PROCEEDINGS OF THE TWENTY-EIGHTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2015
Union College, Schenectady, NY

Dr. Robert J. Varga, Editor
Director, Keck Geology Consortium
Pomona College

Dr. Holli Frey
Symposium Convener
Union College

Carol Morgan
Keck Geology Consortium Administrative Assistant

Christina Kelly
Symposium Proceedings Layout & Design
Office of Communication & Marketing
Scripps College

Keck Geology Consortium
Geology Department, Pomona College
185 E. 6th St., Claremont, CA 91711
(909) 607-0651, keckgeology@pomona.edu, keckgeology.org

ISSN# 1528-7491

The Consortium Colleges The National Science Foundation ExxonMobil Corporation

KECK GEOLOGY CONSORTIUM
PROCEEDINGS OF THE TWENTY-EIGHTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

ISSN# 1528-7491

April 2015

Robert J. Varga
Editor and Keck Director
Pomona College

Keck Geology Consortium
Pomona College
185 E 6th St., Claremont, CA
91711

Christina Kelly
Proceedings Layout & Design
Scripps College

Keck Geology Consortium Member Institutions:
Amherst College, Beloit College, Carleton College, Colgate University, The College of Wooster, The Colorado College, Franklin & Marshall College, Macalester College, Mt Holyoke College, Oberlin College, Pomona College, Smith College, Trinity University, Union College, Washington & Lee University, Wesleyan University, Whitman College, Williams College

---

2014-2015 PROJECTS

RESILIENCE OF ENDANGERED ACROPORA SP. CORALS IN BELIZE. WHY IS CORAL GARDENS REEF THRIVING?:
Faculty: LISA GREER, Washington & Lee University, HALARD LESCINSKY, Otterbein University, KARL WIRTH, Macalester College
Students: ZEBULON MARTIN, Otterbein University, JAMES BUSCH, Washington & Lee University, SHANNON DILLON, Colgate University, SARAH HOLMES, Beloit College, GABRIELA GARCIA, Oberlin College, SARAH BENDER, The College of Wooster, ERIN PEELING, Pennsylvania State University, GREGORY MAK, Trinity University, THOMAS HEROLD, The College of Wooster, ADELE IRWIN, Washington & Lee University, ILLIAN DECORTE, Macalester College

TECTONIC EVOLUTION OF THE CHUGACH-PRINCE WILLIAM TERRANE, SOUTH CENTRAL ALASKA:
Faculty: CAM DAVIDSON, Carleton College, JOHN GARVER Union College
Students: KAITLYN SUAREZ, Union College, WILLIAM GRIMM, Carleton College, RANIER LEMPERT, Amherst College, ELAINE YOUNG, Ohio Wesleyan University, FRANK MOLINEK, Carleton College, EILEEN ALEJOS, Union College

EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SW MONTANA: METASUPRACRUSTAL ROCKS OF THE RUBY RANGE
Faculty: TEKLA HARMS, Amherst College, JULIE BALDWIN, University of Montana
Students: BRIANNA BERG, University of Montana, AMAR MUKUNDA, Amherst College, REBECCA BLAND, Mt. Holyoke College, JACOB HUGHES, Western Kentucky University, LUIS RODRIGUEZ, Universidad de Puerto Rico-Mayaguez , MARIAH ARMENTA, University of Arizona, CLEMENTINE HAMELIN, Smith College

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1358987
ExxonMobil Corporation

GEOMORPHOLOGIC AND PALEOENVIRONMENTAL CHANGE IN GLACIER NATIONAL PARK, MONTANA:
Faculty: KELLY MACGREGOR, Macalester College, AMY MYRBO, LabCore, University of Minnesota
Students: ERIC STEPHENS, Macalester College, KARLY CLIPPINGER, Beloit College, ASHLEIGH, COVARRUBIAS, California State University-San Bernardino, GRAYSON CARLILE, Whitman College, MADISON ANDRES, Colorado College, EMILY DIENER, Macalester College

ANTARCTIC PLIOCENE AND LOWER PLEISTOCENE (GELASIAN) PALEOCLIMATE RECONSTRUCTED FROM OCEAN DRILLING PROGRAM WEDDELL SEA CORES:
Faculty: SUZANNE O'CONNELL, Wesleyan University
Students: JAMES HALL, Wesleyan University, CASSANDRE STIRPE, Vassar College, HALI ENGLERT, Macalester College

HOLOCENE CLIMATIC CHANGE AND ACTIVE TECTONICS IN THE PERUVIAN ANDES: IMPACTS ON GLACIERS AND LAKES:
Faculty: DON RODBELL & DAVID GILLIKIN, Union College
Students: NICHOLAS WEIDHAAS, Union College, ALIA PAYNE, Macalester College, JULIE DANIELS, Northern Illinois University

