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

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

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EXPERIMENTAL MODELING AND ANALYSIS OF THE EFFECT OF LAVA TUBE MORPHOLOGY ON MOLTEN, BASALTIC MATERIAL TRANSPORT

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Research Advisor: Dr. Lawrence Malinconico

INTRODUCTION

A pyroduct, or lava tube, is described by *Kauahikaua et al.* (1998) as a "roofed conduit through which molten lava travels away from its vent." From field and experimental studies, two processes were proven to create these structures. First, during a pahoehoe flow of multiple toes, or lobed portions of flow that have overlapped, the contacting surfaces become heated and phase back into the liquid or semi-plastic state. The result is the growth of a single conduit through which molten material can flow, insulated from the cooling air (Fig.1). The second is the roofing of a singular channeled flow in which the exterior of the flow is impacted by the cooling of both the atmospheric air and the cooler surrounding material. This forces the boundary of the molten flow to cool and solidify, forming a covered channel. Small portions of the lava's margin continue to solidify and adhere to the surround walls and roof of the covered channel and consequently create a fully enclosed lava conduit.

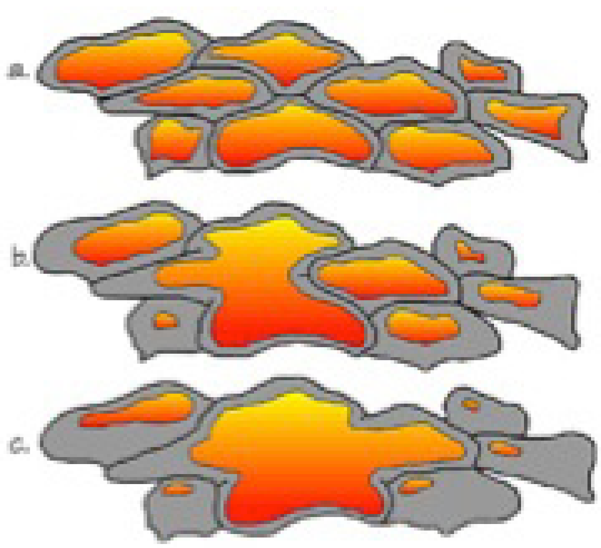

Figure 1. Diagram depicting the creation of a single lava conduit from the coalescence of multiple, smaller conduits and "toes" (Oregon State University, 2015).

The most influential characteristic of a duct is the conduit's ability to minimize heat loss from the flow. Work completed by *Keszthelyi and Self* (1998) determined that conduits can transport molten lava with approximately 1°C or less of heat loss per kilometer. Overall, a lava conduit structure can expel heat in multiple ways and through many surfaces and exposures. *Witter and Harris* (2007) demonstrated a conduit can suffer heat loss through exposure to the conduit-exterior atmospheric air as well as air trapped within the conduit itself. This trapped air however, only occurs under the presumption that the conduit does not fully contain molten material but rather features a flow that is of less volume than the total capacity of the structure. This method of heat loss can be determined from the derivation

$$Q_{blow} = U_{air}(T_{air} - T_{atm})\rho_{air}C_{p\ air} \quad (W\ m^{-1}) \tag{1}$$

where U_{air}, T_{air}, P_{air}, and C_p are velocity, temperature, density, and heat capacity of the hot, expelled air respectively (Witter and Harris, 2007).

Conductive heat loss through either the surrounding conduit walls or ground surface, provide the other primary heat loss. This method of heat loss can be represented and calculated in two standard ways, the first as a constant, time-independent measure

$$Q_{cond} = \frac{2\pi(T_{core} - T_{atm})k_{lava}}{\cosh\left[\left(\frac{2h_{roof}}{D_{tube}}\right) + 1\right]} \quad (W\ m^{-1}) \tag{2}$$

and the second, more realistic calculation, as a time-dependent measure

$$Q_{cond} = \frac{k_{lava}(T_{core} - T_{amb})}{\sqrt{\pi \alpha_{lava} t}} \quad (W\ m^{-2}) \tag{3}$$

Comparing these two, shown by *Witter and Harris* (2007), yields a similar loss of heat, ~10^6 W m^{-2}, in its initial seconds for both conductive and circulation. As time increases (minutes to hours) however, the conductive heat loss trends in a decreasing manner, dropping to ~10^4 W m^{-2}. The circulatory heat loss remains comparatively constant. This establishes that the overall cooling rate of the molten material contained within the conduit structure is most heavily influenced by its interaction with atmospheric air.

The interior of a conduit itself is commonly seen to evolve in cross sectional shape through time. Work completed by *Kauahikaua et al.* (1998) demonstrated that a lava conduit evolves through three distinct phases. The first is the flow's initial flat, expansive shape that generates an elliptical cross sectional shape, with width greater than height. This flow has the most exposure to atmospheric air and, in conjunction with the heat loss work mentioned previously, will cool and roof over. As material flows through this existing conduit, the rim of the flowing lava will cool and solidify to the existing conduit walls due to the drastic temperature differential of the wall and lava. This accretion of material causes the cross sectional shape of the structure to enter its second phase of evolution, with that of a more circular or rectangular cross sectional shape.

