moore and Kachadoorian (1980) and Soule et al. (2004). Moore and

Kachadoorian (1980) used the lava-trees to approximate the maximum flow depth and thereby obtained maximum average flow velocities — 1.56 m/s (near-vent) and 0.14 m/s (distally) — assuming a viscosity of around 2000 Pa s. Velocities and viscosities are also available from features of super-elevation for a lava channel active during this eruption to the north of Keanakāko‘i where lava “raced down a curving gully, with lava banking up against and spraying the outside of several bends” (Lockwood et al. 1999). In this channel, velocities were in excess of 8 m/s and viscosities were calculated by Heslop et al. (1989) as being 80–140 Pa s. In contrast, Soule et al. (2004) examined the pāhoehoe–‘a‘ā transition in the south-eastern flow, which they estimated occurred at a distance of 1.5 km from the vent. In the present work, we examine whether the presence of trees affected downflow cooling, and hence rheological and dynamic changes in the channel-contained lava, as well as the relationship between the presence of lava-trees and the pāhoehoe–‘a‘ā transition.

Methods

Mapping and sampling

The lava flow area, surface morphology and lava-tree locations were mapped using digital elevation model (DEM) with spatial resolution of 10 m and a vertical accuracy of 1–2 m, as derived from TOPSAR (topographic synthetic aperture radar) by Mouginis-Mark and Garbeil (2005). The U.S. Geological Survey 7.5-minute (1:24,000-scale) topographic map sheet for the Kīlauea Crater quadrangle (1981 edition) was also used to support mapping, along with the cloud-free image satellite from GoogleEarth™ (image © 2018 DigitalGlobe – 01/30/2016) in which individual lava-trees, as well as tree trunks lying on the flow surface, can be discerned. Locations of all lava-trees were added as a layer, and the density of lava-trees (number of lava-tree per unit area) was calculated from the number of objects within 200-m-long sectors along the length of the flow. The number of trees per unit area before the

eruption was also estimated via counting treetops in areas of one hectare from an aerial image taken in 1965 (https://guides.library.manoa.hawaii.edu/aerials/digital - see online resource 1) and from an area aside of the flow using the GoogleEarth™ (image © 2018 DigitalGlobe – 01/30/2016).

Additionally, field mapping and sampling were carried out in November 2016. During field work, 35 lava-trees within 200 m from the vent were located with hand-held GPS (WGS84) and their dimensions measured. Measured dimensions are marked on Fig. 1c and included: the diameter of the central hole, the width of the ring of solid lava surrounding the central hole, the height of the lava-tree above the current surface, and the depth of the central hole (i.e., distance from the highest flow level to the pre-existing ground surface). In addition, two sets of samples were collected. The first set corresponds to the sampling of nine lava-trees - one lava-tree every 200 m along a straight line in the centre of the channel between the vent and the flow front (T1–T9, Fig. 2 and 3, Table 1), plus one lava sample located on the eruptive fissure itself (vent sample "V" in Fig. 2). This set of samples is used to study the lava chemical and textural variation down flow. The sampling involved the whole width of the cast at the top of the lava-tree, so that the hand sample included the cast surface that was in contact with the tree (hereafter called "tree-side") and the exterior of the cast that was in contact with the lava when it drained away (hereafter called "lava-side"). All dimensional measurements of Fig. 1c were also taken. Two to three thin sections were made from each lava-tree: one from the tree-side surface (hereafter labelled "-T"), a second from the lava-side surface (hereafter labelled "-L"), and—if possible—a third between the tree and lava sides (hereafter labelled "-M"), for a total of 26 thin sections (Fig. 3). The second set of samples was collected on the lava side of a single tree (T10, Fig. 4) to observe the lava chemical and textural evolution from the bottom to the top of the lava-tree cast. This lava-tree (T10) was selected as it was one of the tallest (1.92 m) found during the down-flow sampling, and showed six level mark-

ers where lava had remained at a stable level for a short period of time during waning flow. One sample was taken from each level (Fig. 4).

Chemical and textural analyses

The dense rock equivalent (DRE) density was determined from powdered sample fragments of known masses and using an Accupyc 1340 Helium Pycnometer that measured their volumes. The bulk density of the samples was measured using an envelope density analyser (Micromeritics Geopyc 1360), which measures the difference in the volume of a quasi-fluid medium with and without the sample embedded in that medium. As presented by Kawabata et al. (2015) the Geopyc instrument can measure the envelope density of objects of different sizes and shapes. Prior to immersion, samples were dried in an oven for 24 hours at a temperature of 70 °C and then wrapped with thin laboratory parafilm®, to preserve external irregularities but to avoid the medium entering the porous sample. The standard deviation was estimated from five measurements to be ± 30 kg/m^3 by Thivet (2016). The density-derived vesicularity was then calculated using the relationship given by Houghton and Wilson (1989).

Bulk rock major element analysis of one sample was carried out with Inductively Coupled Plasma – Atomic Emission Spectroscopy at the Laboratoire Magmas et Volcans (LMV, Université Clermont-Auvergne, France). The chemical composition of the glass and minerals were measured on polished thin sections via electronic microprobe CAMECA SX 100 (at 15 kV and a defocused beam of 20 µm at a current of 8 nA for glass and a focused beam at 15 nA for minerals). The temperature of lava during emplacement was obtained using the glass composition through applying the MgO-glass geothermometer of Helz and Thornber (1987). Backscattered electron (BSE) images were collected by scanning electron microscopy (SEM) at magnifications of 25× and 100× and converted into binary images that were used for extraction of vesicle size distribution (VSD). Following Shea et al. (2010), we considered only vesicles that were larger than 10 pixels, which corresponds to an equivalent diameter of 0.05

mm. Crystal content in the glassy area of the thin section at the contact with the surface of the tree side and lava side was estimated using two images per sample via ImageJ, considering only crystals larger than three pixels; that is, greater in length than 6 µm. The percentage of crystals was corrected for vesicularity and is therefore given for the vesicle-free mixture.

Estimation of lava viscosity and flow velocity

The viscosity of the three-phase lava mixture (fluid+crystals+bubbles) was estimated down the flow following the petrologic approach that considers the chemical, thermal and textural analyses of the samples (e.g., Pinkerton and Stevenson, 1992; Crisp et al. 1994; Guilbaud et al. 2007; Robert et al. 2014; Chevrel et al. 2013, 2018; Rhety et al. 2017). This method was applicable only to samples containing sufficiently large (>1 mm^2) areas of glassy matrix where the composition of the quenched melt could be measured, temperature calculated and crystal content extracted. First the viscosity of the interstitial melt was calculated as a function of chemistry and temperature using the model of Giordano et al. (2008). Second, the effect of the crystal cargo on viscosity was estimated following the method described in Mader et al. (2013), which uses the equation of Maron and Pierce (1956) and considering a crystal maximum packing calculated using the average aspect ratio of the crystals (Mueller et al. 2010). We thereby obtained the vesicle-free mixture viscosity. Third, the effect of bubbles on the mixture viscosity was estimated from the vesicle fraction (obtained from the vesicularity derived from density) via the equation given by Llewellin and Manga (2005) for deformable bubbles. Using these viscosities, we calculated the instantaneous velocity of the lava with the Jeffreys equation (Jeffreys 1925). For this, we considered the maximum and final depths of the flow as measured on each sampled lava-trees and an average underlying slope. Error propagation analyses on the estimation of lava viscosity and flow velocity are detailed in online resource 2.

Results

The July 19, 1974 lava flow and its lava-trees

We measured a length for the south-eastern lava flow of the July 19 flow field of 2200 m, with the unit covering an area of 60.55 × 10^4 m^2 in which a total of 598 lava-trees were mapped (Fig. 2). We note here that the flow generally contained lava-trees, and not tree-molds, indicating a flow-wide lowering of the flow level as the eruption progressed.

Morphologically, the flow can be divided into five zones (Fig. 2 and 5): near-vent pāhoehoe sheet flow, proximal channel, medial channel, distal channel and distal dispersed ‘a‘ā flow. Around the eruptive fissure, the lava is a smooth-surfaced “hummocky” (Swanson 1973) pāhoehoe sheet flow over a surface with a slope of less than 0.5° (estimated from the lava flow surface). At 300 m from the fissure, multiple incipient channels arise within the pāhoehoe sheet flow. This is the zone of proximal channel which extends 200 m over a slope of 1.9° and feeds into the medial channel section at a distance of 500 m from the vent. Here, channels become well-formed across a zone of slightly steeper slopes (2.0°) and the flow becomes concentrated in two 20–30 m-wide main channels. As noted by Soule et al. (2004), here the two channels bifurcate around a topographic high and form streams of ‘a‘ā and thin, broken slabs of pāhoehoe surrounded by low initial levees of pāhoehoe; the channel margin is commonly only marked by a line of shearing between the static levées and the moving lava stream. At a distance of 900 m, the two channels coalesce into a single, broad (~50 m wide) and 500 m-long stream of ‘a‘ā and pāhoehoe slabs between broad initial levees of the same material. Down this distal channel section the slope is 0.75° and, while the occurrence of coherent pāhoehoe slabs within the channel decreases with distance, the percentage of surface area of ‘a‘ā increases (Fig. 2). After a distance of 1450 m, flow is of entirely ‘a‘ā. The zone of dispersed flow is 100 to 180 m wide, lies on a slope of 1.1° and feeds two 70–90 m-wide lobes with 2–3 m high flow fronts (Fig. 5).