GEOLOGICAL HAZARDS, CLIMATE CHANGE, AND HUMAN/ECOSYSTEMS RESILIENCE IN THE ISLANDS OF THE FOUR MOUNTAINS, ALASKA
Faculty: KIRSTEN NICOLAYSEN, Whitman College
Students: LYDIA LOOPESKO, Whitman College, ANNE FULTON, Pomona College, THOMAS BARTLETT, Colgate University

CALIBRATING NATURAL BASALTIC LAVA FLOWS WITH LARGE-SCALE LAVA EXPERIMENTS:
Faculty: JEFF KARSON, Syracuse University, RICK HAZLETT, Pomona College
Students: MARY BROMFIELD, Syracuse University, NICHOLAS BROWNE, Pomona College, NELL DAVIS, Williams College, KELSA WARNER, The University of the South, CHRISTOPHER PELLAND, Lafayette College, WILLA ROWEN, Oberlin College

FIRE AND CATASTROPHIC FLOODING, FOURMILE CATCHMENT, FRONT RANGE, COLORADO:
Faculty: DAVID DETHIER, Williams College, WILLIAM. B. OUIMET, University of Connecticut, WILLIAM KASTE, The College of William and Mary
Students: GREGORY HARRIS, University of Connecticut, EDWARD ABRAHAMS, The College of William & Mary, CHARLES KAUFMAN, Carleton College, VICTOR MAJOR, Williams College, RACHEL SAMUELS, Washington & Lee University, MANEH KOTIKIAN, Mt. Holyoke College

SOPHOMORE PROJECT: **AQUATIC BIOGEOCHEMISTRY: TRACKING POLLUTION IN RIVER SYSTEMS**
Faculty: ANOUK VERHEYDEN-GILLIKIN, Union College
Students: CELINA BRIEVA, Mt. Holyoke College, SARA GUTIERREZ, University of California-Berkeley, ALESIA HUNTER, Beloit College, ANNY KELLY SAINVIL, Smith College, LARENZ STOREY, Union College, ANGEL TATE, Oberlin College

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1358987
ExxonMobil Corporation

Keck Geology Consortium: Projects 2014-2015
Short Contributions—Experimental Basalt Lava Flows Project

CALIBRATING NATURAL BASALTIC LAVA FLOWS WITH LARGE-SCALE LAVA EXPERIMENTS:
JEFF KARSON, Syracuse University
RICK HAZLETT, Pomona College

COMPARISON OF NATURAL AND EXPERIMENTAL BASALT AS AN INVESTIGATION OF PAHOEHOE-‘A’A TRANSITIONAL SURFACE TEXTURES
MARY BROMFIELD, Syracuse University
Research Advisor: Jeffrey Karson

SIZE OF PERCHED LAVA PONDS AS A PRODUCT OF VOLUMETRIC FLUX
NICHOLAS C. BROWNE, Pomona College
Research Advisors: Jeffrey A. Karson, Richard W. Hazlett, Eric B. Grosfils

COMPARISON OF ICELANDIC ROOTLESS CONES WITH EXPERIMENTAL LAVA FEATURES
NELL DAVIS, Williams College
Research Advisor: Bud Wobus

VARIATION IN BREAKOUT MECHANISMS IN EXPERIMENTAL PAHOEHOE FLOWS
KELSA A. WARNER, The University of the South
Research Advisor: Donald B. Potter, Jr.

EXPERIMENTAL MODELING AND ANALYSIS OF THE EFFECT OF LAVA TUBE MORPHOLOGY ON MOLTEN, BASALTIC MATERIAL TRANSPORT
CHRISTOPHER G. PELLAND, Lafayette College
Research Advisor: Dr. Lawrence Malinconico

COMPARING THE ANISOTROPY OF MAGNETIC SUSCEPTIBILITY OF NATURAL AND EXPERIMENTAL LAVA FLOWS
WILLA ROWAN, Oberlin College
Research Advisor: Andrew Horst

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1358987
ExxonMobil Corporation

KECK Geology Consortium
Learning Science Through Research
Published by Keck Geology Consortium
Short Contributions
28th Annual Symposium Volume
25th April, 2015
ISBN: 1528-7491

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).

