Pre-existing ground cracks as lava flow pathways

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Keywords

Hawaii, Kīlauea, Puʻuʻōʻō, volcano, lava flow, ground crack, top-fed dike

Acknowledgements

We thank the staff and volunteers of the U.S. Geological Survey who assisted with collecting the myriad observations that helped us understand the evolution of the 2014 Pāhoa lava flow. David Okita of Volcano Helicopters provided expert piloting, which facilitated unparalleled access to eruptive activity at Kīlauea. David Hyman, Y, and Z provided insightful reviews that greatly improved the manuscript. EWL acknowledges support via Royal Society International Exchanges grant IE130961 and via NSFGEO-NERC grant NE/T009594/1.

Author contributions

All authors contributed to the study conception and design, material preparation, data collection, and analysis. The first draft of the manuscript was written by Tim Orr and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Statements and Declarations

The authors declare no competing interests.

Abstract

In 2014, the Pāhoa lava flow at Kīlauea volcano, on the Island of Hawaiʻi (USA), entered a string of pre-existing meter-width ground cracks in the volcano's East Rift Zone. The ground cracks transported lava below the surface in a direction discordant to the slope of the landscape. The cracks, which were 100s of meters long and 10s to 100s of meters deep, also widened by up to several meters as they filled, probably in part at the expense of adjacent cracks, which likely closed. Widening of the cracks caused shallow crustal blocks on the volcano's flank to shift—this deformation was captured by a nearby GPS station and a borehole tiltmeter. The GPS station moved away from the cracks in response, while the tiltmeter showed tilting toward the cracks, consistent with opening. Noting that the lava-filled cracks act as top-fed dikes, we adapt existing theory for the thermo-rheological evolution of dikes to analyze transport of lava captured by ground cracks. This study shows that ground cracks can facilitate the transport of advancing lava flows and can carry lava in directions that differ from those expected based on surface topography, invalidating flow path projections based on the assumption of subaerial flow.

1. Introduction

Tracking an advancing lava flow relies fundamentally on robust observations, often from frequent field visits and aerial overflights supplemented with unoccupied aircraft and satellite imagery. The observations are used in conjunction with flow path modeling to project future flow paths. Each of these techniques assumes that the lava flow is on the ground surface and directly observable. During 2014–2015, pre-existing ground cracks in Kīlauea volcano's East Rift Zone, on the Island of Hawaiʻi (USA), captured and re-directed the Pāhoa (or "June 27th") lava flow across surface topography. The lava flow traveled out of sight underground, rendering direct observations of the flow impossible and invalidating flow path projections. The ground cracks themselves were not observable from the air or in existing digital elevation models (DEMs) because of the thick vegetation, but their locations were inferred from lines of steam that formed as the cracks filled with lava. Visits on the ground confirmed their existence.

In this paper, we focus on the capture of the Pāhoa lava flow by pre-existing ground cracks. The lava filling the cracks acted as a wedge, driving them open by as much as 4 meters, probably at the expense of adjacent empty cracks, which must have closed, allowing lava to travel farther in the cracks than would have been possible otherwise. This process caused large crack-bounded blocks of rock to shift—blocks tens of meters or more across, hundreds of meters long, and possibly hundreds of meters tall. The capture and transport of lava flows by ground cracks is rare but not unique, having been observed in several other instances at Kīlauea (Swanson et al., 1972; Swanson et al., 1979; Wolfe et al., 1988; Jones et al., 2018; Orr et al., 2018), and possibly two instances in Iceland (Einarsson and Brandsdóttir, 2021; Opheim and Gudmundsson, 1989).

2. Eruption chronology

Kīlauea Volcano is the youngest and southeast-most of the five volcanoes that form the Island of Hawaiʻi (Fig. 1) and was host to the long-lived Puʻuʻōʻō eruption, active 1983–2018 (Wolfe and others, 1988; Heliker and Mattox, 2003; Orr et al., 2015b; Orr et al., 2018; Neal et al., 2019). The Puʻuʻōʻō eruption offered an unparalleled opportunity for studying the evolution and dynamics of a long-lived basaltic eruptive center because of its persistent activity, variety of eruptive styles and behaviors, and relative ease of access. The first three years of the eruption were characterized by episodic lava fountains that built the Puʻuʻōʻō cone (eruptive episodes 1–47), but activity transitioned to nearly continuous effusion in 1986. The eruption thereafter (eruptive episodes 48–62) was typified by shield construction and tube-fed lava flows, interrupted occasionally by brief fissure eruptions nearby.

On June 27, 2014, the opening of a new vent on the Puʻuʻōʻō cone sent flows to the northeast (Fig. 1; Poland et al., 2016; Brantley et al., 2019). We referred to this new breakout as the June 27th flow, but this identifier became cumbersome as the flow carried on for more than a year. It was locally called the Pāhoa flow, and we use this informal designation here.

The Pāhoa flow was the culmination of weeks of gradually increasing activity at Puʻuʻōʻō, which resulted in several brief overflows onto its flanks by flows from vents in the crater. At about 0700 HST on June 27, a string of four fissures opened on Puʻuʻōʻō's northeast flank and fed overlapping sheet and channelized flows. The eruption soon focused on a single vent, and a narrow lava flow began advancing downslope at up to ~600 m per day, but with considerable variability. The time-averaged discharge rate spanning this period of the eruption was 1–2 m^3/s (Patrick et al., 2017).

The flow reached the forest at the northeast edge of the older Puʻuʻōʻō flow field on August 1 and advanced along the axis of Kīlauea's East Rift Zone, slowing to about 280 m per day (range 130–365 m/day). This part of the East Rift Zone is known to host numerous ground cracks up to meters in width that probably formed during past intrusions (M. Poland, personal comm., 2020). In mid-August, the flow turned and began to advance north. However, by the morning of August 18 (and perhaps earlier), the flow had intersected a large ground crack (crack 1), which captured the flow and redirected it toward the northeast (fig. 2), across surface slope. Lava was also deflected about 450 m to the southwest along the crack.

The lava flow in the crack was not visible, but its advance to the northeast was marked by a discontinuous but gradually lengthening line of steam (~320 m/day; range 220–450 m/day) that marked the trace of the crack (fig. 2), which was otherwise hidden by thick vegetation. We infer that the steam farthest downslope marked the terminus of the lava flow advancing in the crack, Thus, the lava flow advance rates on the ground surface and in the crack were about the same. Lava overflowed the crack about 1.6 km downslope and 40 m lower in elevation on August 24 (total crack length ~2.1 km), forming a 500-m-long flow (lava pad A) that quickly overwhelmed a small crack to the south (crack 2; total crack length ~300 m). The flow was captured by a third crack (crack 3; total length ~500 m) the following day that likewise carried the flow northeast underground. Lava emerged from near the midpoint of crack 3 on August 29, forming another 500-m-long flow (lava pad B) that was seen cascading into yet another ground crack (crack 4; Fig. 3) on September 1 that carried the flow farther northeast.

