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VARIATION IN BREAKOUT MECHANISMS IN
EXPERIMENTAL PAHOEHOE FLOWS

KELSA A. WARNER, The University of the South
Research Advisor: Donald B. Potter, Jr.

INTRODUCTION

Basaltic pahoehoe flows grow by a number of emplacement mechanisms including channelized flows and non-channelized sheets (Hon et al., 1994; Peterson et al., 1994). The term “sheet flow” was adopted by Hon et al. (1994) to describe subaerial lava flows with smooth, relatively low-relief upper surfaces. Channelized flows often expand by the breakout of molten lava through a rigid crust of solidified material, and breakouts are the primary method of flow expansion in sheet flows (Hon et al., 1994; Peterson et al., 1994; Blake and Bruno, 2000; Hamilton et al., 2013). Peterson et al. (1994) describe pahoehoe lobe extension, in which the molten interior of an unconfined flow bifurcates into branches to feed new lobes at the margin of the flow, as the process by which pahoehoe sheet flows form. The final form of a pahoehoe flow depends on the substrate topography, the effusion rate, the eruption duration, and the slope (Hon et al., 1994).

Slope, coupled with eruption rate and duration, plays a major role in whether a pahoehoe flow will become channelized or not (Peterson et al., 1994; Hon et al., 1994). On subhorizontal surfaces, microtopography (tens of centimeters relief) can have a strong effect on the initial emplacement of lava flows that can later inflate to reach thickness of several meters (Hon et al., 1994; Hamilton et al., 2013). These variables control the overall morphology of lava fields because they determine if and where breakouts will occur.

The object of this study is to closely examine breakouts in pahoehoe flows and to define the mechanisms (overinflation, exploitation of weak spots in developing crust) by which they occur by conducting large-scale (approximately 90-kg) lava flow experiments. A further aim is to determine if knowledge of substrate slope and microtopography can allow for the prediction of likely breakout sites. Lava flows regularly threaten lives and property in volcanically active locations such as Iceland and Hawaii (Lockwood and Hazlett, 2010). The ability to predict breakouts and, by extension, the advance of a lava flow, could allow for proactive hazard control.

METHODS

Experiments for this study were conducted at the Syracuse University Lava Project’s (http://lava-dev.syr.edu/) facilities on the SU campus. For each lava flow experiment, basaltic material was melted at >1300°C in a large, gas-fired tilt furnace that could hold up to 360 kg of molten lava. For each of the two pours in this study, approximately 90 kg of molten material was extruded onto a sand substrate modified specifically to explore the effect of microtopography on the flow at a given slope angle. Minor topography was created by partially burying six metal barriers at an angle in the sand so they created relief that was approximately 1 cm high along the slope’s centerline and 7 cm high at the pour slope’s flanks (Fig. 1 and 2). Barriers were placed 20-cm apart and on alternating sides of the centerline. They trended downslope at a rake of 30° from the strike of the inclined plane. The pour design was nearly identical for the two pours except for the slope of the sand surface (Pour 1 at 10’ and Pour 2 at 15°). The only other difference was the method of lava delivery to the sand. In the first pour, the lava delivery trough was positioned approximately 32 cm above the sand so that the lava fell vertically.
before flowing down the slope (Fig. 1). In the second pour, the trough rested on the sand so the lava flowed directly down the slope from the trough (Fig. 2).

Pour 1 flowed over the first barrier but was halted by the second barrier. A plastic crust began to form at this point and allowed inflation to begin. After 31 sec, the flow reached its maximum length of 80 cm. Cooling, strengthening, and significant inflation of the crust followed for an additional 1 min 46 sec until a breakout occurred in the flank above the barrier on the right when viewed head-on (Fig. 3b). This breakout initially appeared as three individual adjacent bulges of molten material that flowed from beneath the uplifted crustal edge (Fig. 3c). The bulges quickly coalesced and then lava flowed in a thin, broad lobe along and then around the end of the barrier (Fig. 3).

