SHAPE AND MOVEMENT OF BASALT: LABORATORY INVESTIGATIONS INTO PAHOEHOE LAVA MORPHOLOGIES, AND SLIP OF LAVA DOWNSLOPE

A Research Proposal, submitted to the Faculty of the Department of Earth Sciences, Syracuse University, in partial satisfaction of the requirements for the Ph.D. degree

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Introduction

Basaltic lava is the most abundant volcanic rock on the surface of Earth and other planetary bodies. Basaltic eruptions at mid-ocean ridges comprise more than two-thirds of our planet’s volcanic activity. Basaltic volcanism also occurs at subduction zones, hotspots, and continental rifts. In order to understand the formation and operation of volcanoes, it is imperative to gain an understanding of the behavior of basaltic lava. This is done four ways. First, ancient flows are studied so as to infer conditions during emplacement (Walker, 1973; Rowland and Walker, 1990; Self et al., 1997). Second, researchers study active lava flows to understand its rheology (Macdonald, 1953; Hon et al., 1994; Kauahikaua et al., 1998). However, nature provides only a limited variety of conditions, at unplanned times, and in remote locations. Third, lava flows can be modeled using numerical and computer models (Gregg and Fornari, 1998; Lev et al., 2012). Fourth, scaled flows can be created in a laboratory setting, using a variety of materials (Fink and Griffiths, 1990; Dietterich et al., 2015). The laboratory is a beneficial setting to study active lavas because the appropriate variables can be controlled to more fully understand lava flow behavior and how it ultimately changes its resulting morphology in any set of conditions. It is the fourth method, laboratory experimentation, that will be explored to more completely bridge the gap between laboratory analogs and natural lava flows.

Researchers have been studying lava since the 1800’s (Harris et al., 2017). However, due to the inherent danger of studying active lava flows, various materials have been used that behave similarly to molten rock to study the properties and behavior of lava flows without the danger. There have been many investigations of laboratory-produced lava flow analogs in past decades in order to study lava flow properties and behavior (Hulme, 1974; Hallworth et al., 1987; Fink and Griffiths, 1990; Gregg and Fink, 2000; Garry et al., 2006; Soule and Cashman, 2005). However, a new method has been developed. Creating molten basalt at meter-sized scales and at natural eruption temperatures can serve to yield new insights into lava flow behavior. Syracuse University possesses a laboratory setting that can achieve these goals (Karson and Wysocki, 2017).

Hundreds of experiments at the Syracuse University Lava Project laboratory have been performed since its birth in 2010. By varying key experimental parameters, previous experiments have generated various lava flow morphologies (Kissane, 2012; Karson and Wysocki, 2012,
2017; Karson and Hazlett, 2016), similar to what is seen in natural pahoehoe flows (Figure 1), including lobate flows, toey pahoehoe, folded or ropy flows, sheet flows, leveed flow channels, lava tubes, and hyaloclastites.

**Previous Work**

**LAVA FLOW MORPHOLOGY**

Basaltic lava flows come in many types of morphologies. Basalt occurs all over the planet and there are corresponding terms from various cultures and languages worldwide. However, the two most common basalt morphology terms used in modern literature come from the Hawaiian culture, ‘a’ā and pāhoehoe. In Hawaiian, the term ‘a’ā means to burn, blaze or glow. Contrary to common folklore, the etymology of this term is not derived from the sound that native Hawaiians made when walking across the aa lava surface. In Hawaiian the term pāhoehoe means smooth and unbroken (Harris et al., 2017). Throughout this proposal, the terms ‘a’ā and pāhoehoe will be used without the accents and “A with macron” characters for simplicity. The two main types of basaltic lava, aa and pahoehoe, were described as early as the 1820’s by Ellis, Darwin, Dutton, Dana, and others (Harris et al., 2017). Definitions advanced over the years and researchers described aa lava as rough, jagged, spinose, and clinkery with irregularly shaped vesicles, and pahoehoe lava as smooth, hummocky, and billowy with a ropy surface and containing spherical vesicles (Macdonald, 1953). Although, there are many different variations of pahoehoe and aa lavas, this proposal will focus only on pahoehoe lava, and its corresponding morphologies. The definitions above apply to subaerial basalt flows. However, most basalt flows on Earth are located on the seafloor. Similar morphologies to subaerial basalts are also seen on submarine basalt flows, but they are sometimes referred to by different names. This section will discuss the various basalt morphologies seen on land, and under the sea.