Lava exited crack 4 (total length ~1.2 km) on September 3, forming three new flows (lava pads C–E) about 1.2 km upslope of the Kaʻohe Homesteads housing subdivision. The western of these three new flows (lava pad C) soon captured the entire flow volume, and the lava began to advance toward the north, where it intersected a fifth ground crack (crack 5; total length ~1.0 km) on September 4. Lava traveled to both the east and west within the crack, but when the crack was filled on September 6, the flow exited the crack near the point at which lava first entered it, where the elevation was presumably lowest, and resumed its northward advance. A few weeks later, a sixth crack (crack 6; total crack length ~300 m) captured minor surface breakouts farther upslope, near the west end of crack 1, forming a string of small lava pads that traveled several hundred meters downslope before stalling. Figures 1 and 2 show the arrangement of cracks and flows within the crack system filled by lava during this period of the eruption. Other cracks were also infiltrated, but those did not obviously function as lava flow pathways like cracks 1–6.

The flow continued advancing northeast over the following weeks, bypassing homes in Kaʻohe Homesteads but bearing down on the town of Pāhoa, directly downslope. The flow front eventually stalled a mere 155 m from the main street through Pāhoa and a secondary flow branch came to within 500 m of Highway 130 and the Pāhoa fire and police stations, at the north edge of the town. A rupture of the lava tube near Puʻuʻōʻō on March 9, 2015, finally robbed the supply of lava downslope permanently. Minor residual activity continued at the distal part of the Pāhoa flow until March 13. The vent for the Pāhoa flow remained active for another 14 months, until May 24, 2016.

3. Methods

The descriptive data presented herein were acquired during frequent helicopter overflights of, and ground visits to, the active flow field. The margins of the lava flow and other features were mapped from the air or on the ground using a handheld global positioning system (GPS) unit, or from georegistered aerial and satellite imagery (both visible light and thermal IR).

A continuous GPS receiver (JOKA) and borehole tiltmeter (JKA) were co-located about 600 m south of crack 3 (Figs. 1 and 5). Tiltmeter JKA was an Applied Geomechanics LILY instrument buried at ~5 m depth with a sampling rate of one minute. We apply a notch filter to remove diurnal and semidiurnal noise from the time series. Daily positions for GPS station JOKA were computed using the GIPSY software package.

As the flow migrated northeast from Puʻuʻōʻō and established itself in a topographic drainage that threatened residential areas, we wrote a simple flow path forecasting script which sought to emulate the same basic stochastic approach as that of the DOWNFLOW forecasting tool (Favalli et al., 2005). Our script results were later compared to DOWNFLOW results and showed close similarity, although DOWNFLOW is greatly superior in speed and efficiency. Our script used the 1983 10 m USGS DEM of the Island of Hawaiʻi and calculated repeated (5000 times) steepest descent paths from an origin point, adding random noise (up to 5 m) to the DEM at each iteration. The noise is meant to account for the inherent error of the DEM. Each of the two resulting maps shows a broad swath of possible steepest descent paths, with the color scale showing the frequency of descent simulations which passed through a given pixel.

4. Results and Discussion

Occupation and forced opening of ground cracks

No complete inventory of ground cracks exists for Kīlauea's East Rift Zone. While some crack-bounded grabens are discernable in satellite imagery, most cracks are obscured by the thick vegetation. Conditions on the ground are extremely hazardous for the same reason—many cracks are hidden by the thick mat of vegetation that obscures the forest floor. Field experience by the authors suggests that, for every ground crack large enough to see from the air, there are dozens or hundreds more smaller ones. The ground cracks are discontinuous, extending tens or hundreds of meters along strike before pinching out or intersecting an adjacent crack. The result is a network of closely spaced, nearly parallel cracks bounding large, sliver-like blocks composed of stacked lavas.

There were only a few direct observations of the Pāhoa flow draining into cracks (Fig. 3), with the lava plunging out of sight, and the behavior of the lava once in the cracks was too deep to be observed. No information exists about the depth of the cracks, but anecdotal stories told to us by a resident of Pāhoa suggest a hundred meters or more for some cracks in the area, which is on par with depths modeled for tensional cracks in Iceland (Gudmundsson, 1987a,b; Opheim and Gudmundsson, 1989). If we assume that the along-strike width of the cracks is constant and that they pinch downward, then their shape can be approximated by a narrow isosceles-triangle-shaped wedge. In this case, total crack depth Z [m] is given by:

$$Z = \frac{2V}{Lw_o}, \qquad \text{Eq. 1}$$

where V [m^3] is crack volume, L [m]is crack length along strike, and w_0 [m] is the crack width at the surface. Crack 1 had $L = 2100$ m and $w_0 = 5$ m. It was filled by a lava volume in the range 5.5–11 × 10^5 m^3 as determined from the time-averaged discharge rate during this episode of the eruption (1–2 m^3/s; Patrick et al., 2017). When multiplied by the minimum duration over which the crack filled (just over six days; ~152 hours), the result is a crack depth Z that ranges from about 100 to 200 m. Data for other cracks are less well constrained but similar analysis indicates crack depths in the range 100 to 600 m, albeit with substantial uncertainty.

The duration we use is likely an underestimate because the flow front was already at crack 1 when observed on the morning of August 18—lava may have started filling the crack a day or two earlier, but observations are lacking. Increasing the duration increases the volume of material needed to fill crack 1, which thereby increases the estimated crack depth. Adding 24 hours to the duration, for example, increases crack depth by ~15%. In contrast, not all lava feeding the Pāhoa flow entered crack 1. Weak activity continued upslope from the crack, leading to widening and thickening of the flow. This reduced the volume of material entering crack 1, which likewise reduces the estimated crack depth. For instance, if we assume that 85% of the total flow volume was entering crack 1, consistent with field observations, the corresponding crack depth is reduced by ~15%. Considering these two scenarios broadens the crack depth range to ~90–240 m. We also note that the calculation above assumes complete filling of the crack. Field observations suggest that the crack was not full to the brim along its length, and later analysis (Section 5) indicates that lava is unlikely to have reached all the way to the bottom of the crack. Accounting for partial filling of the crack could increase the inferred crack depth substantially.