Following Moore and Kachadoorian (1980), the thickness of the lava down flow was measured from the highest lava stand as given by the full lava-tree depth (i.e., value *D* in Fig. 1c). Then, following Jones et al. (2017) the final, lowest level was obtained from subtracting the lava-tree height above the current surface from the full lava-tree depth (i.e., value $F = D - H$ in Fig. 1c). In the near-vent zone, lava-tree depths were in the range 1.1–7.7 m, with a mean of 3.2 m and a standard deviation of 1.3 m—this being the maximum flow level around the vent. Heights above the 1974 surface were between 0.42 and 1.95 m (1.1 ± 0.4 m), giving a final lava level of 0.5–6.5 m (2.1 ± 1.1 m). Down-flow, there was no systematic variation in lava level (Fig. 3). However, maximum levels (1.8–5.1 m, 1.9 ± 0.7, n. = 10), as well as minimum flow levels (0.2–2.4 m, 1.2 ± 0.7 m, n. = 10), were generally lower than around the vent. These values compare with the maximum flow thicknesses of Moore and Kachadoorian (1980) of 2.0–5.2 m (3.8 ± 1.1 m, n. = 6), and minimum thicknesses of 1.1–1.7 m (1.3 ± 0.2 m).

In terms of lava-tree density (Fig. 6), the proximal part of the lava flow contains the highest concentration (20-30 lava-trees/ha), with more than half of the lava-trees being located in the first 400 m near the vent (25% of the flow area) where pāhoehoe sheet flow dominated. As distance increases from the zone of pāhoehoe sheet flow, the density of lava-trees steadily decreases as the proportion of ʻaʻā to pāhoehoe increases (Fig. 6). There is a complete absence of lava-trees at the flow front, where ʻaʻā is 100 %; and the last lava-tree is found 200 m from the front. At the flow front, trees in the process of being bulldozed can be found toppled onto the flow surface.

Morphology and dimensions of lava-trees

Near the vent and in the zone of pāhoehoe-sheet flow the lava-trees are, for the most part, well preserved. Most have conserved the initial tree trunk disposition of main trunk and branch systems and are lava-trees “en bouquet”; that is, they form a tightly grouped but upward

300 splaying system of trunks and branches (Fig. 7a). Others are lone standing pillars either closed
301 (Fig. 7b) or open (Fig. 7c) and are associated with the remnant (unburnt) trunks of the trees
302 responsible for the casts (Fig. 7c). The heights of the lava-trees measured from the pre-flow
303 surface to their top are between 1.1–7.7 m (in average 3.2 ± 1.2 m, n. = 42) and their casts
304 have widths in the range 4–20 cm (10.12 ± 3.12 cm), with central hole (trunk) diameters of 6–
305 70 cm (23 ± 11.5 cm). On the tree side of the cast the surface is smooth and tree bark imprints
306 are well preserved. The lava side is rough, often with tension gashes, sharks teeth and stria-
307 tions that can be tied to descending slabs of pāhoehoe (Fig. 7d). All of these features indicate
308 that the outer surface of the cast was still sufficiently plastic to "take the impressions of the
309 crust" (Moore and Richter, 1962) and to deform plastically (Nichols 1939). The descending
310 pāhoehoe slabs remain in-place, surrounding the base of the lava-tree and uptilted towards the
311 lava-tree and often forming a dome like structure around the lava-tree (Fig. 7e).

312 Lava accretion on the up-flow side of lava-trees and on the lava side of the casts was
313 also often observed. The lava-tree of Fig. 4 is a good example. It is 1.9 m high, has a perime-
314 ter of 2.1 m, and is capped by a 20-cm-wide ring of rough-surfaced glassy pāhoehoe blebs,
315 and has five level markers down the lava side of the cast. These markers are expressed as
316 aligned trains of glassy globules and up-flow accretions. Glassy globules are stretched down
317 flow (150° ESE) and plunge downwards at 22–25°. This is much steeper than the ground
318 slope (2°), indicating rapid drainage in the down-flow direction. Up-flow accretions consist of
319 larger blebs of rough surfaced pāhoehoe that wrap around the cast in the down flow direction,
320 and have the same orientation and plunge as the trains of glassy globules (Fig. 4). This attests
321 to maintenance of the high stand for a period of time to build the accreted cap, followed by a
322 rapid decline in flow level with a series of brief stands at a single level to build the train-and-
323 accretion sets. Given the 3-5 hour duration of the eruption, the total time for this process can

be no more than an hour or two and with the transient declines and pauses being of the time scale of minutes.

In some places lava-trees are grouped (Fig. 7f) including two to four trees located at 1 to 2 meters of each other. In such a case, lava-tree casts merge to form a wall-like or barrier-like structure which can be aligned up or cross-flow (Fig. 7f). Their profiles are irregular with high points, marking the lava-trees, joined by lower ridges or "seams" (Lockwood and Williams 1978) of accreted lava that join the lava-tree group together.

Textural and thermal analyses

The texture of the rock is porphyritic with phenocrysts of olivine within a glassy to microcrystalline matrix. Phenocryst content is 3 vol.% and does not change down flow. Microlites (<0.2 mm) include olivine and plagioclase, and their content increases from 0.6 vol.% near the vent to 33.1 vol.% near the front (Fig. 8 and 9, Table 2). This gives a crystallization rate of around 15 vol.% per kilometre. As shown by the detailed sampling of the lava-side cast of T10, the microlite content appears to increase from 12 vol.% at the top of the lava-tree to 25 vol.% at the bottom (Table 3; Fig. 4).

Density and vesicularity derived from density (using a DRE density of 3030 kg/m^3) were in the range 1500–2000 kg/m^3 and 34-53 vol. %, respectively (Table 2, Fig. 10a). Only the sample from the tree side of T9 (near the vent) is markedly different with a density of 760 kg/m^3 and a vesicularity of 75 vol.%, representing at-vent gas-rich lava. Thereafter, there is no down-flow trend in vesicle content (Fig. 10a), but vesicularity of the lava next to the tree is always greater than that in the middle of the cast, attesting to a decrease in the bubble content of the erupted (and flowing) lava with time. The VSD analyses reveal that most samples contain one vesicle population between 0.05 and 5 mm, except T5-T that also comprises some vesicles larger that 10 mm and T1-T that includes two populations (Fig. 10b).

348 The chemical composition of the glassy matrix (online resource 3) decreases down
349 flow from an Mg# of 36 at the vent to 28 near the flow front (at 1.9 km). For the tree side, this
350 decrease in Mg# translates to cooling from 1139±2 °C at the vent and 1132±5 °C at 1.9 km.
351 For the lava side, we calculated cooling from 1140±2 °C to 1118±13 °C. The temperature
352 decline estimated from the quenched lava against the tree is different to that for the lava side,
353 where there is a cooling rate of 4 °C/km for initial lava quenched to the tree, and 10 °C/km for
354 late-stage lava accreted to the outer portion of the cast (Fig. 9). These straddle the average
355 cooling rate of 6 °C/km given for the same flow by Soule et al. (2004) but show a lower cool-
356 ing rate during initial flow than during late-stage flow. From the sampling of the lava-side
357 cast of T10, we see that the temperature may change by 2 °C from level to level, but there was
358 no systematic variation with depth during drainage (Table 3, Fig. 4).

359 Flow dynamics

360 The viscosity of the melt phase varies down flow as glass composition evolves and tempera-
361 ture decreases, so that the melt viscosity increases from 470 Pa s at the vent to 700 Pa s distal-
362 ly. Including the effect of the crystal fraction and deformable bubbles (Table 4), the viscosity
363 of the three-phase mixture was estimated at 90-190 Pa s near the vent (considering the condi-
364 tions at T9: 1140 °C, 3.6–13.5 vol.% crystals and 46-75 vol.% elongated bubbles). These vis-
365 cosities are in-line with those of Heslop et al. (1989) estimated from the super-elevation fea-
366 tures in the near-vent channel active to the north of Keanakāko‘i at the same time. Distally,
367 the three-phase viscosity is up to 3600 Pa s (considering the conditions at T1: 1132 °C, 36
368 vol.% crystals and 50 vol.% bubbles). Our results give a viscosity (η in Pa s) with distance
369 (Dist in m) trend of $\eta = 160e^{0.0017Dist}$ with an R^2 of 0.94 (Fig. 11a).

370 This viscosity variation has a direct influence on the flow velocity (Fig. 11). At vent, at
371 peak flow (maximum depth) velocities were as high as 9.8 ± 2.6 m/s (Table 4); similar to the
372 maximum velocities obtained by Heslop et al. (1989) but higher than what estimated by

373 Moore and Kachadoorian (1980). With distance down flow, the increase in viscosity causes
374 the velocity to fall to 0.3 ± 0.2 m/s at 1915 m. Declining output rate caused decreasing flow
375 levels, so that the typical depth of late-stage flow near-vent (1.2 ± 0.7 m) gives a lower final
376 velocity of 0.2-4 m/s at vent, waning to 0.04 m/s at 1915 m (Table 4). Given channel width of
377 30m, the maximum flow depth and the final flow level measured at T5, this translates to a
378 decrease in effusion rate from 403 ± 250 m^3/s to 15 ± 9 m^3/s.

379 ## Discussion

380 Cooling effects of a forest

381 The 19 July 1974 lava flows advanced through a montane dry forest typical of Kīlauea's
382 vegetation SW of Keanakāko'i crater (Pratt and Gon III 1998). This zone receives less than
383 1000 mm of rain per year and experiences a dry season between mid-May and mid-October
384 when rainfall is less than 100 mm/month (Smathers and Mueller-Dombois 2007). The domi-
385 nant forest tree is the Ōhi'a (Pratt and Gon III 1998), a pioneer species native to Hawaii that
386 forms "the canopy for virtually all Hawaiian forests" (Lincoln 2009). All lava-trees identified
387 in this study were of Ōhi'a. In the zone where the fissures feeding the south-eastern flow of
388 the 19 July eruptive activity broke out, we estimated the number of trees before the eruption at
389 55 to 95 per hectare. Giving the average trunk radii of 10.5 cm and a typical depth of 3.2 m,
390 this gives an area of 2.1 m^2 of cold bark and a volume of 11 m^3 of wood available to interact
391 with the molten lava. The question is: are such tree densities, lava-tree contact areas and wood
392 volumes sufficient to contribute a cooling effect to lava moving through the forest?