**Pahoehoe Morphologies**

Subaerial pahoehoe flows can be subdivided into many varying forms. The morphologies described here are the typical of those seen in locations such as Hawaii, Iceland, and Italy. Variations of pahoehoe flows include: pahoehoe lava tubes, pahoehoe sheet flows, inflated pahoehoe sheets, shelly pahoehoe, ropy pahoehoe, and toey pahoehoe (Hon et al., 1994; Macdonald, 1953; Harris et al., 2017). These types can be distinguished from one another by their surficial features. The final morphologies of lava imply varying conditions of emplacement.
Observations of active lava flows loosely constrain conditions of eruption and flow, and how they are related to the flow’s final morphology, but exact eruption conditions are not fully known. Additional work needs to be completed to more fully understand how lava morphologies are related to emplacement conditions.

Pahoehoe sheet flows are among the most common subaerial lava flows on earth. These types of flows make up a large majority of shield volcanoes on Earth. They are also seen on the seafloor (Fundis et al., 2010). Pahoehoe sheet flows begin as very low-viscosity flows that spread as thin sheets, 5 – 10 cm in thickness (Figure 1a). These flows advance by two mechanisms. First, on slopes below 5° they advance by breakouts of lava toes that coalesce together. Second, on slopes greater than 5° sheet flows advance as a single advancing front that is centimeters thick at the front, and meters thick uphill from the flow, forming a wedge-shaped profile (Hon et al., 1994). They can be kilometers wide and cover large aerial extents. The surface of a sheet flow has been described as billowy, hummocky, and smooth (Macdonald, 1953; Rowland and Walker, 1990; Harris et al., 2017). Sheet flows are a low-viscosity, low-velocity product of late stage eruption (Rowland and Walker, 1990).

Basaltic lavas often focus into lava channels, which can then crust over and form a roof (Figure 1b). Formation of a roof completes the formation of a lava tube. Pahoehoe lava has been measured traveling 3-5 m/s in the Pu‘u O’o tube system (Swanson, 1973). Lava tubes act as high-speed pathways for lava travel, and are also fantastic insulators. Temperature changes, from inflow to outflow, in lava tubes have been measured to have a 1° C/km difference (Cashman et al., 1998). Lava tubes are generally semi-circular with diameters up to 25 m, and can be kilometers in length (Kauahikaua et al., 1998). Some lava tubes remain empty after flow of lava has ceased, and some chill with lava still filling the tube.

Inflated pahoehoe sheets are described as thin pahoehoe sheets that have crusted over and increased in thickness over time (Figure 1c). Inflated flows in Hawaii were measured as initially flowing with a thickness of 5-10 cm, and then inflating to a thickness of 3-4 m (Macdonald, 1953; Hon et al., 1994). As the crust cools and thickens it acts as a thermal barrier for the incoming lava, while getting more rigid. As the crust gets more rigid it can maintain higher hydrostatic head pressure, and can thus accommodate more lava. Continued influx of lava causes
both more inflation, and breakouts at the flow front. Inflated flows suggest a sustained input of lava into the flow front over hours or days (Hon et al., 1994).