The discharge of steam from the cracks occupied by lava suggests an interaction with water, although the water source is unknown. The water table at the True Mid-Pacific geothermal exploration well just a few hundred meters south of cracks 3 and 4 is found at a depth of ~300 m (Sorey and Colvard, 1994). . Thus, it is plausible that the ground cracks intersected the water table. However, we cannot rule out saturated sediments and (or) organic material accumulated in the crack, or perhaps springs associated with impermeable layers, if any are exposed in the walls of the cracks. Eventually, when the crack had filled, lava emerged from the part with the lowest surface elevation, forming a new surface flow. Over time, a lava tube developed that incorporated the section of the flow captured by cracks 1, 3, and 4. The depth of the tube within each crack is not known but is presumed to be near the top of the lava fill.

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Field observations found that the lava flow caused the cracks to widen during filling. When visited on the ground months later, we found that the northeastern end of crack 1, where lava emerged from the crack to form lava pad 1, was about 5 meters wide. Mature trees that had originally grown on the wall at the top of the crack, however, showed that they had grown in a crack that was initially about 1 m wide. Lumps of soil and forest floor duff from the opposite edge of the crack were left clinging to tree roots that now dangled in air (Fig. 4a). Thus, the crack had opened ~4 m as it was being filled.

Similarly, we were able to clamber a short distance down into the southwestern end of crack 5 (also months later), which was about 1 meter wide at that point (Fig. 4b). A lobe of the flow had entered that part of the crack later, providing our access, but we did not climb in far enough to reach the original lava fill that forced the crack open. In the part of the crack we did visit, however, there was clear evidence that the crack had recently opened, including roots stretched across the gap or snapped, and fragile piercing points in the soil layer atop the bedrock. In addition, there was a 1-cm-thick organic layer with patches attached to one wall of the crack matching bare spots on the other, creating jigsaw puzzle-like piercing points, indicating a 1-cm-wide preexisting crack filled with organic material that had opened to its present (1 meter) width. The walls of the crack were otherwise devoid of moss, ferns, or other vegetation, which were observed on the upper walls of unfilled cracks of similar width nearby. It is important to note that the lava flow did not enter a 1-cm-wide crack. Rather, the lava flow entered the crack to the east where it was wider and forced narrower parts of the crack open as it was filled.

Finally, aerial observations of crack 4 while it was being filled also clearly indicated that it had opened (Fig. 3). These observations included piercing points in the new pāhoehoe flow surface where the lava had initially bridged the crack, blocks of new lava that had fallen into the crack after the flow had solidified in that location indicating removal of support, and a veneer of reddish brown, oxidized lava adhered to the south wall of the crack opposite the flow suggesting solidification in a narrower filled crack.

The nearby GPS receiver and borehole tiltmeter recorded ground deformation as the cracks were occupied by lava. The borehole tiltmeter (JKA) south of crack 3 showed two tilt excursions toward the crack system (Fig. 5): the first from August 22–23 during filling and opening of the east end of crack 1, and the second from August 26–27 while crack 3 was being filled. No significant tilt excursions on JKA accompanied the occupation of the other cracks. The continuous GPS receiver (station JOKA) co-located with the tiltmeter showed just over 1 cm of movement to the south-southeast during the period when lava was filling the cracks (Fig. 5), but, due to noise in the time series, motion during individual crack-filling episodes cannot be resolved.

We interpret ground deformation to be indicative of crack opening. Elastic dislocation models (Okada, 1992) can be used to relate the opening geometry (e.g., width and depth) with observed ground deformation. For some geometries, opening cracks do predict displacements away from the crack and tilt towards the crack, consistent with observations. However, although it could not be directly observed due to the difficulty of navigating the thick vegetation, it is likely that the opening of the lava-filled cracks was accommodated in part by the closing of adjacent cracks. Complex structural interactions such as this may pose significant challenges for simple elastic halfspace models, so we do not attempt to quantitatively estimate opening geometry using geodetic observations. Nonetheless, the observations appear generally consistent with filling of ground cracks by lava, possibly causing shallow slivers of rock composing the East Rift Zone in this area to shift.

The progressively lengthening steam trace marking each crack suggests that the cracks were filled by the accumulation of lava below the point where lava entered the crack, forming a gradually growing mound of lava. The slope on the side of the mound probably gradually decreased as the crack was progressively filled. Our observations of the line of steam were made during brief reconnaissance flights every day or two. For this reason, we do not know if the steam trace lengthened continuously or episodically. The tilt measurements (Fig. 5b) indicate that crack 1 opened mostly over the course of around a day, approximately five days after lava entered the crack, and shortly before lava exited the crack. However, the tilt measurements should be treated with caution. It may be that the crack opened gradually throughout the filling period, progressively closing adjacent cracks during the process. Perhaps it was only after all the intervening cracks between crack 1 and the tiltmeter had closed that the tiltmeter began to record movement of the block on which it was located.

Effect on flow path modeling

During 2014, flow-path projections based on the method of Favalli et al. (2005) were used to quickly assess hazards (Brantley et al., 2019). The initial forecast showed the most likely flow paths tracking downslope to the north. These paths became mostly obsolete, however, once the lava flow had been captured by the first ground crack (crack 1), which directed lava across the slope of the land surface. When lava emerged from the northeast end of crack 1, new flow paths were calculated, but these too were negated when lava entered crack 3. This was repeated when lava entered crack 4. It was only when the flow front had traveled beyond crack 5, and no additional cracks were infiltrated, that the paths of steepest descent became valid again in projecting lava flow paths. It is worth noting that some forecasts did follow the trend of the crack system. However, this was due to the presence of a large graben parallel to the crack system but offset about 75 m north.

Figure 6 shows the flow path projections on August 18, 2014, before the flow entered crack 1, and September 3, 2014, after the flow exited crack 4. While the projections are broadly similar, there are important differences. For instance, the September 3 projection shows fewer northerly paths that pass through the Hawaiian Paradise Park housing subdivision. Unlike the September 3 projection, the August 18 projection also shows flow paths that travel toward the south coast of the island, as well as northeast along the rift zone toward Leilani Estates subdivision, before veering north toward Pāhoa. It is important to note that our final flow path projection could only be produced after the lava flow had left the crack system for good—until then, we did not know how far the lava would travel down the East Rift Zone, since the cracks were not mapped. Although the differences between the initial and final flow path projections were subtle in the end, the situation created considerable uncertainty at the time. Varying the lava flow's path by even a few hundred meters can dramatically change the outcome to the people living downslope.