As molten material continues to flow through the conduit, adhering to the sides and walls, thermal erosion is continuously acting on the bottom of the conduit itself. As lava flows, convective heat transfer caused by the laminar nature of the lava flow erodes away at the base of the duct, remelting the preexisting material, causing a keyhole shape to form (Kauahikaua et al., 2003).

EXPERIMENTAL DESIGN

Pyroducts form in minimally explosive, volcanic environments of typically Hawaiian style eruptions with effusive pahoehoe flows. These environments, commonly fostering low slope terrains characteristic of the shield shape structure, provide an ideal environment for the formation of lava conduits. Such environments, often with slopes under approximately 10^{o}, can be recreated in large scale modeling as to observe and study the creation and evolution of conduits (Keszthelyi & Self, 1998). This study served to compare the predefined stages of the evolution of a conduit by identifying three distinct shapes through which a "standard" tube system will progress. These shapes, or cross sections, were created by changing aspect ratios or the relationship of height to width. The first of the experimental trial conduits was created to portray a cross section with width exceeding its height. The second of these trials was created with the intent of having the cross sectional height exceeding its width. Finally, the third of the experiments was modeled to create a circular cross sectional shape, with height equaling width. These shapes were referred to as A_w, A_h, and A_c respectively (Fig. 2).

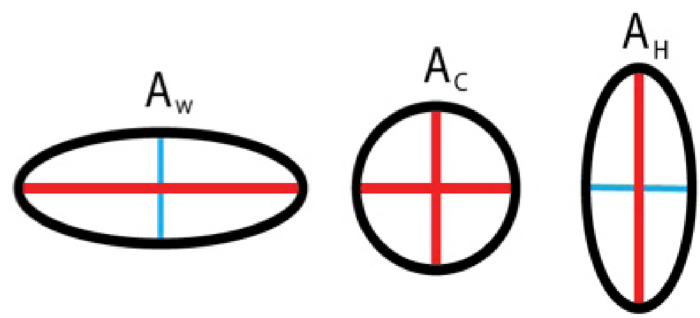

Figure 2. Depiction of the three separate cross sectional shapes of lava conduit interiors to be studied by this experiment.

Hypothesis

This study was rooted in a hypothesis constructed from field observations in Iceland as well as lava conduit evolution concepts presented both by *Lockwood and Hazlett* (2010) and by *Kauahikaua et al.* (1998 and 2003). It is believed that a tube of greater cross sectional height than width, that is to say an A_h conduit (Fig. 2), will transport molten material with less heat and velocity lost, and a smaller change in viscosity than that of a tube with greater cross sectional width than height, or A_w conduit.

Methods

In conjunction with the Syracuse University Lava Project, work was completed using controlled, large-scale simulated lava pours (Karson and Wysocki, 2012). Melting basaltic material to approximately 1400^{o}C, three experimental environments were created in which to pour the molten lava. These environments attempted to simulate the creation of lava conduits. The first of the pours was a channeled system, laterally bounded by cinderblock and sheet metal on a slope of unconsolidated sand at 7^{o}. Material was poured from the furnace, downslope through the 12.7 cm channel. For the final two trials, steel was used as sidewalls on a platform of similar material covered with a layer of sand at a slope of 7^{o}. For the second of the pours, the width of the channel was confined to 10.16 cm whereas the third pour was extended to 11.43 cm. For each of these pours, temperature, using a FLIR T300 infrared camera, and distance and time of pour, using standard video recording equipment and metric measurement tools, were recorded.

Using the data and observations collected during these experimental trials, analyses were completed to measurably interpret the raw data. Video recordings of the experimental trials were analyzed to obtain flow velocity measurements. Observations were made for any unexpected variations or occurrences during each of the pours. Three subsequent metrics were calculated for each of the trials. These metrics were each pour's viscosity, calculated using the Jeffery Equation

$$\eta = \frac{\rho g t^2}{3V} \sin\alpha \tag{4}$$

where ρ is viscosity, ρ is melt density, g is gravity, t is thickness, and α is slope (Nichols, 1939). Also completed in analysis was the energy and heat lost through convection and through interaction with the atmospheric air. Lastly calculated was the aspect ratio, which is to say the height to width ratio for each of the experimentally created conduits.

RESULTS

Three experimental trials, of aspect ratios A_w, A_h, and A_c, ranged from 60.96cm to 121.92 cm in length. Between the second and third trials the length of the flows were altered due to the previous trial's solidification of the material before traveling the length of the pre-designed channel.