Shelly pahoehoe flows are defined as sheet flows that have large, 5-50 cm tall, cavities capped by a thin 3-6 cm crust (Figure 1d). They have been seen forming when the crust of a pahoehoe flow is immobile, and the flow begins degassing, forming bubbles in the still pliable crust (Swanson, 1973). Shelly pahoehoe flows are difficult to distinguish from sheet flows based on surface appearance alone because the surface often looks like a sheet flow, smooth, billowy, or hummocky. However, they differ from pahoehoe sheets in that they have a thin crust that is easily broken under the weight of a human foot, and often collapses when walked upon (Harris et al., 2017). These flows indicate gas rich conditions during the latter phase of the flow when the crust has thickened and solidified to the point of being impervious to gas escape, forming large gas bubbles at the surface. Shelly pahoehoe is most often observed proximal to the vent (Swanson, 1973), and indicates relatively gas-rich flows that exhibit degassing as the flow crust solidifies.

Ropy pahoehoe flows are one of the most recognizable lava features. This surface texture was described in the late 1800’s by Dana (1890) in (Harris et al., 2017) (Figure 1e). He describes pahoehoe ropes as “a series of parallel curved wrinkles, which give a look of tapestry to the folds surface.” Pahoehoe ropes are bow-shaped corrugations several centimeters tall, with their fold axes oriented perpendicular to flow direction (Figure 1f). The folds develop in response to shortening of the lava surface (Fink and Fletcher, 1978). Ropy pahoehoe indicates that the flow was slow moving, and that a viscoelastic crust formed while the core of the flow was still molten, and in motion. The ropes form due to differential surface velocities, and typically form with the convex side pointing in the downstream direction.

Toey pahoehoe is commonly observed at flow fronts where the crust is solidified. Hon and others (1994) recorded that the most abundant features on sheet flows observed in Hawaii were coalesced lava toes, comprising about 60% of the sheet flow surface. Pahoehoe toes are defined as small-lobed breakouts of lava at the flow front (Figure 1g). Lava toes can remain separated, or coalesce to form a uniform sheet flow surface. Sizes of toes can be up to 70 cm wide and 15 cm thick, with the size being proportional to lava supply rate (Hon et al., 1994; Self et al., 1998). Breakouts form as lava continues to flow internally and the pressure inside the lava crust rises.
When the pressure is great enough the crust’s tensile strength is exceeded, and it breaks open, extruding fresh lava (Hon et al., 1994). This results in a blob of lava flowing away from the margin of the flow. These blobs often look like the shape of a human big toe or thumb. Thus, with many breakouts, it is easy to imagine why observers call this “toey” pahoehoe.

**Submarine Morphologies**

Submarine lava flows are named differently than subaerial lava flows, though they share some similar morphologies, leading scientists to assume similar eruption conditions. However, because a deep-sea eruption on a mid-ocean ridge has never been witnessed, conditions of seafloor eruptions remain unknown. Lavas on the seafloor have a variety of morphologies referred to as sheet, hackly, jumbled, lobate, and pillowed flows (Kennish and Lutz, 1998; Fundis et al., 2010; Chadwick and Embley, 1994).

Submarine sheet flows are flat lying, thin (<10 cm) lavas (Figure 2e), but some sheet flows are inflated to several meters in thickness (Gregg and Fornari, 1998). Sheet flows can be seen at fast spreading centers, having flowed as far as several kilometers off axis. Hackly flows are a surface texture associated with sheet flows where the solidified crust has broken and piled up on itself. Jumbled flows are another surface texture of sheet flows with broken solidified crust that contains large surface folds (Kennish and Lutz, 1998).

Lobate flows are also commonly seen on the seafloor (Figure 2d). Lobate flows have a hummocky appearance with individual hummocks being over 1 m wide (Perfit and Chadwick, 1998). They can form as separate lobes, or coalesce back together to form one flow surface (Swanson, 1973). Lobate flows can be found atop pillars of collapsed lava lakes (Figure 2a), and spilling over the rim of axial summit troughs (Perfit and Chadwick, 1998; Perfit et al., 2003).