Other examples

Looking through existing literature, we found a few other examples of crack filling and opening, showing that, though rare, it is not unique to the 2014 Pu'u'ō'ō activity. Two examples occurred during the early part of the Mauna Ulu eruption of Kīlauea volcano. First, Jones et al., 2018, showed evidence that ground cracks opened beneath the flow field during the waning stage of episode 1 of the eruption, or possibly shortly after it ended, and lava drained into the crack. The cause of the crack opening is not known, however, and there is no evidence that lava used it as a pathway. A more pertinent example occurred three months later, during August 1969. About 4 hours after the cessation of strong fountaining at Mauna Ulu, lava that had mostly filled the nearby Alae Crater drained abruptly, accompanied by intense ground cracking that extended northeast into the forest beyond the Mauna Ulu flow field, as reported in Swanson et al., 1972 and Swanson et al., 1979. Their observations showed that this was a pre-existing ground crack that widened dramatically during the event. Later that day, lava with a chemical composition like that which had drained from Alae Crater was seen passively oozing from a crack about 7 km northeast of Alae Crater. No seaward displacement of Kīlauea's south flank occurred, ruling that out as the cause of the crack opening (Swanson et al., 1979).

Another example occurred at Kīlauea in 1983 at the start of the Pu'u'ō'ō eruption (Wolfe et al., 1988). For a few days, lava disappeared into a gaping crack, which was subsequently found to have widened 2–3 m. The lava that entered the crack did not reappear at the surface. A third example occurred later in 1983, following the emplacement of lava flows from Pu'u'ō'ō's high fountaining episode 12. A new zone of steaming cracks, parallel to the strike of the East Rift Zone, was discovered beyond the tip of the flow active at that time northeast of the vent (Wolfe et al., 1988). Ground observations found about 1 m of opening perpendicular to the rift zone that appeared to have occurred during flow emplacement. Wolfe et al. (1988) give no interpretation for the formation of the cracks, which extended northeast about 1 km and occurred in the same general area as the 2014 activity we describe. The consensus at the time, however, was that the lava flow had entered and forced open a pre-existing ground crack (C. Heliker, personal comm., 2020).

Finally, on February 1, 1987, during a routine helicopter overflight of the Pu'u'ō'ō flow field, steam was seen rising from a new crack downrift from the Pu'ukia'i cone, 4 km northeast of the active Kupaianaha lava shield (Orr et al., 2018). The 1-km-long crack, which opened in an older flow, slowly widened to about 2 m, and viscous pāhoehoe oozed passively from its lower end, forming a small lava pad. It was thought initially that this activity was the result of a new intrusion (U.S. Geological Survey, unpublished data, 1987)—presumably an offshoot from the dike feeding the Kupaianaha eruption—but the lack of accompanying seismicity and the relatively outgassed condition of the erupting lava argued against this interpretation. It was soon discovered that a lava flow fed from the east flank of Kupaianaha was draining into a large ground crack aligned with, and about 1 km upslope from, the new crack. It became clear then that the lava flow from the Kupaianaha lava shield had traveled underground within this older crack and emerged at a lower elevation. It was uncertain at the time if the crack had widened or if the lava reaching the surface was simply breaking through the older flow where it had bridged the crack. By comparison with the 2014 cracks, we know now that the 1987 crack had likely been forced open by the lava flow.

This process is not limited just to Kīlauea and has been identified in Iceland, where there is also extensive ground cracking. An example from the Krafla volcanic system is described by Einarsson and Brandsdóttir (2021). During an eruption there in July 1980, the erupted lava flowed into an open crack for several hours, causing the crack to widen and extend in both directions and forming a top-fed dike. Opheim and Gudmundsson (1989) also describe ground cracks in the Gjástykki rift valley north of Krafla volcano that passively erupted lava during eruptions in the 1980s, forming small pads of lava. While they suggest that these are primary vents, we wonder if lava from the adjacent flow could have used the cracks as pathways there too. Erupting fissures are normally accompanied by at least some level of fountaining and bubble bursting, while the description of the eruption in this case as being passive matches observations at Kīlauea of lava flows emerging from ground cracks like we describe above. We were unable to find other examples in the literature, although it seems likely that this process may have occurred in other volcanic areas where ground cracks are found.

5. Physical analysis of cracks as lava transport pathways

In this section we investigate some of the key physical processes associated with the capture of lava by a crack and its subsequent transport within the crack. These processes are complex in detail, involving the flow and solidification of a rheologically complex fluid within a poorly constrained (and evolving) geometry. This analysis is not, therefore, intended be a complete physical description of the behavior of the phenomena—rather, it is intended to support us in developing a plausible conceptual model for the behavior of cracks as lava transport pathways: i.e., as top-fed dikes. In the following we take parameter values appropriate for a crack similar to crack 1 unless otherwise stated: crack width $w_0 = 1$ m; crack depth $Z = 200$ m; volume flux of lava $Q = 1$ m^3 s^{-1}; lava density $\rho = 1375$ kg m^{-3} (based on assumed melt density of 2750 kg m^{-3} and 50% vesicularity); lava viscosity $\mu = 100$ Pa s (order of magnitude value for typical Kilauea basalt composition at eruption temperature, using the model of Giordano et al, 2008); and gravitational acceleration $g = 9.81$ m s^{-2}.

Isothermal flow of lava in a crack, neglecting solidification

We begin simply and consider the behaviour of a Newtonian liquid draining into a vertical crack that has planar walls, a v-shaped cross-section, and translational symmetry along strike. We assume that the aspect ratio is very high ($w_0 \ll Z$) such that cross-crack flow is negligible compared with down-crack flow and the walls can locally be approximated as parallel. In this scenario we can apply, locally, the Hagen–Poiseuille equation for flow in a parallel duct:

$$Q = \frac{\rho g w^3 l}{12\mu}, \qquad \text{Eq. 2}$$

where w [m] is the local crack width, and l [m] is the local, along-strike length of the descending flow. We note that Eq. 2 is strictly only valid for flow in which the downward flux per unit length is uniform along strike, which is unlikely to be the case in nature, but it is useful nonetheless to consider behaviour in this idealized case. This simple analysis also assumes incompressible flow at low Reynolds number, and that the lava is in contact with both walls of the crack.

Consideration of Eq. 2 can help us to understand the conditions under which a lava flow advancing towards a crack of width w_0 is likely to be captured by the crack. A typical pahoehoe lobe advancing over new ground has width of order 1 m and height of order 0.1 m, hence it has an aspect ratio of around 10. It is reasonable to suppose that a lobe would be captured easily by a crack if the captured, down-crack flow had an aspect ratio (i.e., l/w_0) that is much smaller than 10. In this case the flow would have to narrow considerably to reach the other side of the crack and avoid complete capture, and it is likely that the flow would form a lava veneer down the closer crack wall – perhaps similar to the scenario in Figure 3. Conversely, if the aspect ratio of the down-crack flow were much larger than 10, the flow would have to widen very considerably to be fully captured. In this case it is likely that only a fraction of the flow would be captured, with the rest advancing over the crack. By setting $w = w_0$ in Eq. 2, and rearranging, we can estimate the aspect ratio of a gravity-driven, down-crack Poiseuille flow as a function of the flux Q of the feeding lava flow.