393 Lava flowing through the forest underwent an initial cooling rate of 4 °C/km which in-
394 creased to 10 °C/km late in the eruption. This compares with cooling rates of 7 °C/km esti-
395 mated for this same lava flow by Soule et al. (2004) and for other lava flowing down channels
396 in tree-free environments on Kīlauea and Mauna Loa (Crisp et al. 1994; Cashman et al. 1999;

Riker et al. 2009; Robert et al. 2014). Thus, the cooling rates appear normal, so there was no discernible enhanced cooling effect due to the forest. The increase in cooling rate between the beginning and end of the eruption was likely due to the decrease in velocity in the channels with time as output rate feeding the channel system, and flow levels in the channels, declined. Following Keszthelyi and Self (1998), a lower velocity flow will undergo a higher rate of cooling per unit distance than a higher velocity flow. Simply, there is more time for lava moving at low velocity to cool as it passes from one location to the next than if it is moving at higher speed (Harris and Rowland 2009). In our case, the increase in cooling rate is consistent with a decrease in velocity in the proximal section (Tables 3 and 4).

The lack of a significant thermal interaction between the flowing lava and the trees, and hence no enhanced cooling effect, could be due to three reasons. First, the casts would have formed almost immediately and, as is the case for a tube roof (Keszthelyi 1995), would have provided excellent thermal insulation to the lava flowing around the tree and thereby isolating the tree from lava flowing down the channel. Second, the velocity of the lava (2–10 m/s) and the small tree diameter (typically 0.2 m) would have meant that the flowing lava would have had a short interaction time (less than a tenth of a second) with the tree. Third, the forest had suffered damage due to fall-out during the Kīlauea Iki eruption of 1959 so that, as of 1962, the forest consisted of damaged Ōhi'a trees undergoing re-foliation, and lacked dense, mature undergrowth (Smathers and Mueller-Dombois 2007). This, coupled with the fact that the eruption occurred during the middle of the dry season, would have meant that the moisture loads and vegetation densities would not have been as high as in a mature, undamaged forest. In the wet forest type that characterises the eastern edge of the flow and most of Kīlauea's east rift zone (Pratt and Gon III 1998), vegetation and water would have been more abundant still. Following Pratt and Gon III (1998), such zones consist of a closed-canopy (i.e., high density) of Ōhi'a with an understory of dense tree fern. The dominant fern is the Ciboti-

um species (Pratt and Gon III 1998), notably Hapu'u which can reach heights of 6–9 m, has "loose, fibrous bark on their trunks" (Lincoln 2009) and large (2–4 m long) fonds (Merlin 2005) which are loaded with water. Finally, locally, trees quenched the lava to solidify a zone of lava typically 10 cm wide. Considering the typical lava-tree height of 3.2 m, the quenched lava volume is 0.3 m^3 per tree, and around 180 m^3 within the flow. This volume is therefore rather small in comparison to the volume of the entire flow (3.5×10^6 m^3).

Mechanical interactions

The initial solidification of lava around the trees formed numerous lava-trees which remained in place as vertical pillars and provided a series of obstacles around which the lava had to pass. In the pāhoehoe sheet area of the flow, within 250 m of the fissure, about half of the trees have been changed into lava-trees, while further down flow, where the lava is of a'ā type, the lava destroyed all of the trees without creating any lava-trees.

Direction markers on the lava-side of the casts (Lockwood and Williams 1978) show that lava did have to move around each lava-tree. Three cases of diversion can be identified (Fig. 12): scattered (isolated), cross-flow grouped, and down-flow grouped. In the isolated case, there is an exceedingly local effect where flow paths diverge around the pillar-like obstacle which is just 0.06–0.6 m wide. In the case of the cross-flow grouped lava-trees, we have a barrier that can be up to 5 m wide (Fig. 7f). This impedes flow, causing flow to move laterally as well as to back up behind the barrier to build accretions that pile up on the up-flow side of the barrier. In the down-flow grouped case, a similar barrier to that formed in the cross-flow case is formed, but because of its down-flow alignment it has less effect on flow lines. However, the effect on diverging flow lines is greater than in the scattered case because enhanced accretion around the lava-tree group causes the obstacle to be wider (1–2 m) than in the case of an isolated lava-tree.

446 According to Dietterich et al. (2015), the velocity of the lava is halved after passing by
447 an obstacle. It therefore seems that although we find the trees did not affect thermally the la-
448 va, the lava-trees, once formed, act as a network of solid pillars or obstacles around which the
449 flow must move. Following Bernabeu et al. (2018) this can be viewed as a porous medium
450 through which the fluid must move. The greater the number of lava-trees, the lower the poros-
451 ity and hence the greater the effect on the dynamics for the fluid moving through the obstacle
452 network. High obstacle densities cause the flow to be impeded and delayed, with the shape of
453 the flow being changed (over the obstacle-free case), where fluid will spread and pile up in
454 the porous zone (Bernabeu et al. 2018). Thus, a lava flow moving through a forest should be
455 wider, thicker and shorter than for the same flow moving over a tree-free surface. This is also
456 in agreement with previous observation of lava flows being thicker and slower where they
457 branch or encounter obstacles (Dietterich and Cashman 2014). This effect on lava flow ad-
458 vance could also be compared with the recent study of Rumpf et al. (2018) where they find
459 that flow front velocities are lower on rough terrain. However, they suggested that the slower
460 advance rate is due to enhanced cooling through the higher surface contact area of an irregular
461 substrate. Here we suggest that the thermal effect caused by the contact with the trees might
462 be rather trivial and that the mechanical effect caused by vertical obstacles might be the main
463 factor affecting the flow advances rate.

464 Interaction of lava with a forest might therefore affect lava flow hazard assessment be-
465 cause of the potential mechanical effect of the trees once turned into lava-trees. Following
466 Bernabeu et al. (2018), further modelling is necessary to quantify the effect of vertical pillars
467 as local lava diverter or flow delaying mechanism. As argued by Dietterich et al. (2015), “mit-
468 igation of lava-flow hazards must incorporate the dynamics of lava flow–obstacle interactions
469 into barrier design”. To go further, we suggest here that once and if the trees have been suc-
470 cessfully transform into lava-trees, they may play the role of a “leaky” barrier (Dietterich and

Cashman 2014). Growing well-designed forests between potential source vents and vulnerable infrastructure may therefore offer a way to mitigate the risk caused by low viscosity lava flows. However, experiments should be carried out to test if and how a dense forest would affectively split the flow and slow down the advance. Scenarios including various types of trees and different tree arrangements need to be designed and tested.

Lava-trees and the pāhoehoe-ʻaʻā transition

There is a progressive down-flow transition from pāhoehoe to ʻaʻā, beginning at a distance of 400–500 m from the vent, and is complete by a distance of 1500 m (Fig. 6). This is consistent with the findings of Soule et al. (2004) who found the pāhoehoe-ʻaʻā transition occurring in this flow between 500 m and 1500 m. Soule et al. (2004) ascribed the transition to crystallinity, with ʻaʻā formation initiating when a critical crystallinity of 18 vol.% was reached. Likewise, we find that this transition initiates at 15–20 vol. %, which is the typical crystallinity between 400 m and 1000 m (Fig. 9), and a viscosity of 10^3 Pa s (Fig. 11).

We also find a coincidence between the incidence of lava-tree formation and the pāhoehoe-ʻaʻā transition which progressively declines from 20–30 lava-trees per hectare in pure pāhoehoe to zero in pure ʻaʻā (Fig. 6). However, this is the pāhoehoe-ʻaʻā transition influencing the process of tree-formation; and not vice-versa. Simply, fluid pāhoehoe can flow between trees without toppling them, quenching to their trunks to allow lava-tree formation. In contrast, ʻaʻā bulldozes trees (as seen from the back-toppling cases at the flow front) knocking them down so that they do not remain as vertical structures around which the lava has to flow (Fig. 12). Thus, lava-tree formation (and flow impediment) is precluded. Instead, trees topple onto the flow to be rafted down flow to eventually be heated and burnt on the flow surface or rolled along in the basal clinker (Fig. 12). Thus, as lava progressively transitions to ʻaʻā the incidence of lava-trees progressively declines. This decline follows a linear relationship whereby the number of lava-trees of per hectare (NT) is related to the percentage

of lava as pāhoehoe (AA) through NT = -0.17(AA) + 17 (R^2 = 0.7). Considering that the number of pre-existing tree per hectare is constant, this means that in the pāhoehoe sheet area of the flow, within the 150 m from the fissure, nearly all the trees have been changed into lava-trees, while further down flow, where the lava is of a'ā type, all of the trees have been destroyed.

Re-creating the emission history from a single lava-tree

Using the level markers on lava-tree T10 we can recreate the emplacement history of the lava flow. Initial flow entered the channel (17.5 m wide) in which T10 resided at an effusion rate of 305 m^3/s (Table 3). This is 75 % of the value obtained for the single master channel at 920 m and into which this channel feeds (Table 4). Waning levels of flow in the channel reflected waning velocity and effusion rate, which dropped to a final value of 7 m^3/s. This is now around 50 % of the value obtained for the master channel at the end of the eruption at 920 m. Thus, it appears, the channel branch in which T10 resided took between 50 and 75 % of the total lava flux.

The distribution of effusion rate (E_r) with lava depth (D) shown in Table 3 has an exponential decaying form ($E_r = 1.4e^{1.87\,D}$, R^2 = 0.97). If we distribute these effusion rates through time to fit to the total erupted volume ($3.5 \times 10^6\ m^3$) and eruption duration (3.5 hours) this gives a function for the duration at which each level (#) was maintained of duration $=3.5e^{-693\#}$. If we distribute the volume through time using this function we obtain the timings shown in Table 5. These timings suggest that peak flow was maintained the first half of the 3.5 hour-long eruptive period, with waning emission occurring over the second half. During waning, flow level (lava thickness) was maintained for an increasingly short period of time with shut down being abrupt. This is consistent with the observation by Lockwood et al. (1999) that "discharge rates at all fissures gradually began to decline" from around 2 hours

after the eruption began, with all activity having ceased another one hour and 40 minutes later.