Pillow lavas are the most well-known submarine volcanic product. Pillow lavas are bulbous extrusions of basaltic melt that resemble a pillow shape with parallel striations on the surface (Figures 2b and 2c). The individual pillows occur at flow-fronts and can be centimeters to meters in diameter. New pillows can breakout from previous pillows, or any other minor tear in the crust (Ballard and Moore, 1977).
Lava Analogs

Various analog materials have been used to study viscous flow including kaolin, kaolin slurry, silicone oil, polyethylene glycol, corn syrup, honey, and fudge (Rust et al., 2008; Edwards et al., 2000; Hulme, 1974; Hallworth et al., 1987; Huppert, 1982; Soule and Cashman, 2005). Hulme (1974) used a kaolin slurry to investigate lava flow behavior. Huppert (1982) used oils to study viscous flow down a slope. Hallworth (1987), however, was the first to use analog materials to specifically study basalt flows.

Researchers injected polyethylene glycol wax 600 (PEG) into a body of water to minimize surface tension effects and the increase cooling rate to realistic values (Fink and Griffiths, 1990; Hallworth et al., 1987). They studied the effects of heat loss from the flow and its implications for crust formation. Gregg and others (Gregg and Fink, 2000; Gregg and Kesztölyi, 2004) carried this work forward by analyzing PEG flows on different slopes, and then applying that to the interpretation of seafloor and extraterrestrial lavas (Gregg and Fink, 1995; Gregg et al., 1996; Gregg and Fink, 2000). Much other work has been done with wax analogs including mechanical properties of the PEG crust, shear rate dependence in the pahoehoe to aa transition, non-uniform channels, and many others (Griffiths et al., 2003; Sehlke et al., 2014; Soule and Cashman, 2005, 2004).

Some of the first wax analog flows that were performed underwater (Hallworth et al., 1987) produced morphologies that were similar to natural basalt morphologies. Fink and Griffiths (1990) explored the various morphologies and what causes the transition between observed morphologies. PEG wax behaves similarly to lava in that it has a temperature dependent viscosity, and it develops a mechanical crust as it cools. Crust formation of PEG wax is primarily controlled by heat loss from the surface of the flow. Higher heat loss results in faster crust formation, typical of flows closer to vents. They applied their calculations to laboratory-created PEG wax flows because performing sensitive measurements on active lava flows is difficult and dangerous. They found that the wax flows showed a continuum of morphologies (Figure 3) classified as pillow, rifted flows, folded flows, and leveed flows (Fink and Griffiths, 1990; Gregg and Fink, 2000).
COMPARING LAVA FLOWS

Many ways to compare lava flows have been employed over the years (Cashman and Sparks, 2013). Methods of comparison have included physical dimensions (Malin, 1980; Walker, 1973; Garry et al., 2007), viscosity (Huppert, 1982; Nichols, 1939; Shaw, 1972; Giordano et al., 2008; Bottinga and Weill, 1972; McClinton et al., 2014), effusion rate (Walker, 1973), temperature (Macdonald, 1953; Peck, 1978), composition (Shaw, 1972; Giordano et al., 2008), and surface morphology (Macdonald, 1953; Rowland and Walker, 1990; Hon et al., 1994; Harris et al., 2017; Griffiths and Fink, 1992b; Gregg and Fink, 1995, 2000). How can lava flows from different volcanoes and flows formed from different materials be compared to one another? Comparison is made using ratios, scaling, and dimensionless units.

Viscosity Comparison

Viscosity, internal resistance to flow, is caused by friction between material in a fluid. The viscosity of lava is controlled by four variables; temperature, composition, vesicle content, and crystal content. Figure 4 (McBirney and Murase, 1984) displays variation of various composition lavas at different eruptive temperatures, clearly showing the relationship of temperature on lava viscosity. The methods for determining viscosity of fluids are: theoretical composition calculations, calculations from measurements of a flowing fluid, and direct measurements using instrumentation.