These scenarios are shown quantitatively in Figure 7, in which Eq. 2 is rearranged to find the crack width at which $l/w_0 = 1, 10$, and 100, for lava flux in the range $0.1 \leq Q \leq 100$ m^3 s^{-1}, and using the standard parameter values given at the start of this section. It can be inferred from Figure 7 that a crack that is a meter or more wide at the surface is very likely to capture a lava flow with a flux typical of the Pāhoa flow (i.e., Q is around 1–2 m^3 s^{-1}); whereas a crack that is only 10 cm wide is unlikely to capture a significant fraction of such a lava flow. Although this analysis assumes constant Newtonian viscosity, we consider it applicable to flow capture and the onset of crack flow, before cooling and solidification become dominant.

We now explore the behaviour of the flow once lava has entered the crack, considering how the along-strike length of the flow varies with depth z in the crack. We assume, for now, isothermal, gravity-driven Poiseuille flow. Noting the geometric relationship $w(z) = w_0(1 - z/Z)$, Eq.2 can be rewritten as:

$$l = \frac{12Q\mu}{\rho g {w_0}^3}\left(1 - \frac{z}{Z}\right)^{-3}. \qquad \text{Eq. 3}$$

Assuming our standard parameter values, we obtain the curve shown in Figure 8.

The dotted blue line shows the depth ($z = 91$ m) at which the length of the flow is equal to the crack width ($l = w = 0.55$ m), indicating that the along-strike length of the flow in the upper part of the crack is much less than the local crack width. Under these conditions it is clear that the assumption of uniform Poiseuille flow is violated; nonetheless, the results suggest that it is likely that the flow would not span the width of the crack on entry but would instead form a narrow rivulet draining down one side. The dashed blue line shows the depth ($z = 139$ m) at which the along-strike length of the flow is ten times greater than the local crack width ($l = 10w = 3.1$ m). It is reasonable to assume that the flow would span the width of the crack by this depth, and it will more nearly satisfy the assumptions that underpin this analysis.

The inverse third-power dependence of flow length on local crack width manifests as a dramatic lengthening of the flow along-strike in the bottom half of the crack. This supports the intuitive inference that lateral flow must start to dominate over vertical flow once the lava reaches a certain depth in the crack. This lateral spreading also greatly increases the area of the flow that is in contact with the relatively cool crack walls, promoting cooling and solidification. Accumulation of solidified lava will likely begin directly beneath the entry point, pushing lava that enters later to flow progressively more laterally. As cooling and solidification come to dominate the flow geometry, the assumptions that underpin Eqs. 2 and 3 become increasingly violated. To progress further, we must explicitly account for solidification.

Flow and solidification of lava in a crack

The thermo-rheological evolution of magma flowing in a crack has been addressed by several workers, both theoretically (Delaney and Pollard, 1982; Bruce and Huppert, 1989; Lister and Dellar, 1996; Fialko and Rubin, 1998) and experimentally (Chanceaux and Menand, 2014; Pansino et al, 2019). In all cases the geometry of interest was a dike or sill, rather than a top-fed crack, but the salient elements of the problem are the same. Fialko and Rubin (1998) consider the lateral flow of magma in a dike, which is directly analogous to the lateral flow of lava in a top-fed crack, and we follow their approach to analyze this scenario.

The emplacement/solidification problem is controlled by two dimensionless parameters: the dimensionless solidification temperature Θ; and the Stefan number S (Bruce and Huppert, 1989; Lister and Dellar 1996; Fialko and Rubin, 1998; Pansino et al. 2019):

$$\Theta = \frac{T_s - T_\infty}{T_0 - T_\infty}\ , \quad \mathrm{S} = \frac{L_h}{C(T_0 - T_\infty)}\,, \qquad \text{Eq. 4a,b}$$

where T_s, T_0, and T_∞ [K] are, respectively, the solidification temperature of the magma, the initial temperature of the magma on entering the crack, and the temperature of the country rock, L_h [J kg^{-1}] is the latent heat of crystallization of the magma, and C [J kg^{-1} K^{-1}] is the specific heat capacity of the magma.

Fialko and Rubin (1998) consider two different scenarios. In the first, the lateral flow of magma is driven by a constant pressure difference between the ends of the flow; in the second, the flow is driven by the downward slope of the flow. They determine the thermal entry length x_t [m], which is the distance that magma will travel along a crack before it solidifies completely:

$$\begin{aligned} &\text{pressure-driven flow} \quad x_t = \psi \frac{w^2}{4}\left(\frac{\Delta P}{\kappa\mu}\right)^{\frac{1}{2}} \\ &\text{slope-driven flow} \quad x_t = \psi \frac{w^4 \rho g \sin\alpha}{64\kappa\mu} \end{aligned} \qquad \text{Eq. 5a,b}$$

where ΔP is the pressure difference between the head and toe of the flow (i.e., the pressure driving the flow), κ [m^2 s^{-1}] is the thermal diffusivity, and α is the angle of the flow direction from horizontal. The scaling factor ψ accounts for the specific thermal conditions of the flow and is a function of Θ and S; it must be computed numerically. We determine relevant values for ψ by reading from the $\psi(\Theta, S)$ plots presented in Figure 7 of Fialko and Rubin (1998). We take typical parameter values for basaltic lava $T_s =$ 1070 °C (Hardee, 1980), $T_0 = 1140$ °C, and $T_\infty = 20$ °C, and $\kappa = 10^{-6}$ m^2 s^{-1}, $L_h = 5 \times 10^5$ J kg^{-1}, $C = 1000$ J kg^{-1} K^{-1}, following Fialko and Rubin (1998), giving $\Theta = 0.94$ and $\mathrm{S} = 0.45$. These values correspond to ψ =0.30 for pressure-driven flow, and ψ =0.052 for slope-driven flow.

We assume that, for pressure-driven flow, $\Delta P = \rho g z$ where z is the depth to the lateral flow; this assumes that the lava transport system within the crack, feeding the propagating flow front, is pressure-tight. We assume that, for slope-driven flow, $\alpha = 1.4°$ (based on the geometry of crack 1). Using the $w(z)$ relationship given earlier, equations 5a,b, and the appropriate values for ψ, we can determine the thermal entry length x_t for pressure-driven and slope-driven flows of lava as a function of depth in the crack. Figure 9 shows $x_t(z)$ for w_0 of 1 and 5 m for both flow scenarios. Flows that have both a pressure-driven and a slope-driven component fall between these two end-members.

The results show that the thermal entry length of pressure-driven flows (blue lines) is a non-monotonic function of depth: in the upper crack, entry length is short because the driving pressure head is small; near the base of the crack, entry length is short because the crack width is very narrow; and at intermediate depths, the entry length is maximal. By contrast, the thermal entry length for slope-driven flows is a monotonic function of depth: it is always shorter for flows that are deeper in the crack, where the crack is narrower.