Conclusion

We studied the relationship between lava flow dynamics and lava-tree formation for the case of the July 19, 1974 lava flow of Kīlauea. We mapped the lava flow morphology (pāhoehoe vs. ʻaʻā) and the distribution of lava-trees along the flow path. We found that lava-trees are abundant (>20 lava-trees/ha) in the pāhoehoe area but sparse (<5 lava-trees/ha) in the ʻaʻā section of the flow. We conclude that lava-trees can be formed when the lava flow is fluid enough; in such a regime lava-trees can form in spite of high flow velocities (~10 m/s). However, when the lava becomes too viscous, a living tree will be overridden and no lava-tree can be formed. This threshold occurs at a crystallinity of 15–20 vol% and viscosity of 10^3 Pa s where the pāhoehoe-ʻaʻā transition takes place so that trees begin to be bulldozed by the ʻaʻā flow rather than flooded by pāhoehoe lava. If lava-trees form, markers on their outer surface allow the eruption history to be recreated, which in this case involved 1.5 hours of high effusion rate flow (at ~400 m^3/s) followed by 1.5 hours of waning flow and abrupt shutdown.

In this case, no enhanced cooling effect due to the presence of the trees was recorded, but this may be a function of the rapidity of the inundation and the type of vegetation, which was in poor health at the time of inundation. Mechanically, though, the lava was locally diverted by the array of solid cylinders formed by the lava-trees. Forests may thus have an effect in delaying flow advance and may be able to locally divert a flow from the expected path. Further study on the effect of trees depending on their type will permit definition as to whether tree stands of certain types could be used, once turned into lava-trees, as local lava diverter or flow delaying mechanism. Note, though, that if the lava is more viscous than a critical

543 threshold, that is here given at 10^3 Pa s, lava-trees will not form. Further work in this direction
544 is clearly needed to assess the potential for vegetation barriers as a mitigation tool.

545

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757

758 **Figure captions**

759 Figure 1: Lava-tree formation (modified from Lockwood and Hazlett, 2010). a) Pristine forest
760 contains trees of various sizes and heights. b) When lava is in contact with air or with cooler
761 surfaces (ground and vertical obstacles like trees) it rapidly quenches and forms a chilled crust
762 (black) surrounding the hot, fluid interior (orange), and vegetation dries and burns. c) Lava
763 drains away, causing the subsidence of the flow surface and leaving behind standing lava-tree
764 casts and a dead forest. Measured lava tree dimensions are given in c.

765

766 Figure 2: Map of the south-eastern July 1974 lava flow showing the studied unit and location
767 of samples and lava-trees (background of GoogleEarth image © 2018 DigitalGlobe). Inset
768 map showing the location of the studied lava flow, modified from Lockwood et al. (1999).

769 *Lava-trees* (black points) were located based on aerial photography, TOPSAR images and
770 ground truthing. "*Sampled lava-trees"* indicates location were rock samples were taken (T1 to
771 T10; Table 1); "V" is the location of a sample taken at the vent.
772
773 Figure 3: Sampling methodology along the lava flow and thin section positions on lava-tree
774 casts. Yellow dots indicate the presence of glassy matrix in the thin section.
775
776 Figure 4: Sampling of a single lava-tree (T10). From left to right: photo of T10 with location
777 of samples) from top to bottom (labeled from A to G); sketch of the main features and dimen-
778 sions, and variation of temperature (*circles*) and crystallinity (*squares*) as function the height.
779
780 Figure 5: Evolution of width (*empty circles*) and thickness (*full circles*) of the studied lava
781 flow as function of distance from the vent. Vertical dashed lines and numbers outline the five
782 zones of the lava flow morphology: 1) near-vent pāhoehoe sheet flow; 2) proximal channel
783 area with multiple incipient channels; 3) well-formed channel that divided in two main chan-
784 nels; 4) coalescence into a single broad channel made of ʻaʻā and pāhoehoe slabs between
785 broad initial levées; 5) dispersed ʻaʻā flow.
786
787 Figure 6: Number of lava-trees per hectare and percentage of lava type (pāhoehoe vs. ʻaʻā)
788 down flow.
789
790 Figure 7: Examples of lava-tree morphologies: a) lava-trees "en bouquet" near the vent; b)
791 vertical closed lava-tree; c) open lava-tree with remaining dead tree; d) scratching of the plas-
792 tic outer surface of the cast causing striations and tension gashes; e) uptilted pāhoehoe slabs

793 remaining in-place surrounding the base of a lava-tree, forming a dome like structure; f) barri-
794 er made by accretion around and between two lava-trees.
795
796 Figure 8: SEM images of the matrix crystallization down flow.
797
798 Figure 9: Down flow variations in the temperature obtained from the glassy matrix on the lava
799 side (*open circles*) and on the tree side (*full circles*) of each sample, and crystal content in-
800 cluding phenocrysts + microlites (*squares*). Linear regression lines indicate 10°C/km on the
801 lava side (R^2=0.78) and 4 °C/km on the tree side (R^2=0.60). The temperature gradient from
802 Soule et al. (2004) is also reported for comparison (7 °C/km R^2=0.71). The linear regression
803 for the crystallinity indicates 16.2 vol.% / km (R^2=0.9).
804
805 Figure 10: a) Down flow variation of the vesicularity derived from density; b) Cumulative
806 vesicle number density plot considering the vesicle number density per volume in mm^{-3} (Nv)
807 with diameter greater than L (the equivalent diameter of the vesicle).
808
809 Figure 11: a) Down flow variation in the velocity (*diamonds*) and viscosity (*crosses)*. The
810 *black diamonds* are our calculations and the *open diamonds* are the estimations given by
811 Moore and Kachadorian (1980); b) Velocity (*diamonds*) and viscosity (*crosses)* calculated
812 with flow depth around T10.
813
814 Figure 12: Conceptual model for the interaction of lava and trees depending on the lava type.
815
816 **Table captions**
817 Table 1: Sample location and description

818 Table 2: Textural analyses down the flow

819 Table 3: Textural analyses and viscosity estimation along a single tree (T10)

820 Table 4: Viscosity and velocity estimation along the flow

821 Table 5: Reconstruction of the effusion rate history

822

Figure 1

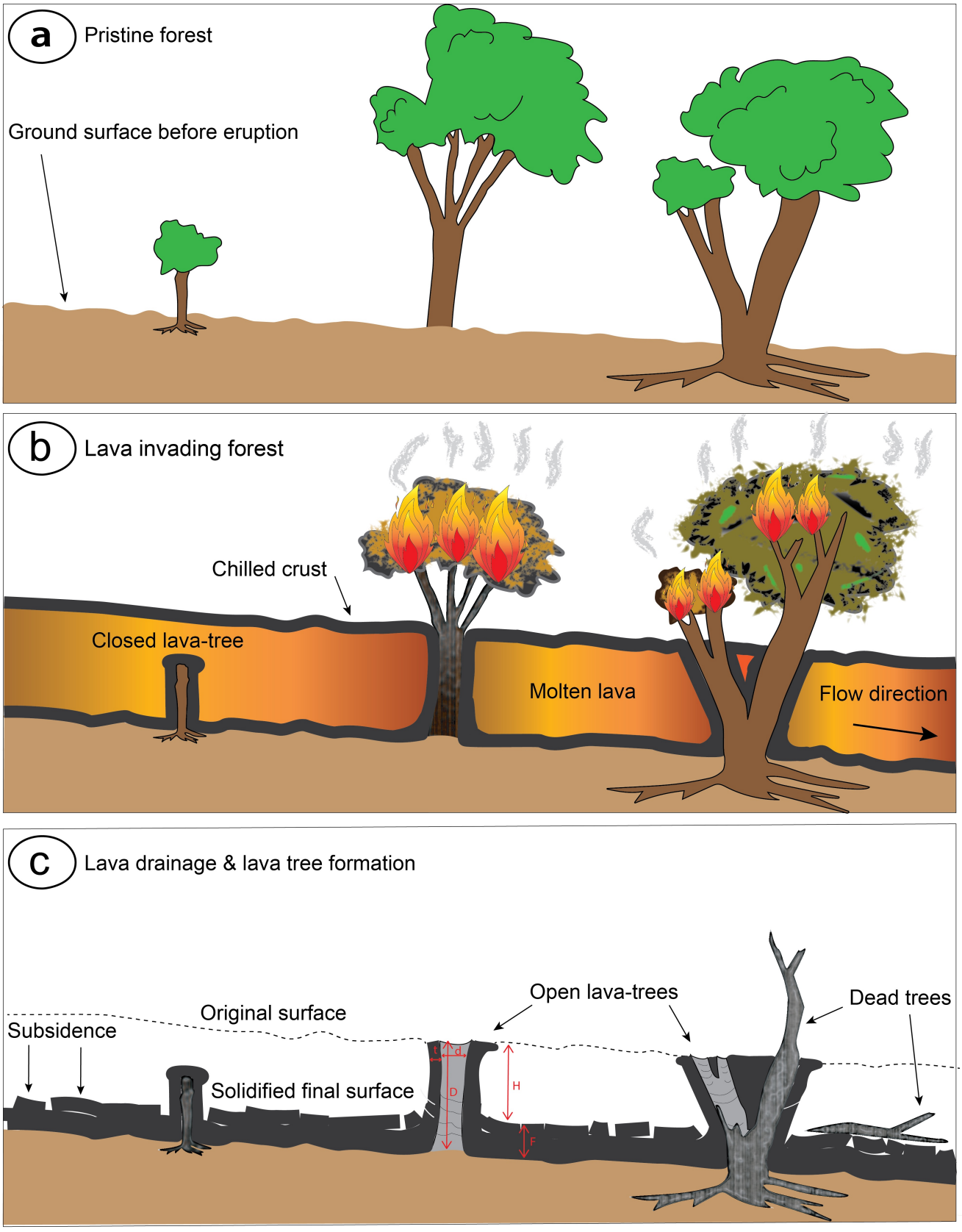
a
Pristine forest
Ground surface before eruption
b
Lava invading forest
Chilled crust
Closed lava-tree
Molten lava
Flow direction
c
Lava drainage & lava tree formation
Original surface
Subsidence
Open lava-trees
Dead trees
Solidified final surface
d
D
H
F