Theoretical viscosity calculations based on composition are commonly used to determine the viscosity of a fluid at a specific temperature of a prescribed composition (Bottinga and Weill, 1972; Shaw, 1972; Giordano and Dingwell, 2003). This is accomplished by using the Arrhenius, and the VFT (Vogel-Fulcher-Tammann) equations.

The equation derived by George Jeffrey (Jeffreys, 1925) is commonly used to calculate viscosities of actively flowing lavas, using a few simple field measurements of an actively flowing fluid. The equation is defined as

\[ v = \frac{g \cdot \rho \cdot \sin(\beta) \cdot d^2}{n \cdot \mu} \]
where \( g \) is gravitational acceleration, \( \rho \) is density of the fluid, \( \beta \) is the slope angle, \( d \) is the thickness, \( n \) is a constant (3 for non-channelized flow, 4 for channelized flows), and \( \mu \) is dynamic viscosity. The equation can easily be rearranged to solve for \( \mu \).

Direct measurements of fluid viscosities can be completed by using a wide variety of different instruments. One example is from measurement of lavas from Mt. Etna, Italy The viscosity was measured directly, during active-flow, using a rotating vane viscometer (Pinkerton and Norton, 1995), and was found to have a viscosity of 1385 Pa s at 1095° C.

### Dimensionless Parameter Comparison

One goal of volcanologists is to determine emplacement conditions (effusion rate, cooling rate, and rheology) of unobserved lava flows from their final morphology (Fink and Griffiths, 1992). To aid in this goal, Fink and Griffiths (1990) derived a dimensionless parameter, \( \Psi \), that relates flows of any material to one another. The dimensionless parameter \( \Psi \) is given as

\[
\Psi = \frac{t_s}{t_a}
\]

where \( t_s \) is the time for solidification, and \( t_a \) is the time for advection of the flow. Fink and Griffiths (1990) derived \( \Psi \) by relating the amount of heat loss to the amount of heat advected within a viscous flow. Time for advection (\( t_a \)) is given by

\[
t_a = \left( \frac{\eta g^* \rho}{Q} \right)^{3/4} \cdot Q^{-1/4}
\]

where \( g \) is gravitational acceleration, \( \rho \) is density of the lava, \( \eta \) is the dynamic viscosity, and \( Q \) is volumetric effusion rate. Thus, by measuring time to solidification, the density of the lava, the viscosity of the lava, and its effusion rate, \( \Psi \) can be calculated. It is dimensionless \( \Psi \) that is the link between analog flows and natural flows because it applies to any substance that cools and develops a mechanical crust.

Low \( \Psi \) values indicate relatively rapid crust solidification compared to heat loss during flow, typical of conditions close to a vent. High \( \Psi \) values indicate relatively slow crust solidification (high values of \( t_s \)) compared to heat loss during flow. Each \( \Psi \) value was correlated to morphologies in wax flows (Fink and Griffiths, 1990; Gregg and Fink, 2000) (Figure 3).
Psi of PEG Wax

Over 180 experiments were performed using PEG. Investigators saw that the wax formed four different flow morphologies; pillows, rifts, folds, and levees (Fink and Griffiths, 1990). They found that the morphologies formed along a spectrum, with pillows on one end, and leveed flows on the other.

Psi of Natural Lavas

Calculations relating $\Psi$ to natural lavas has been performed for flows on Earth and other planetary bodies. Gregg and Kesztelyi (2004) calculated $\Psi$ values for pahoehoe toes from active lava flows of Kilauea in May and June 1996. They found that $\Psi$ for individual pahoehoe lobes correlate well with wax experiments, with values ranging from 2 to 8, but not for entire lava fields because each flow lobe only records the local conditions of emplacement, rather than conditions for the entire lava field. Thus, Gregg and Kesztelyi (2004) recommend that $\Psi$ values only be used for single continuous events, in order to be relatable to laboratory experiments.