Crack 1 transported lava 1,600 m laterally—this distance is plotted as a vertical dotted line in Figure 9. Horizontal dotted lines show the depths at which the thermal entry length is equal to this distance for each scenario investigated. For crack width $w_0 = 1$ m (i.e., the inferred starting width of crack 1) a pressure-driven flow would have to be shallower than 118 m to transport lava 1,600 m without solidifying completely (local $w = 0.41$ m); whereas a slope-driven flow would have to be shallower than 76 m (local $w = 0.62$ m). For crack width $w_0 = 5$ m (i.e the inferred final width of crack 1) a pressure-driven flow would have to be shallower than 185 m to transport lava 1,600 m without solidifying completely (local $w = 0.37$ m); whereas a slope-driven flow would have to be shallower than 175 m (local $w = 0.62$ m)—note that this critical crack width is independent of depth for slope-driven flow.

The mean flow velocity can be estimated as $\overline{u_x} = w^2 \Delta P / 12 \mu x$ for pressure-driven flow (where x is the length of the flow along-strike) and as $\overline{u_x} = w^2 \rho g \sin(\alpha) / 12 \mu$ for slope-driven flow (Fialko and Rubin, 1998). Using these expressions, we can estimate the vertical extent of the lateral flow as $H = Q / \overline{u_x} w$; in all scenarios investigated for crack 1 in the previous paragraph, $H > 10w$, indicating that the flow geometry is consistent with the assumptions of Fialko and Rubin (1998).

Conceptual model based on analysis

The simple physical analysis presented in this section provides additional insight into the capture and transport of lava in cracks. Here we use this insight, along with field observations, to propose a conceptual model for these processes during the Pāhoa flow.

The front of the Pāhoa flow propagated via repeated cycles of inflation and breakout of lava lobes and toes that were a few decimeters up to a meter or two across. Since multiple lobes and toes were active at the same time, any single lobe carried only a small fraction of the 1–2 $m^3 s^{-1}$ total flux of the whole flow. Inspecting Figure 7, we can see that a propagating lobe carrying a tenth of the total flux would likely be captured by a crack wider than 20–30 cm. Capture of the entire flow would either require all the lobes to be captured by the crack, or for flow to localize onto a captured lobe. Either way, it seems unlikely that a crack narrower than around 50 cm would have been able to capture the whole of the Pāhoa flow. This is consistent with the field evidence that, whilst small cracks < 50 cm wide are common in the area of interest, the Pāhoa flow was only captured fully by three of the larger cracks.

A 1-m-wide crack—such as crack 1—would easily be able to capture the whole flux of the Pāhoa flow. On entering a crack of this width, the lava would likely flow initially as a rivulet down one wall, until it reached a depth at which the crack narrowed sufficiently for the flow to be confined by both walls. This depth might be as much as 100 m (Figure 8), although accumulation of solidified rivulet lava against the crack wall could effectively narrow the crack, causing this confinement to occur nearer the surface. Once confined, the vanguard lava of a captured flow would likely cool rapidly against the crack wall, particularly once it reached a depth at which its along-strike length had to increase rapidly to accommodate the flux (Fig. 8). This cooling would be enhanced by the interaction with water evidenced by steam produced above the cracks transporting lava.

The cooling effects on first entry of the lava into the crack are not well captured by the physical analysis presented here, but it is intuitive to assume that accumulation of solidified lava would begin directly under the entry point, and that solidification would propagate laterally as the flow system developed. We expect, therefore, that lava entering the crack after the vanguard lava would flow down the sloping upper surface of the solidified mass of earlier lava, and that the slope would shallow progressively over time. The morphology of the flow would depend on the width of the crack (and therefore on depth in the crack) and the thermal maturity of the system locally. Where the solidified surface is shallow, and the crack wide (consider the eventual 5-m width of crack 1), the flow could progress in a manner similar to a channelized surface flow. Where the lava has penetrated deep into the crack, it may adopt a morphology more like a localized channel within a dike. Two potential scenarios for the evolving geometry of the flow are presented in cartoon form in Figure 10.

Analysis of the thermal entry length indicates that a 200-m-deep crack that is 1–5 m wide should easily be able to transport lava more than 1 km laterally without the lava freezing (Fig. 9). The analysis shows that there is a wide range of depths over which the transport length could greatly exceed 1 km, particularly for the case of a 5-m-wide crack, suggesting that this finding is robust even if some of the assumptions that underpin the Fialko and Rubin (1998) analysis are not completely met. In fact, the great depth at which lava could be transported along a 5-m-wide crack suggests that it might only be able to escape from the crack when there is substantial along-strike narrowing. In this case, it is interesting to speculate on how the lava might climb out of the crack, and two scenarios present themselves:

1) On encountering a narrowing of the crack along-strike, enhanced solidification of the lava at the head of the flow could cause progressive pressurization of the transport system. If the transport were sufficiently well developed to be able to sustain overpressure, this could drive the distal lava upwards. Repeated breakouts at the distal end could build a 'conduit' within the crack, eventually allowing the lava to exit the crack. The geometry of the mature transport system would then resemble a sump pipe, connecting the lava entry and exit points via a pressure-tight flow path that reached deep within the crack (Figure 10a).

2) Solidification of the lava at the head of the flow and consequent pressurization of the more proximal lava transport system could, instead, induce repeated breakouts upstream. These would progressively fill the crack such that the transport depth of the lava could eventually become sufficiently shallow for the lava to overflow the crack at the lower, distal end (Figure 10b).

In the field, the upper surface of the lava transport system was sometimes visible at points along the crack, both to the naked eye, and via thermal camera. Furthermore, crack 4 fed several small lava pads along its length, which all emerged at around the same time This suggests that scenario 2, in which the crack is substantially filled along its length, is more likely, at least for some of the cracks. We also note that pressurization of the transport system, as envisaged in scenario 1, could be implicated in opening the cracks, as observed in the field.

6. Conclusions

In this paper, we described how the 2014 Pāhoa lava flow took advantage of pre-existing ground cracks, forming top-fed dikes and using the cracks as pathways to transport lava downslope. A summary of our findings is as follows:

- Pre-existing ground cracks on Kīlauea's East Rift Zone captured the 2014 Pāhoa lava flow and transported it across the topographic grain of the landscape. This posed significant challenges for flow path projections since the path of the flow, once it was captured by the cracks, was no longer controlled by surface slope.
- The lava that filled the cracks acted as a wedge, driving the cracks open and widening them by up to several meters. This opening, which was also recorded by a nearby GPS station and tiltmeter, was probably accommodated by the closing of adjacent cracks and caused the shifting of large slivers of rock that compose the shallow flank of the volcano in that area.
- This process is not unique, having been identified at Kīlauea during the Puʻuʻōʻō eruption in 1983 and 1987 and during the Mauna Ulu eruption in 1969, and at Krafla in Iceland during eruptions in the 1980s.
- Physical analysis of flow and solidification of lava in a top-fed dike suggests that cracks that are as little as 50 cm wide are sufficient to capture a potentially hazardous lava flow, and to divert it by many hundreds of meters.