Figure 2

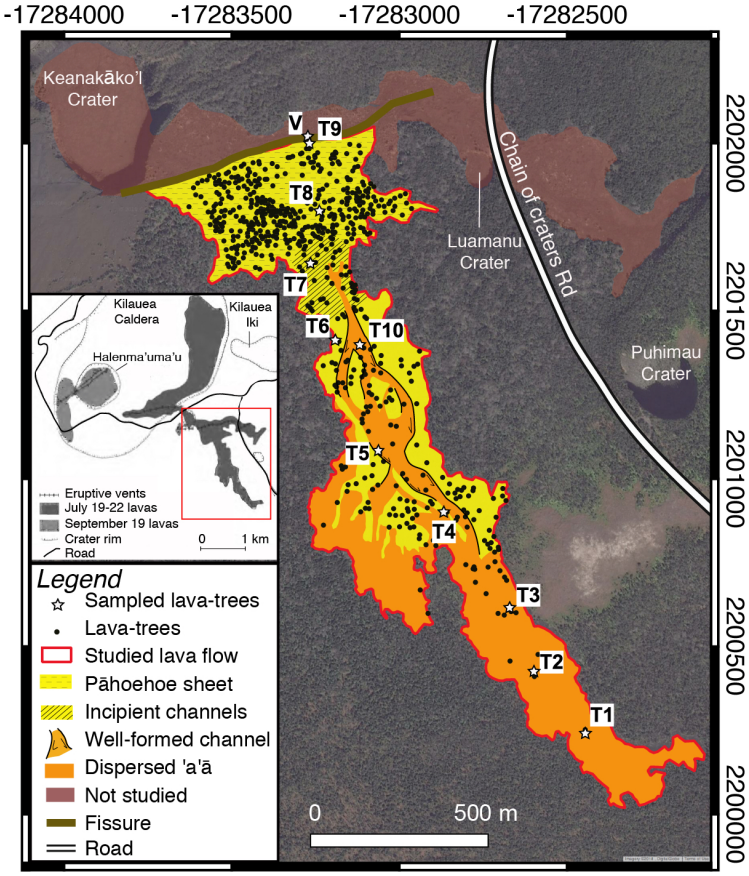
-17284000
-17283500
-17283000
-17282500
2202000
2201500
2201000
2200500
2200000
Keanakāko'i Crater
Chain of craters Rd
Luamanu Crater
Puhimau Crater
V
T9
T8
T7
T6
T10
T5
T4
T3
T2
T1
0
500 m
Kilauea Caldera
Kilauea Iki
Halema'uma'u
Eruptive vents
July 19-22 lavas
September 19 lavas
Crater rim
Road
0
1 km
Legend
Sampled lava-trees
Lava-trees
Studied lava flow
Pāhoehoe sheet
Incipient channels
Well-formed channel
Dispersed 'a'ā
Not studied
Fissure
Road

Figure 3

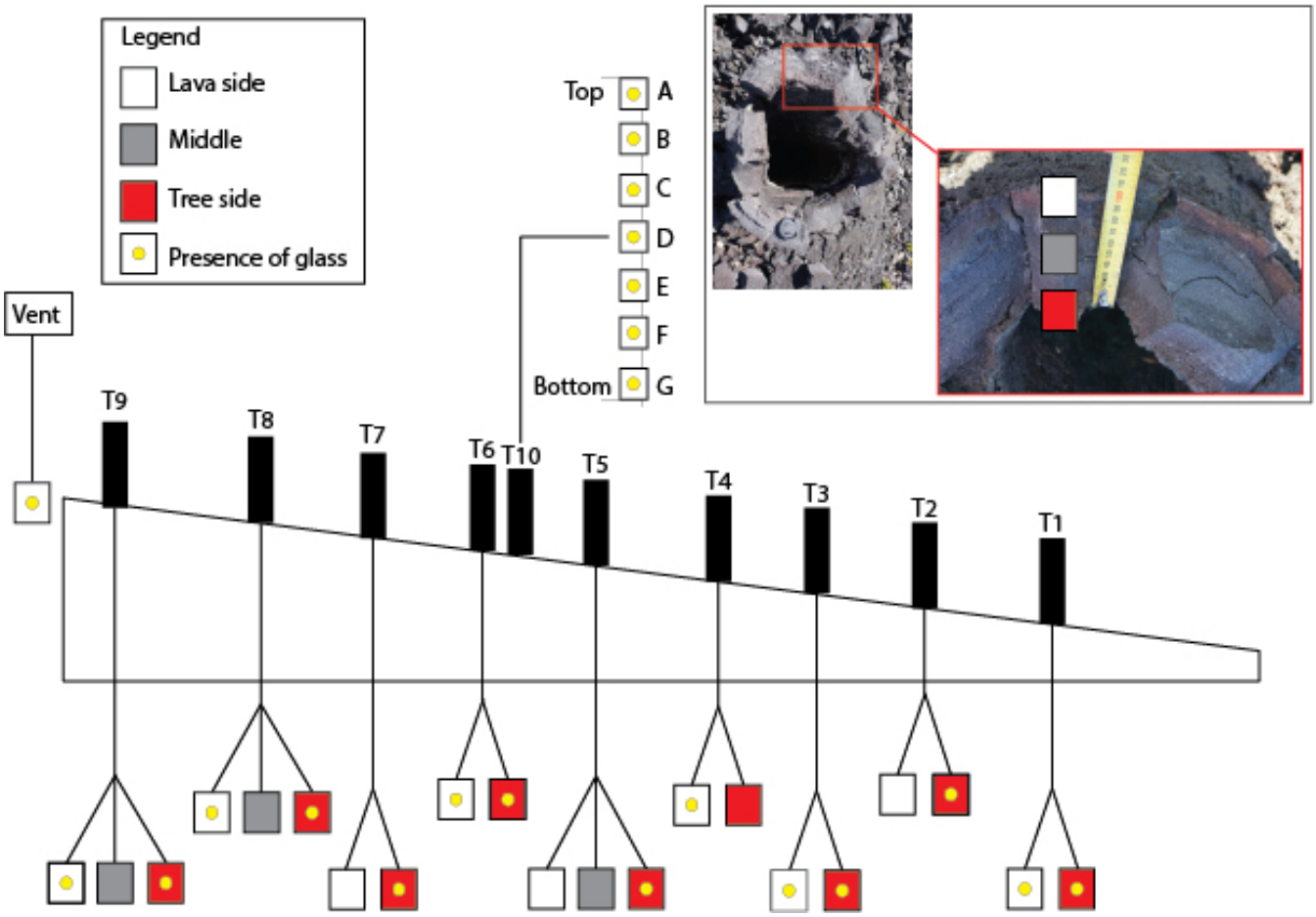
Legend
Lava side
Middle
Tree side
Presence of glass
Top
A
B
C
D
E
F
Bottom
G
Vent
T9
T8
T7
T6
T10
T5
T4
T3
T2
T1

Figure 4

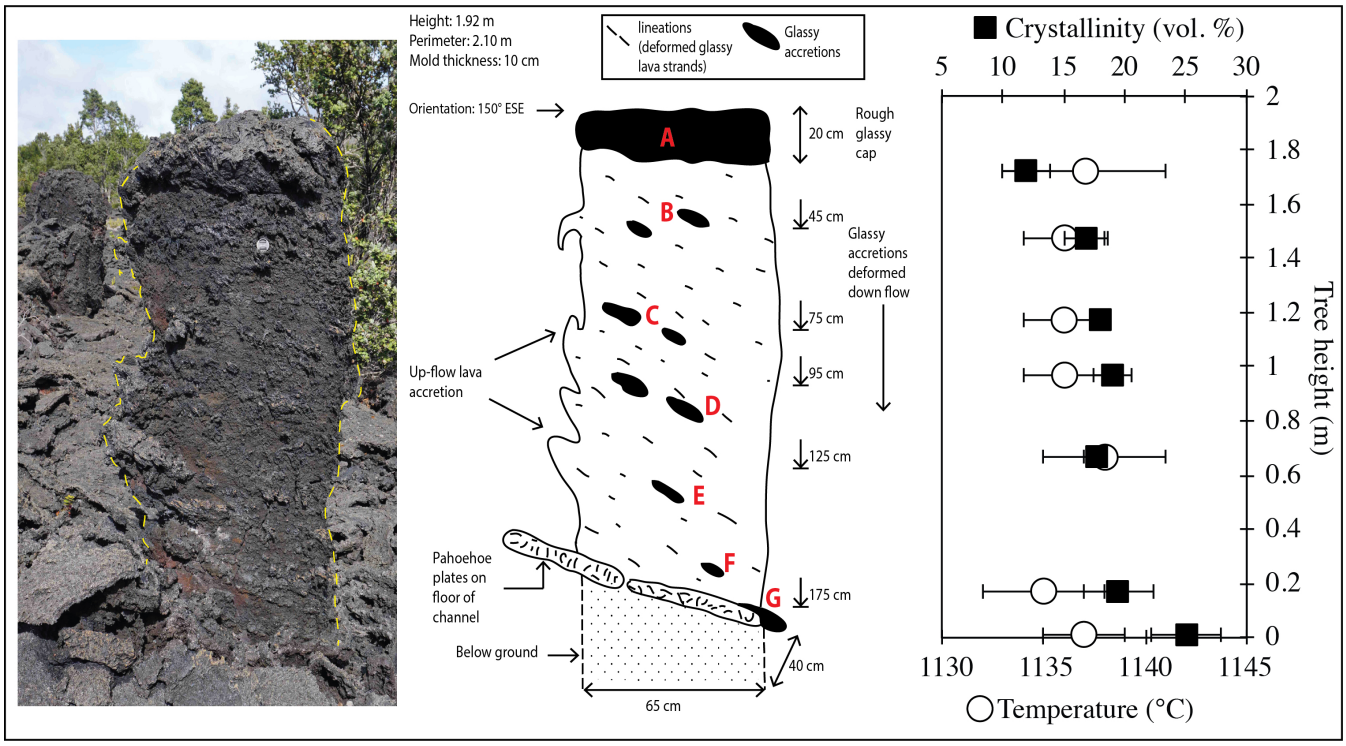
Height: 1.92 m
Perimeter: 2.10 m
Mold thickness: 10 cm
lineations (deformed glassy lava strands)
Glassy accretions
Orientation: 150° ESE
A
B
C
D
E
F
G
20 cm
Rough glassy cap
45 cm
Glassy accretions deformed down flow
75 cm
95 cm
125 cm
175 cm
Up-flow lava accretion
Pahoehoe plates on floor of channel
Below ground
40 cm
65 cm
Crystallinity (vol. %)
5 10 15 20 25 30
2 1.8 1.6 1.4 1.2 1 0.8 0.6 0.4 0.2 0
Tree height (m)
1130 1135 1140 1145
Temperature (°C)