Using PEG flows, calculated $\Psi$ values, and assumed viscosity and effusion rates for submarine flows, Gregg and Fink (1995) found that pillow lavas form with an expected $\Psi$ value less than three. Pillow lavas were shown to be able to form under a large variety of effusion rates (Griffiths and Fink, 1992a). Using assumed volume, temperature, and viscosity values, identified surface morphologies, and $\Psi$ values as a guide, Gregg and Fink concluded that sheet flows could form at 10 $\text{m}^3/\text{s}$, assuming a viscosity of 1000 Pa s, and that lava lakes could form at 2000 – 3000 $\text{m}^3/\text{s}$, with an assumed viscosity of 100 Pa s (Gregg and Fink, 1995).

Gregg and Fink (1996) investigated lava flows on the Moon, Mars, and Venus. Using $\Psi$ values from laboratory simulations, in addition to assumed values for eruption temperature, viscosity, and density, they calculated effusion rates of extraterrestrial lava flows to imply general compositions of lava on the planetary bodies. The found that the lavas studied on the Moon, Mars, and Venus could be of basaltic or andesitic composition. A study of channelized lavas on Mars was conducted (Garry et al., 2007), and they found that downstream changes in surface morphology of lava channels on Mars varies in a similar manner to PEG simulations and the 1907 and 1984 eruptions of Mauna Loa, Hawaii.

Similar morphologic types from different environments are assumed to have similar eruption conditions, and have been compared to laboratory experiments (Gregg and Fink, 2000; Griffiths
and Fink, 1992b; Gregg and Fink, 1995). Table 1 shows the inferred relationships of laboratory and natural flows. One of the limitations of wax morphology studies is that the morphologic types created using wax experiments are assumed to be similar to morphologies observed in nature. By using molten basalt, a more accurate representation of natural morphologies can be created, which can help clarify current understanding of morphologic transitions.

LONG RUN-OUT LAVA FLOWS

Long lava flows are defined as being more than 100 km in length (Keszthelyi and Self, 1998). Most lava flows on Earth are less than 30 km in length (Walker, 1973). The control behind length of lava flows has been debated for decades. George Walker presented evidence that suggested an effusion rate control (Walker, 1973), while Michael Malin suggested a volume control to length of lava flows (Malin, 1980). However, some of the longest lava flows discovered are hundreds of kilometers in length (Wilson and Head, 1983; Gregg and Fornari, 1998; Garry et al., 2007), for which there is no conclusive explanation as to their extraordinary lengths (Cashman et al., 1998).

Some of the longest lava flows on Earth are the Queensland flows in Australia, measured at 55, 120, and 160 km (Stephenson et al., 1998), and submarine flows on the Puna Ridge, Hawaii and on the Juan de Fuca Ridge that each measure 60 km (Gregg and Fornari, 1998). Even more impressive are the longest extraterrestrial lava flows on the Moon, Mars, and Venus that traveled 400 km, 690 km, and 1000 km, respectively (Wilson and Head, 1983; Cashman et al., 1998; Garry et al., 2007). The explanation as to how such extremely long lava flows travel such distances is not well understood. Cashman et al. (1998) state that the assumed and accepted high-effusion rate explanation for long run-out lava flows may not satisfy the observations.

Another observed geologic phenomenon similar to long run-out lava flows are long run-out landslides. The travel mechanism of long run-out landslides has been studied due to direct relevance to human safety. Several different travel mechanisms have been proposed for long run-out landslides, including entrapment of air underneath a rock mass, steam generated by vaporization of groundwater, and lubrication by liquefied saturated soil (Shreve, 1959; Legros, 2002; Hungr and Evans, 2004). The above-mentioned mechanisms also reduce friction, enabling high velocity travel of material. Shreve (1959) suggested that the Blackhawk landslide traveled at speeds of 50 km/hr. Could any of these mechanisms proposed for landslide events explain the
travel distances of long run-out lava flows? Can long run-out lava flows be emplaced by rapid slip events?