Recognizing the potential influence of ground cracks will be important when forecasting flow paths for future eruptions in Kīlauea's East Rift Zone, and at other volcanoes where ground cracks are prevalent. While high-resolution, vegetation-free topographic models might pinpoint the locations of cracks, the transport of lava within those cracks, and their forced opening when being filled, renders those topographic models obsolete. Therefore, frequent observations of the advancing flow and the flexibility to rapidly recalculate flow paths are still necessary for accurate and timely hazard assessments. The physical analysis we present might help with the assessment of the potential for transport of lava in cracks in anticipation of, and during, future eruptions.

References

Brantley SR, Kauahikaua JP, Babb JL, Orr TR, Patrick MR, Poland MP, Trusdell FA, Oliveira D, Garcia MO, Camp VE, Grunder A (2019) Communication strategy of the U.S. Geological Survey Hawaiian Volcano Observatory during the lava-flow crisis of 2014–2015, Kīlauea Volcano, Hawai‘i. In: Poland MP, Garcia MO, Camp VE, Grunder A (eds) Field Volcanology: A Tribute to the Distinguished Career of Don Swanson. Geol Soc Am Bull Special Paper 588:351–373. https://doi.org/10.1130/2018.2538(16)

Bruce PM, Huppert HE (1989) Thermal control of basaltic fissure eruptions. Nature 342(6250):665–667. https://doi.org/10.1038/342665a0

Chanceaux L, Menand T (2014) Solidification effects on sill formation: An experimental approach. Earth Planet Sci Lett 403:79–88. https://doi.org/10.1016/j.epsl.2014.06.018

Delaney PT, Pollard DD (1982) Solidification of basaltic magma during flow in a dike. Am J Sci 282(6):856–885. https://doi.org/10.2475/ajs.282.6.856

Delaney PT, Miklius A, Arnadottir T, Okamura AT, Sako MK (1993) Motion of Kilauea Volcano during sustained eruption from the Puu Oo and Kupaianaha Vents, 1983–1991. J Geophys Res Solid Earth 98(B10):17801–17820. https://doi.org/10.1029/93JB01819

Einarsson P, Brandsdóttir B (2021) Seismicity of the Northern Volcanic Zone of Iceland. Front Earth Sci 9. https://doi.org/10.3389/feart.2021.628967

Favalli M, Pareschi MT, Neri A, Isola I (2005) Forecasting lava flow paths by a stochastic approach. Geophys Res Lett 32(3):L03305. https://doi.org/10.1029/2004GL021718

Fialko YA, Rubin AM (1998) Thermodynamics of lateral dike propagation: Implications for crustal accretion at slow spreading mid-ocean ridges. J Geophys Res Solid Earth 103(B2):2501–2514. https://doi.org/10.1029/97JB03105

Giordano, D., Russell, J.K. and Dingwell, D.B., 2008. Viscosity of magmatic liquids: a model. Earth Plan Sci Lett, 271(1-4), pp.123-134.

Gudmundsson A (1987a) Tectonics of the Thingvellir fissure swarm, SW Iceland. J Struct Geol 9(1):61–69. https://doi.org/10.1016/0191-8141(87)90044-7

Gudmundsson A (1987) Geometry, formation and development of tectonic fractures on the Reykjanes Peninsula, southwest Iceland. Tectonophysics 139(3):295–308. https://doi.org/10.1016/0040-1951(87)90103-X

Jones TJ, Houghton BF, Llewellin EW, Parcheta CE, Höltgen L (2018) Spatter matters—distinguishing primary (eruptive) and secondary (non-eruptive) spatter deposits. Sci Rep 8(1):9179. https://doi.org/10.1038/s41598-018-27065-1

Hardee, H.C., 1980. Solidification in Kilauea Iki lava lake. J Volcanol Geotherm Res, 7(3-4), pp.211-223.

Heliker C, Mattox TN (2003) The first two decades of the Pu‘u ‘Ō‘ō-Kūpaianaha eruption; chronology and selected bibliography. In: Heliker C, Swanson DA, Takahashi TJ (eds) The Pu‘u ‘Ō‘ō-

Kupaianaha Eruption of Kilauea Volcano, Hawaii—The First 20 Years. US Geol Surv Prof Pap 1676. pp 1–27. https://doi.org/10.3133/pp1676

Lister JR, Dellar PJ (1996) Solidification of pressure-driven flow in a finite rigid channel with application to volcanic eruptions. J Fluid Mech 323:267–283. https://doi.org/10.1017/S0022112096000912

Okada Y (1992) Internal deformation due to shear and tensile faults in a half-space. Bull Seismol Soc Am 82(2):1018–1040. https://doi.org/10.1785/BSSA0820021018

Neal CA, Brantley SR, Antolik L, Babb JL, Burgess M, Calles K, Cappos M, Chang JC, Conway S, Desmither L, Dotray P, Elias T, Fukunaga P, Fuke S, Johanson IA, Kamibayashi K, Kauahikaua J, Lee RL, Pekalib S, Miklius A, Million W, Moniz CJ, Nadeau PA, Okubo P, Parcheta C, Patrick MR, Shiro B, Swanson DA, Tollett W, Trusdell F, Younger EF, Zoeller MH, Montgomery-Brown EK, Anderson KR, Poland MP, Ball JL, Bard J, Coombs M, Dietterich HR, Kern C, Thelen WA, Cervelli PF, Orr T, Houghton BF, Gansecki C, Hazlett R, Lundgren P, Diefenbach AK, Lerner AH, Waite G, Kelly P, Clor L, Werner C, Mulliken K, Fisher G, Damby D (2019) The 2018 rift eruption and summit collapse of Kīlauea Volcano: Science 363(6425):367–374. https://doi.org/10.1126/science.aav7046

Opheim JA, Gudmundsson A (1989) Formation and geometry of fractures, and related volcanism, of the Krafla fissure swarm, northeast Iceland: Geol Soc Am Bull 101(12):1608–1622. https://doi.org/10.1130/0016-7606(1989)101<1608:FAGOFA>2.3.CO;2