Figure 5

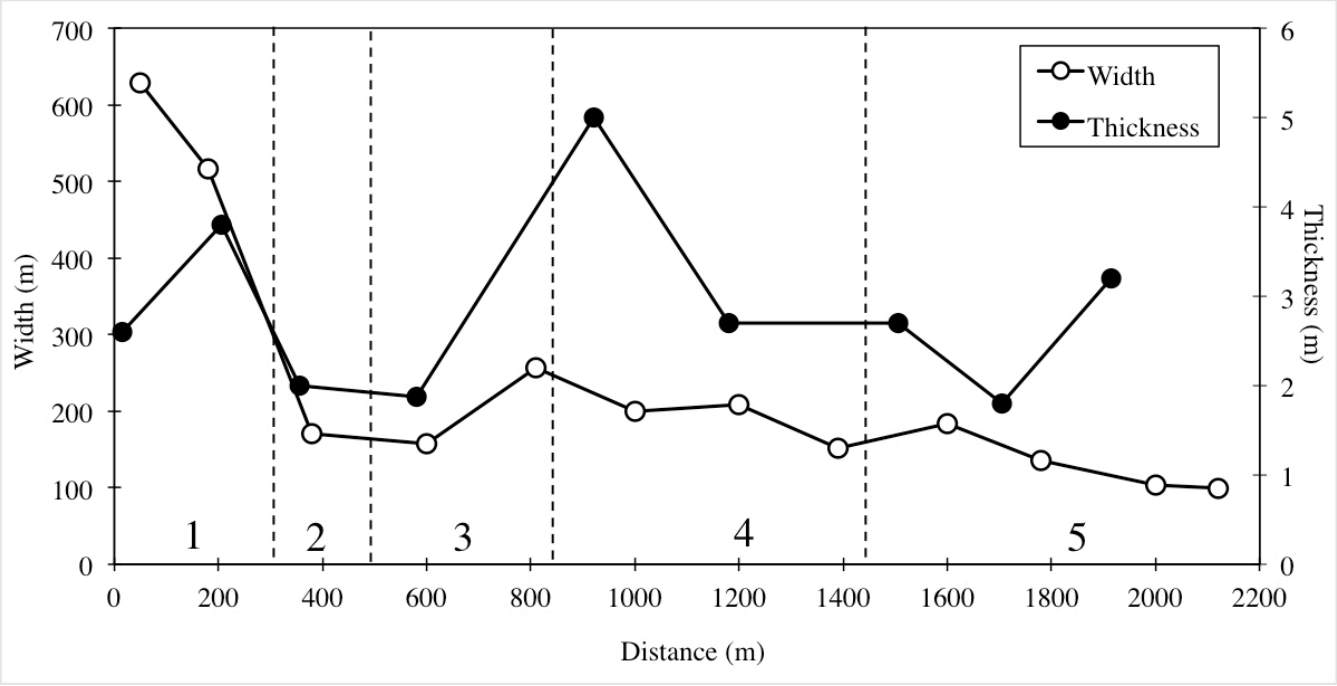
Width
Thickness
Width (m)
Thickness (m)
Distance (m)
1
2
3
4
5
0
100
200
300
400
500
600
700
0
1
2
3
4
5
6
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200

Figure 6

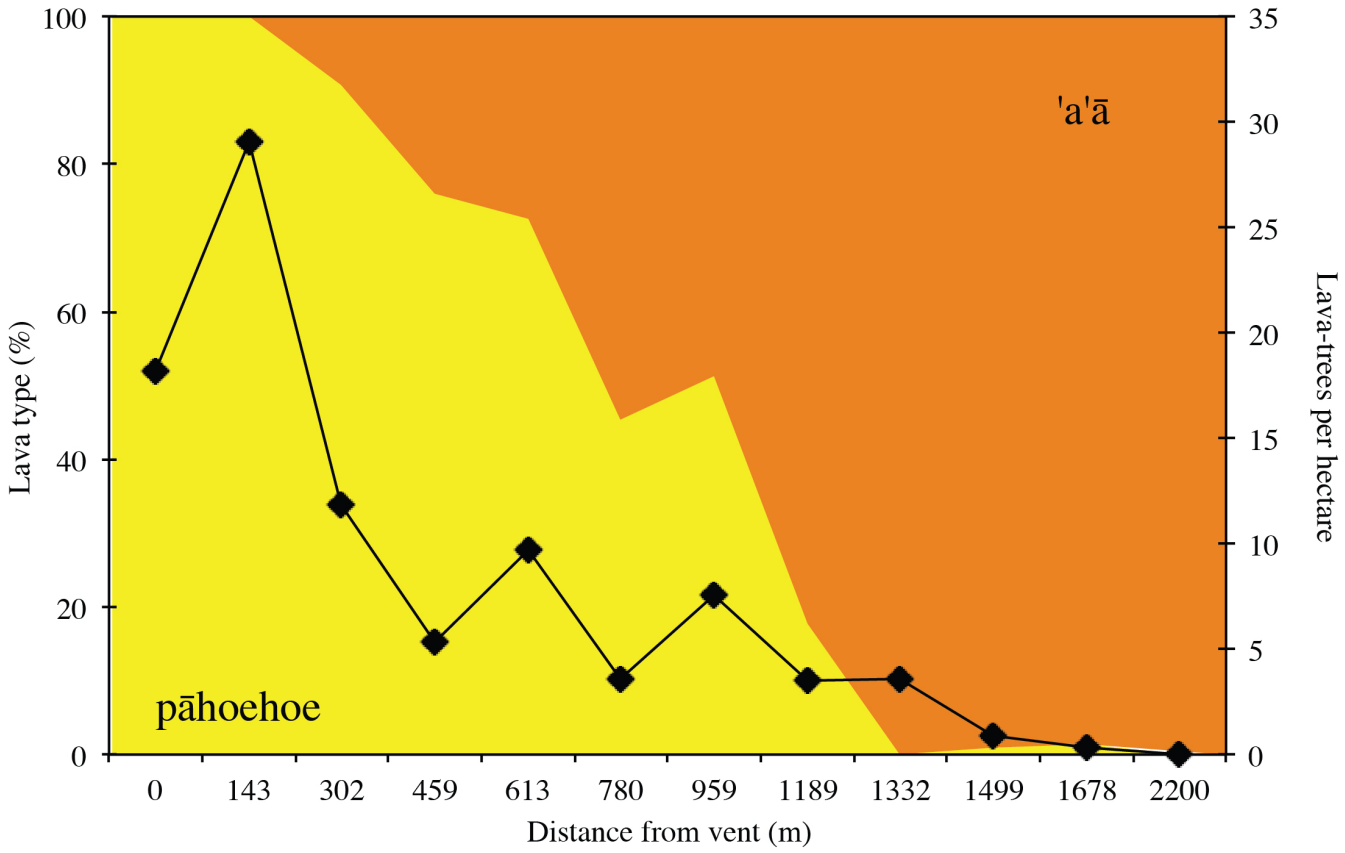
100
80
60
40
20
0
Lava type (%)
35
30
25
20
15
10
5
0
Lava-trees per hectare
'a'ā
pāhoehoe
0
143
302
459
613
780
959
1189
1332
1499
1678
2200
Distance from vent (m)