Methods
SYRACUSE UNIVERSITY LAVA PROJECT LABORATORY
The Syracuse University Lava Project is an interdisciplinary project between science and the arts created in tandem by Robert Wysocki and Jeff Karson (http://lavaproject.syr.edu/). The Lava Project uses a former bronze tilt furnace that has been modified to melt and deliver molten basalt (Figure 5). The Lava Project creates the largest laboratory synthetic molten basalt flows in the country that are ideal for studying active lava flows with great control.

At the laboratory located on the Syracuse University campus researchers have studied flow dynamics, interactions with barriers, and lava-ice interactions (Lev et al., 2012; Dietterich et al., 2015; Edwards et al., 2013). The Lava Project has created lava flows for many different projects, and has flowed onto many different substrates including ice, snow, dry ice, clay, sand, steel, and into water (Karson and Wysocki, 2012). The Lava Project can provide detailed study of various aspects of lava by varying controllable attributes: temperature, effusion rate, slope angle, and substrate material.

Procedures
The Syracuse University Lava Project laboratory gas-fired tilting furnace is capable of melting up to 170 L (0.17 m³) of basalt at one time (Karson and Wysocki, 2012). The starting amterial for all experiments is 1.2 Ga Keweenawan basalt, which is shown to have a viscosity similar to Etnean basalts (Figure 6). Variable parameters include temperature (900°-1250° C), effusion rate (100-700 cm³/sec), slope angle (0° to 20°), and substrate material. The density of the melt is calculated to be 2.7 g/cm³.

Flows are observed in real-time and recorded using vertical and oblique-angle high-definition video cameras, K-Type thermocouples, and a handheld FLIR (Forward-Looking InfraRed) camera. Thermocouples will be used to measure the internal lava temperature, and a FLIR camera to measure the surface temperature of the lava. Other measured parameters include flow width, length, thickness, and slope angle.
Data Analysis
Calculated variables include, velocity, effusion rate, viscosity, and the $\Psi$ parameter.
Solidification time, temperature of crust formation, and flow morphologies will be determined using video recordings and photographs. Data will be analyzed using Microsoft Excel, digital video players, FLIR Tools Infrared analysis software. Measured and calculated values will be used to calculate the $\Psi$ parameter as outlined in Fink and Griffiths (1990). Data will be compared to natural basaltic lava flows where eruption variables are known and to results from wax analog experiments.

Research Objectives and Hypotheses
CHAPTER 1: MORPHOLOGIC TRANSITIONS OF MOLTEN BASALT
Some of the most well-known studies of lava morphologies used wax as a lava analog (Fink and Griffiths, 1990; Gregg and Fink, 2000). However, laboratory created molten basalt flows also produce a variety of morphologies similar to those seen in nature (Figure 7). Other than an unpublished Master’s thesis (Kissane, 2012), no studies have been pursued toward relating molten basalt flow morphologies to natural and wax flows. Further investigation into morphologic transitions using molten basalt will yield a fuller understanding of exactly which eruption conditions yield morphologies seen in nature.

Hypotheses
The objective of this study is to investigate the formation of basalt flow morphologies using molten basalts created from the Syracuse University Lava Project. This project will quantify specific conditions at which morphologic transitions occur, and relate the findings to natural basaltic lava flows. Gregg and Fink (1995) correlated flow morphologies of PEG wax to natural subaerial and submarine flows. Here a similar approach will be taken, but using real, subaerial, basaltic lava flows.

The hypothesis is that the flow morphologies produced will systematically change with changes in a limited family of eruption parameters (slope angle, temperature, and effusion rate) and that the morphologies can be correlated with ranges of $\Psi$ for comparison with values of both natural lavas and analog materials. As the individual parameters of slope, temperature, and effusion rate are varied independently, the flow morphologies will progress from one end of the spectrum to
Specifically, as temperature, slope angle, and effusion are each increased, the morphologies will change from pahoehoe toes, to folded flows, to leveed flows, to sheet flows.