RESULTS/OBSERVATIONS

Although breakouts were achieved in both Pours 1 and 2, there were significant differences between the two, primarily in flow style, breakout mechanics, and final flow morphology. The material from Pour 1 traveled at a rate of 6.5 cm s\(^{-1}\) through the trough then fell approximately 32 cm from the trough, which temporarily halted its downslope velocity (time 0 when lava reached sand). The lava puddled in place and then, after first spreading laterally in all directions, flowed downslope at a rate of 3 cm s\(^{-1}\). In contrast, the lava from Pour 2 traveled at a rate of 6 cm s\(^{-1}\) through the trough and then flowed directly onto the sand (time 0 when lava reached sand). Although the lava in Pour 2 did spread laterally to a maximum width of 60 cm, downslope motion was dominant at an initial rate of 3.8 cm s\(^{-1}\) and an average rate of 1.4 cm s\(^{-1}\).

The pours were analyzed primarily by the careful study of video footage. One video camera, mounted on a tripod at the bottom of the slope, captured a ground view of the pour upslope. A second video camera, handheld on a scaffold above the pour, captured overhead footage. Continuous video footage was also captured with a handheld FLIR thermal imaging camera and digital images were taken throughout the pours. Sketches of the pours were made on-site. Videos, photographs, and sketches were used to closely examine breakout mechanisms as well as to approximate flow dimensions, rates, and temperatures.
3d). Sand was visible on the top of the breakout lobe directly adjacent to the main flow body.

Figure 3. Breakout sequence in Pour 1 (10° slope). A) 1:53 sec after flowing onto sand, flow has crusted over and is inflating. B) 24 seconds later, the rigid crust is pushed up by internal pressure on right flank above barrier. C) 6 seconds later the molten lava has begun to flow in three bulges from beneath the crust. D) 7 seconds later bulges have coalesced and breakout flows out and around obstacle. Note the sand (arrow) on top of the flow at the breakout location. Also note the convex toe of the main flow compared to the more planar crust on the flank. Scale bar in decimeter increments.

Terminal breakout inflated from a thickness of a few cm to a final thickness of 13 cm (Fig. 5b). Lift caused by inflation of the terminal breakout revealed sand adhering to the lower portion of the toe (Fig. 5b). The final longitudinal profile of Pour 2 showed a significant thickening towards the toe. Where it exited the trough, the flow was 4 cm thick after complete solidification. It was 6 cm thick at the first barrier, 9 cm thick at the second barrier, 11 cm thick right before the third barrier, and 20 cm thick before the fourth barrier (Fig. 2b). The maximum width of the flow was 60 cm at the first barrier.

Figure 5. Terminal breakout in Pour 2 (15° slope). Overhead view (A) shows smooth inflated surface of breakout compared to ropey surface of main flow. The breakout is 23 cm long and begins at the right hand obstacle. Side view (B) shows sandy lower portion of breakout that formed as a basal crust beneath the flow before the toe was inflated. Pencil in A and B is 11.5 cm long.
DISCUSSION

The advantage of conducting experimental pours is that they allow for the study of lava flows in a controlled environment. Natural lava flows are difficult and dangerous to study during eruption and detailed flow sequences are difficult to recreate after the flow has been emplaced. This study focuses on flow morphology and requires the accurate reproduction of a sequence of events leading to a final morphology. In this study, the primary drawback was the difficulty with scaling in both time and space. The experiments were limited by the amount of melted material. Valuable data would certainly have come from the observation of subsequent breakouts that would likely have occurred if more material had been available.

These experiments produced two markedly different types of breakouts. The breakout in Pour 1 on the 10° slope only occurred after an extended period of crustal cooling and inflation. It progressed by uplift of the inflated flow’s flank behind the confining barrier. In contrast, on the 15° slope of Pour 2 the terminal breakout as well as the flank buds exploited weak points in the crust and began to grow even before the main flow stopped moving downslope. Observations suggest that variable breakout mechanisms exist that can change based on the rate of delivery to the flow margins as well as the rate of cooling and crust strengthening.

In these two pours, effusion rate was approximately the same, so variation in velocity can be attributed to slope and the method of delivery of molten material to the sand. In Pour 1, the combination of vertical delivery and the decreased slope meant that lava flowed more slowly away from its origin. In Pour 2, significant velocity was maintained from the trough onto the sand and this, combined with a greater slope angle, resulted in a higher rate of downslope movement. According to Hamilton et al. (2013), pahoehoe toes cool first through radiation and then through conduction. As temperature decreases, a crust thickens by accretion to its inner surface as heat is conducted away through the outer surface (Peterson et al., 1994). This crust behaves plastically at first but after it reaches a certain thickness, it becomes more rigid (Hon et al., 1994). Inflation occurred while the crust was still behaving plastically because the crust deformed but did not break in response to internal pressure. The crustal weaknesses in Pour 2 formed by plastic deformation of the crust in response to external shear stress.