Figure 7

Figure 8

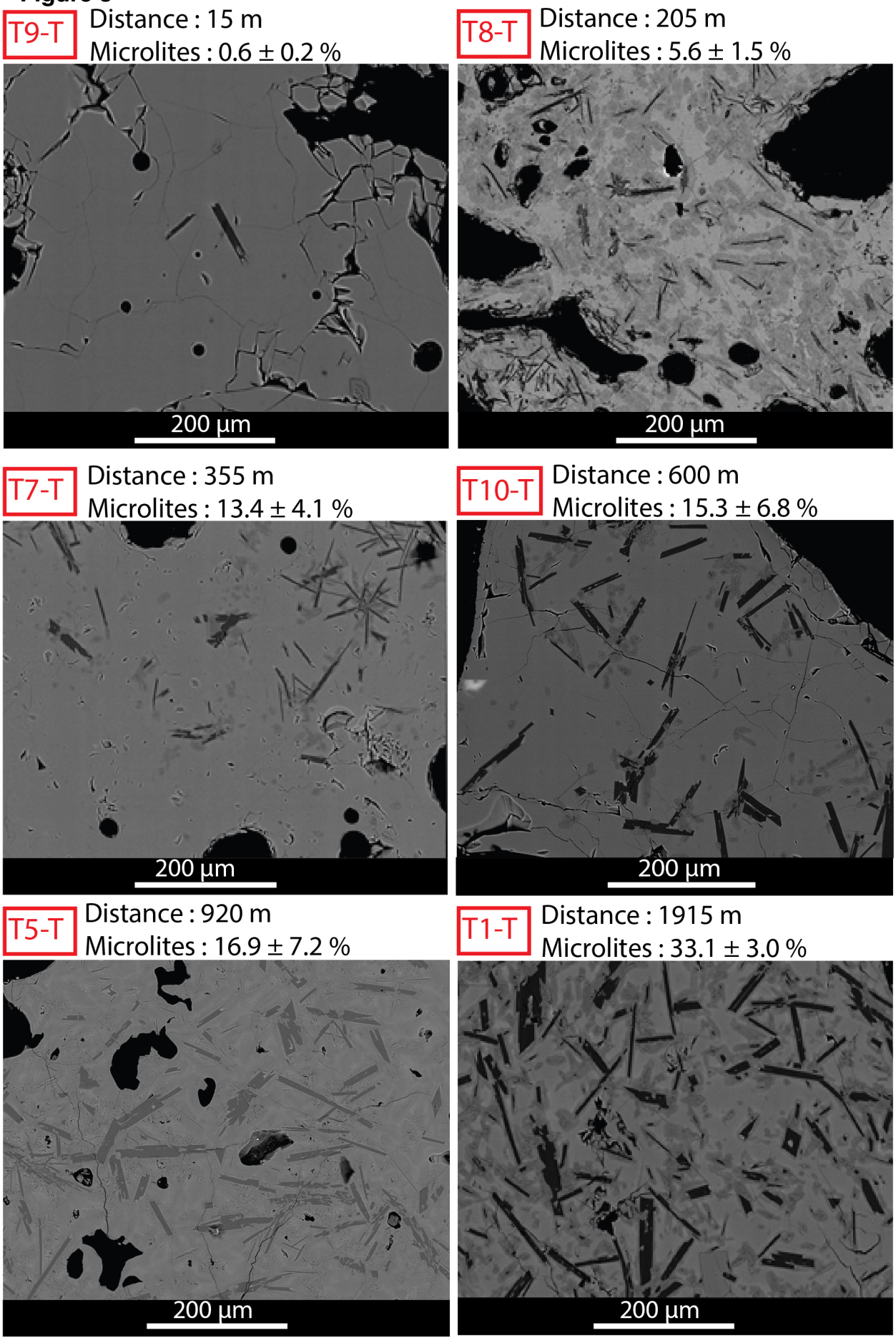
T9-T
Distance : 15 m
Microlites : 0.6 ± 0.2 %
200 µm
T8-T
Distance : 205 m
Microlites : 5.6 ± 1.5 %
200 µm
T7-T
Distance : 355 m
Microlites : 13.4 ± 4.1 %
200 µm
T10-T
Distance : 600 m
Microlites : 15.3 ± 6.8 %
200 µm
T5-T
Distance : 920 m
Microlites : 16.9 ± 7.2 %
200 µm
T1-T
Distance : 1915 m
Microlites : 33.1 ± 3.0 %
200 µm

Figure 9

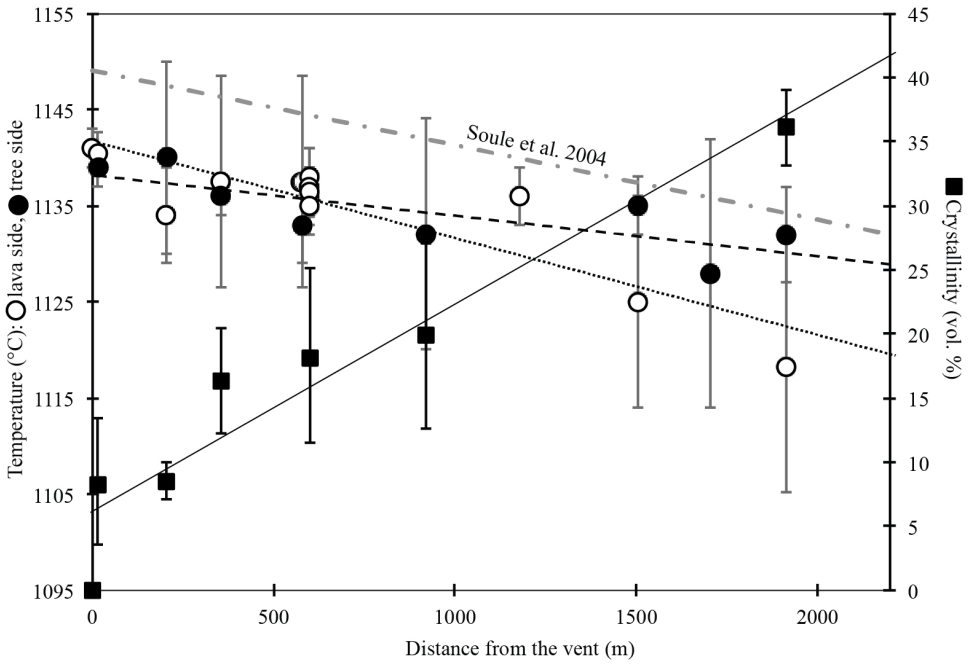
1155
1145
1135
1125
1115
1105
1095
0
500
1000
1500
2000
45
40
35
30
25
20
15
10
5
0
Soule et al. 2004
Temperature (°C): ○ lava side, ● tree side
■ Crystallinity (vol. %)
Distance from the vent (m)

Figure 10

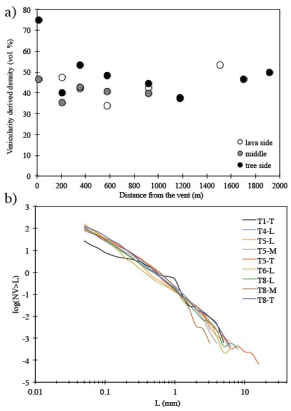
a)
Vesicularity derived density (vol. %)
Distance from the vent (m)
lava side
middle
tree side
b)
log(N>L)
L (mm)
T1-T
T4-L
T5-L
T5-M
T5-T
T6-L
T8-L
T8-M
T8-T

Figure 11

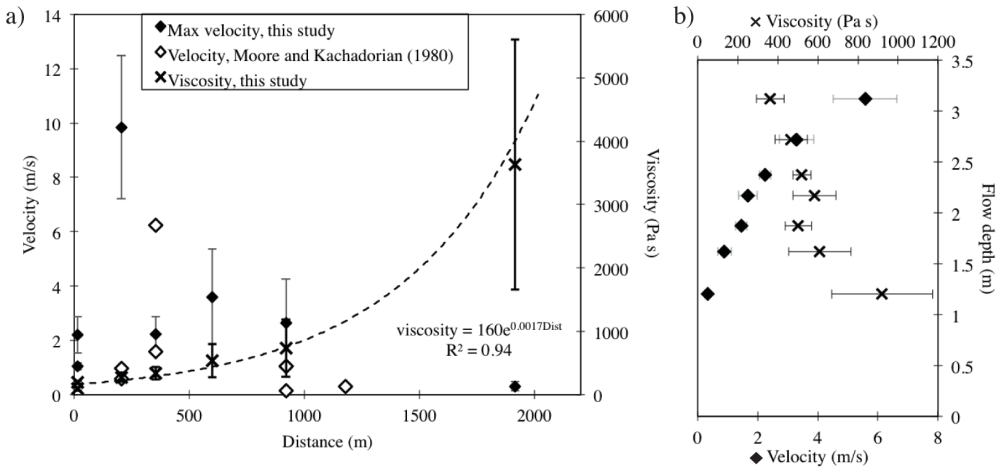
a)
Max velocity, this study
Velocity, Moore and Kachadorian (1980)
Viscosity, this study
viscosity = 160e^0.0017Dist
R² = 0.94
Velocity (m/s)
Viscosity (Pa s)
Distance (m)
b)
Viscosity (Pa s)
Flow depth (m)
Velocity (m/s)