The aspect ratios obtained from cross section examination of the three experimental trials, were found to mirror the intended cross sectional elliptical shapes (Tab. 1). Although these ratios, taken from the maximum height and width of each of the conduits, can represent the transport of material through such a cross sectional shape of the conduit, it cannot be interpreted that this ratio remains constant throughout the entirety of the duct.

Experimental Trial	Aspect Ratio	Velocity Change (cm s^{-1})	Initial Temperature (^{o}C)	Exiting Temperature (^{o}C)	Q_{cond} (W m^{-2})	Initial Viscosity (Pa s)	Exiting Viscosity (Pa s)	Viscosity Change (Pa s)
1	0.7:1	0.44	1062	850	79458	857	1651.5	794.5
2	1.3:1	1.27	1022	975	84617.5	924.7	526.8	-397.9
3	0.9:1	0.3	870	840	77516.8	735.6	482.3	-253.3

Table 1. Data collected and calculated from the three experimental trials of this lava conduit study.

Measured just prior to each trial, the atmospheric temperatures were 30^{o}C, 17.2^{o}C, and 26.6^{o}C. The lava channel entry and exiting temperatures are shown in Table 1. During the first of the three trials, the lava did not travel the entire length of the designed channel-way and therefore, its final measurement of temperature is a surface temperature that cannot be fully correlated to the molten temperature of the material contained within the enclosed duct.

The three trials showed relatively similar initial flow speeds of 5.55cm s^{-1}, 3.70cm s^{-1}, and 4.61cm s^{-1} upon exit of the furnace, however drastic cooling was observed within the following five seconds of each trail. In total, the trials showed variable changes in flow rate (Tab. 1). It was observed during trial 1 that material did not flow smoothly from the furnace into the channel-way but rather pooled and, after a buildup of material, began to spill into the channel-way.

From the obtained data, viscosity (η) and conductive heat loss (Q_{cond}) for each of the three flows was obtained (Tab. 1). The heat loss caused by exposure to air (Q_{blow}) was unable to be calculated as certain metrics, including the temperature of the air expelled by the lava, was not collected during the experimental trials.

INTERPRETATIONS

Trial one showed an increase in viscosity, representing a normal progression of flow through a channel, reflecting a greater resistance to flow as the material cooled. Atypical to normal viscosity changes however, which would show an increase in viscosity, trials two and three represent a decrease in viscosity as the material traveled (Tab. 1). This creates an inability of this metric to be used for analysis in attempting to determine the impact of cross sectional shape on transport of molten material through the lava conduit.

It was observed during trial 1 that as the molten material was poured from the furnace into the conduit-creating channel, a build-up of lava occurred at the entrance to the channel. Although the thickness measurements, which are a driving factor in the viscosity calculation, were collected to the down slope side of this build-up, it is interpreted that the decrease in flow velocity and increase in material build-up created an interior funnel feature, not representative of the conduit shape down slope. This interior funnel would create a Venturi effect, which refers to the increase in fluid velocity due to a decrease in the flow section of a confined flow (Blocken et al., 2008). Therefore, the surface flow velocity would be observed as drastically lower than its true value. This, paired with the increased thickness of the flow at that location, would account for the atypical decrease in lava viscosity seen at the commencement of this channelized flow.

Also determined from these data, was the conductive heat loss associated with these experimental trials. Interpreting these flows to exhibit time dependent heat loss and thus using Equation 4, the three flows displayed conductive heat losses of ~80,000 W m^{-2} (Tab.1). These values demonstrate that significant heat loss occurred through the exterior walls and surfaces of the lava conduits in addition to the uncalculated heat loss from exposure to air. No correlation however, can be made between the cross sectional shape of the conduit and its subsequent conductive heat loss without more trials.

This analysis of energy loss however, while not directly correlated to this study's hypothesis does aid in the broader goal of this project to further determine the correlation of these large scale, model lava flows with field studies and observations. The Q_{cond} values for this study, at ~10^4 W m^{-2}, coincide with the observations made by *Witter and Harris* (2007), aiding the accuracy and applicability of these large scale model lava experiments to field studies.

CONCLUSIONS

The purpose of this study was to experimentally determine the heat loss, velocity loss and viscosity changes in pyroducts or "lava tubes" of three cross sectional shapes in transporting molten basaltic material (Lockwood and Hazlett, 2010; Kauahikaua et al., 1998). Using a large scale modeling system and three conduit forming experimental trials, data were collected. Using the calculated metrics of viscosity and energy differentials, no strong correlations were observed or determined by this study. While it appeared there may be some correlation between heat and energy loss through conductive processes within a lava conduit, significantly more trials would be necessary as to accurately determine this. Finally, due to the generally limited data that was collected, correlations between study factors such as viscosity versus aspect ratio or cross sectional area of the tubes proved to be inconsequential.

Further Study

More experimental trials would be beneficial to this study in determining correlations and statistical inferences. Also, an increase in the number of data collected for each trial, such as more temperature measurements, could prove to be useful in analyzing the variation and rate of change through the length of the conduit.

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