In contrast, the breakout in Pour 1 appears to have occurred when the crust became too rigid to continue to accept the input of new material through inflation. Assuming that hydrostatic pressure was distributed evenly throughout the liquid core (Hon et al., 1994), the location of the breakout can likely be attributed to the shape of the crustal margins at the sand interface. The crust at the toe of the flow was convex where it met the sand in contrast to the more planar, angled crustal profile on the flank above the barrier (Fig. 3). Thus, when the crust became too rigid to inflate further, pressure forced the molten material between the flank crust and the sand substrate, lifting it, and removing the confining pressure along that flank. Apparently, the sand on top of the breakout originated from beneath the crustal margin and was scraped from the base of the primary flow. The breakout in Pour 1 flowed perpendicular to the 10° slope, a manifestation of the control that the adjacent obstacle exerted.

In Pour 2, a skin began to form early on; however, gravity overcame the incipient crust’s strength and the flow rolled over the skin at the toe and, to a lesser degree, at the flanks. This dragging of the crust beneath the flow appears to have caused the weak spots in the crust along the flow margins. Hot spots in FLIR images suggest that the stretching/shearing was exacerbated when the crustal material crossed the barriers. As the flow neared its final length and the skin thickened, the weak spots at the margin were exploited by the gravity-driven liquid interior of the flow. Of the three weak spots, the terminal one quickly became the dominant outlet for the lava, and growth of the flank buds stopped. When the strength of the breakout’s crust became great enough to confine the flow, significant inflation occurred, particularly in the lower third of the flow. Inflation was focused at the farthest extent of the flow as gravity-driven material from the upper part of the flow drained to the bottom.

Inflation in the terminal breakout of Pour 2 was of special interest (Fig. 5). The skin of the breakout demonstrated a remarkable combination of strength and plasticity. It was strong enough to confine the still-
molten flow, but plastic enough to deform and inflate significantly (approximately 10 vertical cm). The shape of the inflated toe suggests that as a crust was forming on the surface of the flow, a similar crust was forming beneath the flow. Sand on the upturned edge of the inflated toe distinguishes the crust that formed beneath the flow before inflation caused it to deform into a convex shape. Despite the marked increase in volume at the first breakout, a subsequent breakout did not occur.

This study demonstrates that breakouts in pahoehoe flows can occur by a variety of mechanisms, including 1) the over-inflation of a pahoehoe toe that had developed a rigid crust and 2) the development of weaknesses by stretching and shearing in a young, mobile crust and subsequent exploitation of those weaknesses by the still molten interior material. Both slope and microtopography affected the formation of breakouts. On the shallower slope (10°), the transverse obstacles quickly reduced the rate of flow and allowed for crust formation and inflation. This eventually led to a breakout upslope of the topographical barrier. On the steeper slope (15°), the microtopography did not notably impede the flow. As the lava encountered the obstacles, weaknesses caused by uneven stretching developed in overlying incipient crust. Although weaknesses on either flank did not evolve beyond buds, the leading weakness eventually developed into a proper breakout.

CONCLUSIONS

This limited study allows for some general statements concerning pahoehoe flow expansion. 1) The concept of a pahoehoe sheet expanding by rupture at one or more locations along the front of an inflated lobe (Hon et al., 1994; Peterson et al., 1994) is accurate but can be expanded. “Rupture” may occur by at least two different mechanisms: a) inflation and crustal uplift or b) exploitation of crustal weaknesses at the edge of an advancing lobe. 2) Microtopography can create weaknesses in the crust that may preferentially lead to breakouts. 3) Microtopography can impede the forward motion of flowing lava for long enough that a confining crust develops and 4) microtopography may reduce the effect of local slope and direct a breakout along strike. Although this project was not extensive enough to advance specific criteria for predicting breakouts, its results suggest that a larger study with similar goals may have more success.

REFERENCES