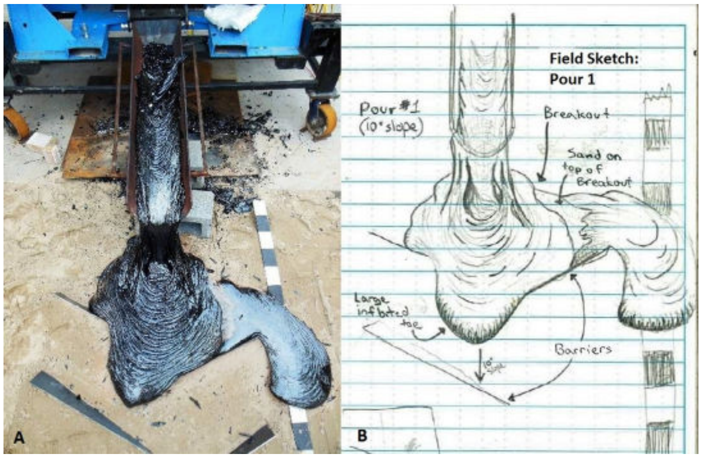

Figure 1. Photo (A) and field sketch (B) of final morphology of Pour 1 (10˚ slope). Lava fell approx. 32 cm from trough onto sand. It overcame the first obstacle (on left) but was halted at the second obstacle (on right). Flank breakout occurred after approx. 15-20 cm of inflation. Scale bar in decimeter increments. Main flow is ≃80cm long and 60cm wide. Breakout is ≃60cm long and 25cm wide.

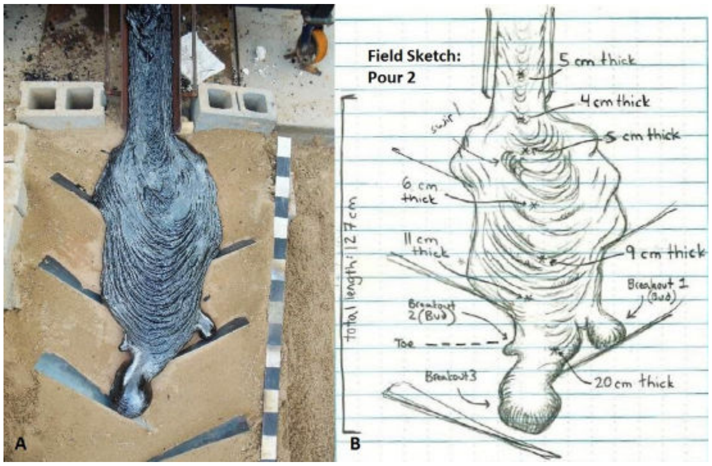

Figure 2. Photo (A) and field sketch (B) of final morphology of Pour 2 (15˚ slope). Lava flowed from the trough onto the sand and flowed easily over the first three obstacles. After the third obstacle, weaknesses in the crust developed into two buds and one breakout. Approx. 10-15 cm of inflation occurred after breakout. Scale bar in decimeter increments. Length is 127cm.

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.

Pour 1 for this study was the first of a series of pours completed over four days. Pour 2 for this study was done partway through this series and was thus set up with more experience. More complete data was collected for Pour 2. No final flow dimensions were collected for Pour 1 although estimates have been made from photos. Final dimensions were collected on-site for Pour 2, including length, width, and seven thickness measurements along the long axis of the flow (Fig. 2).

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}.

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.

3d). Sand was visible on the top of the breakout lobe directly adjacent to the main flow body.

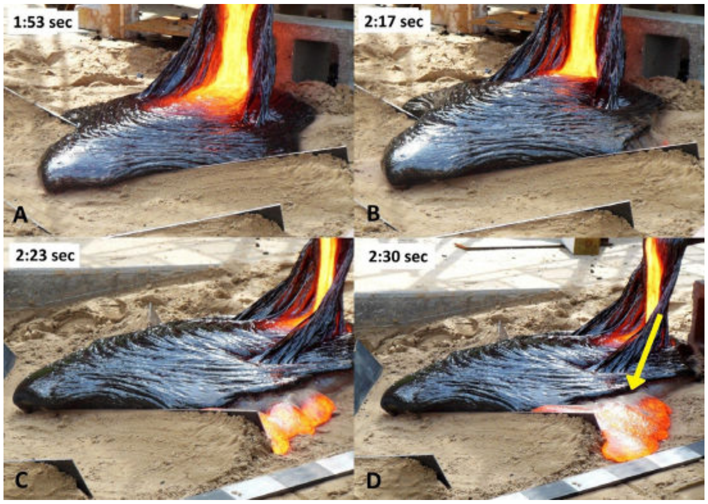

Figure 3. Breakout sequence in Pour 1 (10˚ slope). A) 1:53 sec after flowing onto sand, flow has crusted over and is inflating. B) 24 seconds later, the rigid crust is pushed up by internal pressure on right flank above barrier. C) 6 seconds later the molten lava has begun to flow in three bulges from 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.