Orr TR, Poland MP, Patrick MR, Thelen WA, Sutton AJ, Elias, T, Thornber CR, Parcheta C, Wooten KM (2015) Kīlauea's 5–9 March 2011 Kamoamoa Fissure Eruption and Its Relation to 30+ Years of Activity from Puʻu ʻŌ ʻō. In: Carey R, Poland M, Cayol V, Weis D (eds) Hawaiian Volcanism: From Source to Surface. Wiley, New Jersey, Am Geophys Union Geophys Monogr 208: pp 393–420. https://doi.org/10.1002/9781118872079.ch18

Orr TR, Ulrich GE, Heliker C, DeSmither LG, Hoffmann JP (2018) The Puʻu ʻŌʻō eruption of Kīlauea Volcano, Hawaiʻi—Episode 21 through early episode 48, June 1984–April 1987. US Geol Surv Sci Invest Rep 2018-5109. https://doi.org/10.3133/sir20185109

Pansino S, Emadzadeh A, Taisne B (2019) Dike Channelization and Solidification: Time Scale Controls on the Geometry and Placement of Magma Migration Pathways. J Geophys Res Solid Earth 124(9):9580–9599. https://doi.org/10.1029/2019JB018191

Patrick M, Orr T, Fisher G, Trusdell F, Kauahikaua J (2017) Thermal mapping of a pāhoehoe lava flow, Kīlauea Volcano. J Volcanol Geotherm Res 332:71–87. https://doi.org/10.1016/j.jvolgeores.2016.12.007

Poland M, Orr T, Kauahikaua J, Brantley S, Babb J, Patrick M, Neal C, Anderson K, Antolik L, Burgess M, Elias T, Fuke S, Fukunaga P, Johanson I, Kagimoto M, Kamibayashi K, Lee L, Miklius A, Million W, Moniz C, Okubo P, Sutton A, Takahashi T, Thelen W, Tollett W, Trusdell F (2016) The 2014–2015 Pāhoa lava flow crisis at Kīlauea Volcano, Hawaiʻi: Disaster avoided and lessons learned. GSA Today 26(2):4–10. https://doi.org/10.1130/GSATG262A.1

Sorey ML, Colvard EM (1994) Potential effects of the Hawaii Geothermal Project on ground-water resources on the Island of Hawaii. US Geol Surv Water Resour Invest Rep 94-4028. https://doi.org/10.3133/wri944028

Wolfe EW, Neal CA, Banks NG, Duggan TJ (1988) Geologic observations and chronology of eruptive events. In: Wolfe EW (ed) The Puu Oo eruption of Kilauea Volcano, Hawaii; episodes 1 through 20, January 3, 1983, through June 8, 1984: US Geol Surv Prof Pap 1463: pp 1–97. https://doi.org/10.3133/pp146

Figure Captions

Fig. 1 Map showing Kīlauea's Pāhoa flow (blue outline) and East Rift Zone ground cracks (yellow) discussed in text as of March 13, 2015. White dot marks JKA tiltmeter co-located with JOKA GPS receiver; W is True Mid-Pacific geothermal exploration well site. Base image © 2016 DigitalGlobe NextView License. (Inset) Island of Hawai‘i, showing map area

Fig. 2 **a** Aerial view looking northeast showing steam marking the trace of crack 1. Bluish fume indicates where lava empties from the nascent lava tube into the crack. USGS photograph by T. Orr, August 22, 2014. **b** Aerial view looking southwest at ground cracks occupied by lava and lava pads connecting cracks. Smoke marks flow front advancing north. Crack 6 too distant to show effectively. White dot is location of JKA tiltmeter and JOKA GPS receiver; W is True Mid-Pacific geothermal exploration well site. USGS photograph by T. Orr, September 6, 2014. **c** Aerial view looking northeast at skylight above the point where lava traveling through the nascent lava tube flowed into a pre-existing ground crack. The line of steam in the forest beyond marks the trace of the ground crack. USGS photograph by T. Orr, August 22, 2014

Fig. 3 **a**, **b** Aerial views of lava entering crack 4. Note lava veneer attached to the crack wall, showing emplacement in a narrower crack. Piercing points on the fresh lava surface along the crack and blocks from the edge of the new flow that had fallen deeper into the crack were also visible. USGS photograph by T. Orr, September 1, 2014

Fig. 4 **a** Northeast end of ~5-m-wide crack 1. Wads of forest floor duff attached to the roots of trees growing in the crack show original crack width to be ~1 m. USGS photograph by T. Orr, July 22, 2015. **b** Southwest end of ~1-m-wide crack 4, invaded by a later flow. USGS photograph by T. Orr, March 26, 2015

Fig. 5 **a** Graph showing GPS time series at station JOKA for period from late June to late October, 2014. **b** Graph showing tilt time series at station JKA for period from August 19 to September 1, 2014. Black bars indicate approximate timing of the filling of cracks 1–3. **c** Map showing evolution of tilt with time (colored dots) and net GPS ground movement vector over the period bounded by the gray bars in a and b

Fig. 6 Results of stochastic flow projections with the model starting point at the flow front on **a** August 18 compared to **b** September 3, showing a subtle shift in projections before and after the flow front entered the crack system. Ground cracks discussed in the text are shown with black lines

Fig. 7 The crack width at which the along-strike length l of a descending flow is $1, 10,$ and 100 times the crack width w_0, over a range of values of lava flux Q. For crack width $w_0 \gtrsim l$ it is very likely that a flow will be fully captured by a crack; for crack width $w_0 \ll l$ it is unlikely a flow would be fully captured

Fig. 8 Crack width w and along-strike length l of descending lava as functions of depth z in the crack. Origin of the x-axis is referenced to the centerline of the crack for w (black lines), and the center of the descending flow for l (red lines); note that the x-axis represents orthogonal directions for these two variables. Blue dotted and blue dashed lines represent depths $z = 91$ m and $z = 139$ m, at which $l = w$ and $l = 10w$ respectively

Fig. 9 Thermal entry length of lateral flow of lava at different depths within a top-filled crack, for pressure- and slope-driven flows, shown by blue and red curves respectively. Results are shown for crack width at the surface of 1 m and 5 m. Horizontal dotted lines show the depths below which the different flows would freeze before transporting lava 1,600 m (vertical dotted line), which is the distance lava was transported northeast within crack 1

Fig. 10 Conceptual models for transport in a top-fed dike—see main text for further details. Oldest solidified lava is shown in darkest grey; actively flowing lava is shown in orange. A) Scenario 1: lava flows into the crack and solidifies at depth; successive flows propagate further along the crack, at a shallower depth, until a stable transport system develops. At the distal end of the crack, successive breakouts and overflows build a ‘conduit’ that allows lava to escape the crack. B) Scenario 2: similar to scenario 1 at first, but repeated breakouts fill the crack until the transport system is shallow enough for lava to escape the crack