Figure 12

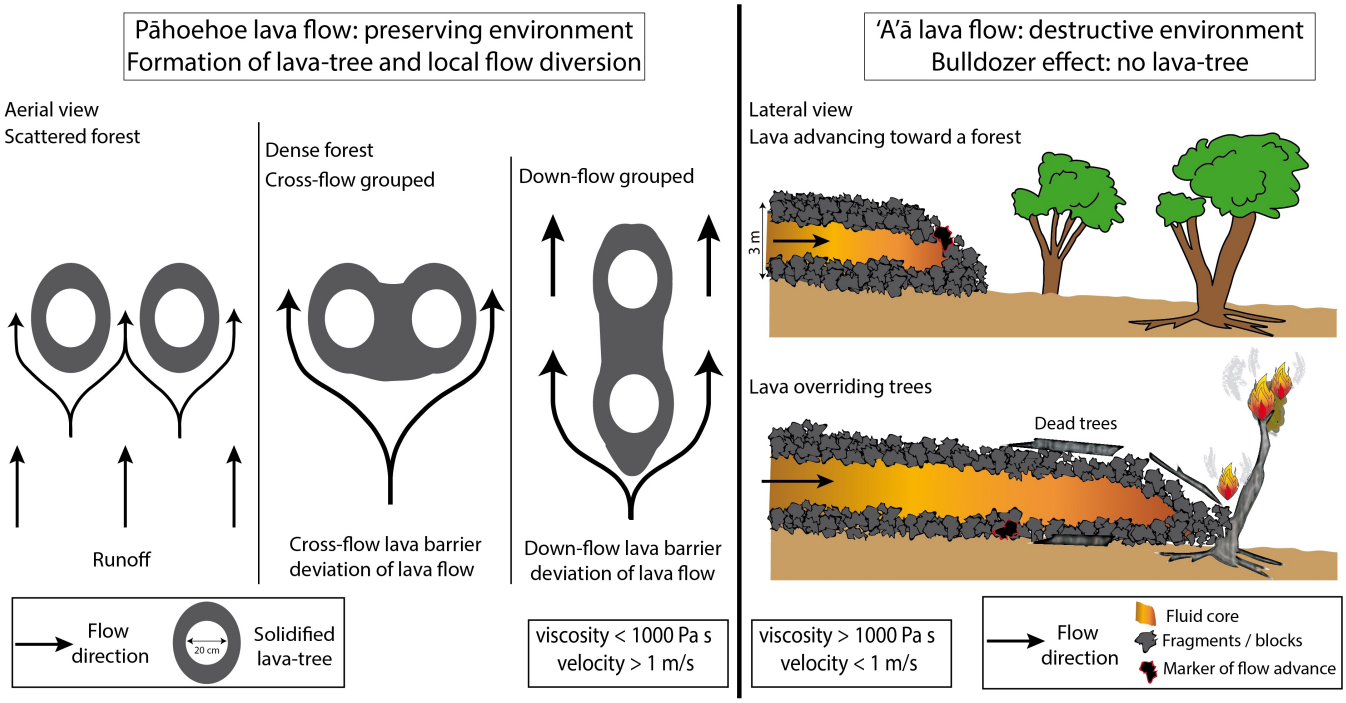
Pāhoehoe lava flow: preserving environment
Formation of lava-tree and local flow diversion
'A'ā lava flow: destructive environment
Bulldozer effect: no lava-tree
Aerial view
Scattered forest
Dense forest
Cross-flow grouped
Down-flow grouped
Runoff
Cross-flow lava barrier
deviation of lava flow
Down-flow lava barrier
deviation of lava flow
Flow
direction
20 cm
Solidified
lava-tree
viscosity < 1000 Pa s
velocity > 1 m/s
Lateral view
Lava advancing toward a forest
3 m
Lava overriding trees
Dead trees
viscosity > 1000 Pa s
velocity < 1 m/s
Flow
direction
Fluid core
Fragments / blocks
Marker of flow advance

Table 1

Sample	GPS coordinates		Distance from vent (m)	Height of the lava-tree (m)	Description
	Latitude (N)	Longitude (W)			
Vent	19°23'57.8710"	155°15'29.6680"	0	--	Glassy spatter t vent
T9	19°23'57.3504"	155°15'29.5245"	15	2.6	Near the vent, sheet pahoehoe
T8	19°23'51.2160"	155°15'28.5489"	205	3.8	Sheet pahoehoe zone
T7	19°23'46.4604"	155°15'29.3742"	355	2	Gas-rich zone, shelly pahoehoe
T6	19°23'39.4332"	155°15'27.0157"	580	1.88	Shear zone in the channel, slabby pahoehoe
T10	19°23'39.0408"	155°15'24.6118"	600	1.92	Near T6, edge of the channel
T5	19°23'29.2380"	155°15'23.2431"	920	5	Tree with three trunks, in channel of slabby pahoehoe
T4	19°23'23.8272"	155°15'16.5212"	1180	2.7	Slabby pahoehoe
T3	19°23'14.9604"	155°15'10.4030"	1505	2.7	Slabby pahoehoe to 'a'a lava
T2	19°23'08.8764"	155°15'08.1606"	1705	--	Slabby pahoehoe to 'a'a lava
T1	19°23'04.0596"	155°15'03.2633"	1915	3.2	First lava tree found since the front, essentially 'a'a lava

Table 2

Sample	Distance from vent (m)	Number of glass per sample	Temperature (°C)*	+/-	Density (kg/m3)	vesicularity-derived density (vol. %)	2D vesicularity (vol. %)	Microlite (vol. %)	Total crystal content (vol. %)**	+/-
VENT	0	20	1141	2	--	--	--	--	3	--
T9-L	15	11	1140	2	--	--	--	10.5	13.5	1.6
T9-M	15	--	--	--	1620	46.5	--	--	--	--
T9-T	15	10	1139	2	756	75.1	--	0.6	3.6	0.2
T8-L	205	10	1134	5	1599	47.2	44.4	--	--	--
T8-M	205	--	--	--	1959	35.4	38.4	--	--	--
T8-T	205	30	1140	10	1811	40.2	54.8	5.6	8.6	1.4
T7-L	355	10	1138	11	1757	42.0	--	--	--	--
T7-M	355	--	--	--	1743	42.5	--	--	--	--
T7-T	355	10	1136	2	1416	53.3	--	13.4	16.4	4.1
T6-L	580	10	1138	11	2001	34.0	37.6	-	-	--
T6-M	580	--	--	--	1798	40.7	--	--	--	--
T6-T	580	10	1133	4	1566	48.3	--	--	--	--
T10-L mean	600	--	1136	3	--	--	--	15.3	18.3	6.8
T5-L	920	--	--	--	1749	42.3	40.8	--	--	--
T5-M	920	--	--	--	1821	39.9	39.1	--	--	--
T5-T	920	11	1132	12	1677	44.6	60.4	16.8	19.8	7.2
T4-L	1180	10	1136	3	1887	37.7	44.6	--	--	--
T4-T	1180	--	--	--	1898	37.4	--	--	--	--
T3-L	1505	10	1125	11	1412	53.4	--	--	--	--
T3-T	1505	10	1135	3	1507	50.3	--	--	--	--
T2-L	1705	--	--	--	0	--	--	--	--	--
T2-T	1705	10	1128	14	1626	46.3	--	--	--	--
T1-L	1915	10	1118	13	0	--	--	--	--	--
T1-T	1915	15	1132	5	1522	49.8	54.3	33.1	36.1	3.0

* Mg-thermometer from 10 glass analyses per sample

** + 3 vol. % of phenocrysts

Table 3

Level	Sample	Distance from top (m)	Flow Depth (m)	Temperature (°C)a	±	Melt viscosity (Pa s)b	±	Crystallinity (vol.%)c	±	Relative viscosity crystal effectd	±	Viscosity of three phase mixture (Pa s)e	±	Velocity (m/s)f	±	Effusion Rate (m3/s)	±
High-Stand	A	0	3.12	1137	4	481	27	11.9	2.0	1.8	0.6	363	124	5.6	1.9	304	58
1	B	0.4	2.72	1137	2	460	22	16.9	1.7	2.4	0.5	467	99	3.3	0.7	157	27
2	C	0.75	2.37	1136	2	475	14	18.0	0.3	2.6	0.1	520	24	2.2	0.1	93	8
3	D	0.95	2.17	1136	2	498	28	19.0	1.6	2.7	0.5	583	101	1.7	0.3	64	12
4	E	1.25	1.87	1138	3	469	19	17.7	1.0	2.5	0.3	502	61	1.4	0.2	47	6
5	F	1.5	1.62	1135	3	505	29	19.5	2.9	2.8	0.8	610	185	0.9	0.3	25	6
Low-Stand	G	1.75	1.20	1137	2	491	20	25.1	2.9	4.4	1.0	921	213	0.3	0.1	7	2

a Mg-thermometer from 10 glass analyses per sample

b caluclated via Giordano et al. 2008

c including phenocrysts and microlites

d considering the crystallinity and calculated via Mader et al. 2014 for phi max =0.48 (r=3.6)

e considering 40+/- 0.1% of deformable bubble via Llewelin and Manga 2005

f Jeffreys equation with slope of 2° and density of 1.82

Table 4

Tree	Zone	Distance from vent (m)	Max flow Depth (m)	Final Flow Depth (m)	Slope (°)	Melt viscosity (Pa s)a	±	Viscosity of three phase mixture (Pa s)b	±	Max velocity (m/s)c	±	Min velocity (m/s)c	±
T9-T	1: sheet flow	15	2.6	0.9	0.3	471	54	193	23	1.0	0.1	0.1	0.0
T9-L	1: sheet flow	15	2.6	0.9	0.3	478	41	91	28	2.2	0.7	0.3	0.1
T8	1: sheet flow	205	3.8	2.4	1.9	441	113	277	74	9.8	2.6	3.9	1.1
T7	2: proximal channel	355	2.0	0.2	1.9	523	61	338	97	2.2	0.6	0.01	0.0
T6	3: Medial channel	580	1.9	0.7	2.0	--	--	--	--	--	--	--	--
T10	3: Medial channel	600	3.1	1.7	2.0	483	164	538	263	3.6	1.8	1.1	0.5
T5	3: Medial channel	920	5.1	1.7	0.8	678	236	735	457	2.6	1.6	0.3	0.2
T4	4. Distal channel	1180	2.7	1.4	0.8	--	--	--	--	--	--	--	--
T3	5. Dispersed flow	1505	2.7	0.6	0.8	--	--	--	--	--	--	--	--
T2	5. Dispersed flow	1705	1.8	1.8	1.1	--	--	--	--	--	--	--	--
T1	5. Dispersed flow	1915	3.2	1.2	1.1	702	145	3634	1975	0.3	0.2	0.04	0.02

a caluclated via Giordano et al. 2008 using the glass composition and temperature reported in Table 2

b considering the crystal content and vesicularity reported in Table 2 and assuming phi max =0.48 (r=3.6) and deformable bubble via Llewelin and Manga 2005

c Calculated from Jeffreys equation with a density of 1740 kg/m3

Table 5

Time (hours)	Effusion Rate	(m3/s)	Duration (h)	Volume Emplaced (m3)
1.8	403		1.8	2.55 × 106
2.6	209		0.9	6.57 × 105
3.1	124		0.4	1.95 × 105
3.3	85		0.2	6.68 × 104
3.4	63		0.1	2.48 × 104
3.4	34		0.05	6.64 ×103
3.5	9		0.03	8.93 × 102
Total	280		3.5	3.5 × 106