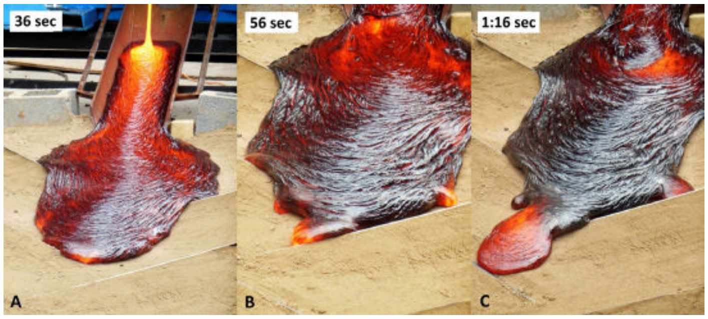

Figure 4. Breakout sequence in Pour 2 (15˚ slope). A) 36 sec after flowing onto sand, lava begins to flow over third obstacle. Note bright orange weaknesses in crust at leading edge (Temp ≃ 770˚C - 850˚C). B) Crust thickens and molten material exploits weaknesses at toe and flanks. C) Terminal weakness becomes dominant breakout and flank buds crust over. Terminal breakout then crusts over and inflates significantly. See also Figure 5.

Beyond the trough, Pour 2 continued moving downslope and, as a skin began to form on the surface, proceeded to flow over the first three barriers. Weak points, visible to the naked eye as incandescent spots (Fig. 4a) and as high temperature zones on the thermal images (up to ~850˚C), developed in the skin at the edge of the flow as the material flowed over the obstacles. Some weaknesses were rolled beneath the flow as it advanced; however, one that formed at the toe of the flow after 34 sec and two that formed above the toe on either flank after 48 sec remained and were exploited by the pressure of the molten material (Fig. 4b). The two flank weaknesses formed small buds (11 cm and 4.5 cm long; Fig. 4c) as the crust on the main body of the flow cooled and the forward motion of the flow halted just before the fourth barrier. Molten material continued to flow through the weakness at the toe and formed a breakout that continued flowing downslope beyond the fourth barrier for a total breakout length of 23 cm (Fig. 4c and Fig. 5a). After 1 min 22 sec, Pour 2 reached its maximum length of 127 cm. Inflation to a maximum thickness of 20 cm continued after downslope motion ceased. The 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.

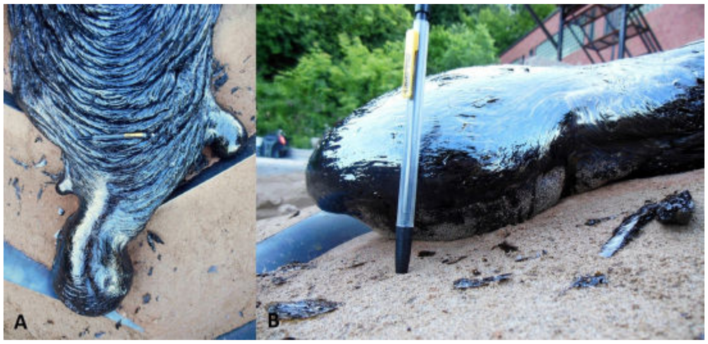

Figure 5. Terminal breakout in Pour 2 (15˚ slope). Overhead view (A) shows smooth inflated surface of breakout compared to ropey surface of main flow. The breakout is 23 cm long and begins at the right hand obstacle. Side view (B) shows sandy lower portion of breakout that formed as a basal crust beneath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

Blake, S. and Bruno, B.C., 2000, Modeling the emplacement of compound lava flows: Earth and Planetary Science Letters, v. 184, p. 181-197.

Hamilton, C.W., Glaze, L.S., James, M.R., and Baloga, S.M., 2013, Topographic and stochastic influences on pahoehoe lava lobe emplacement: Bulletin of Volcanology, v.75, p. 756, doi: 10.1007/s00445-013-0756-8.

Hon, K., Kauahikaua, J., Denlinger, R., and MacKay, K., 1994, Emplacement and inflation of pahoehoe sheet flows: Observations and measurements of active lava flows on Kilauea Volcano, Hawaii: Geological Society of America Bulletin, v. 106, p. 351-370, doi: 10.1130/0016-7606(1994)106<0351.

Lockwood, J.P. and Hazlett, R.W., 2010, Volcanoes: Global Perspectives: West Sussex, UK, Wiley-Blackwell, p. 408-411.

Peterson, D.W., Holcomb, R.T., Tilling, R.I., and Christiansen, R.L., 1994, Development of lava tubes in the light of observations at Mauna Ulu, Kilauea Volcano, Hawaii: Bulletin of Volcanology, v. 56, p. 343-360.