Experiments

The experiments to determine the transition of one morphology to another will be a family of three sets of experiments poured over a dry planar sand substrate. The first set of experiments will be a variation of temperature while effusion rate and slope are held constant, ranging from 900°C to 1250°C, progressing in steps of approximately 50°C. Each experiment will be performed twice for a total of 16 experiments. During the second set of experiments, slope will vary while temperature and effusion rate are held constant. Slope angles will range from 0° to 20° from horizontal, decreasing the slope 5° with each experiment performed. Each experiment will be performed twice for a total of 10 experiments. The third set of experiments will be a variation of effusion rate while temperature and slope angle are held constant. Effusion rates will range from 100 – 700 cm³/sec, increasing the effusion rate by 100 cm³/sec with each change in effusion rate. Each experiment will be performed twice, for a total of 14 experiments. All constant temperatures, effusion rates, and slopes for all experiments will be held at a 1150°C, 250 cm³/sec, and 15°, respectively.

Years of lava flow data, comprising hundreds of lava flows, have been gathered, sorted, and compiled. Lava flows with usable data have been analyzed from photographs, videos, and temperature recordings. Of flows with recorded data, approximately 50 flows contain known values for all parameters. Of the 50 flows, less than ten fall within the proposed eruption parameters (1150°C, 250 cm³/sec, 15° slope, dry sand). The lava flows that fit the proposed family of experiments have been analyzed and included in Tables 2-4.

Despite having a small number of flows that fit into the proposed experimental set, 14 flows have been carefully measured and analyzed for a variety of conditions. Results from these flows (Figure 8) generally agree with results from Gregg (2000). After all data have been collected and analyzed, they will be compared to lava flow results for wax and natural flows. Preliminary results indicate progression from folded to sheet flows with increasing temperature, slope, and effusion rate (Figure 8).
CHAPTER 2: SLIP OF MOLTEN BASALT

Most lava flows move across the landscape by viscous flow. However, in some conditions, lava may not move as an ideal viscous fluid. Lava flows created with the Syracuse University Lava Project have been observed slipping downslope (Figure 9), exhibiting signs of high vapor pressure, such as lava bubbles and sand jetting from under the margins of the flow. Slip of lava is defined as a coherent mass sliding along the fluid-solid interface. This project aims to investigate sliding of lava flows, and the mechanism behind the slip. No research projects to date have involved the slip of lava downslope.

Hypotheses

The objective of this project is to determine the conditions at which slip of molten basalt occurs, possibly providing an explanation for the mechanism of long run-out lava flows. This project will investigate lava slip events on substrates of dry sand, wet sand, clay, packed shaved ice, and dry ice, to determine the critical slope angle for each substrate.

The hypothesis is that each substrate tested will exhibit a different critical angle for slip at similar temperatures and effusion rates. Each lava flow will show signs of slip on slopes steeper than the critical angle. Signs of slip include coherent mass slip, high velocity during slip (experiment 140705 slipped at 45 cm/s), and elevated vapor pressure (bubbles and sand jets).

Experiments

The experiments to determine the critical angle at which slip of basalt occurs will consist of a family of four experiment sets. Four experiments on each substrate will be performed, totaling a minimum of 16 experiments. Each experimental set will take place on slopes ranging from 5° to 20°, increasing the slope by five degrees with each experiment performed. Once slip has been observed, experiments will be repeated between the bounding slope angles to constrain the critical angle needed for slip to occur. Each experiment will hold temperature and effusion rate constant at 1150° C and 250 cm³/sec, respectively.

Several experimental lava flows at the Syracuse University Lava Project laboratory that have exhibited slip have been documented. Of the instances of documented slip, the slope angle transition for slip has not been constrained. Each flow showed signs of elevated vapor pressure by presence of bubbles, and one contained escaping air from under the flow. Table 5 summarizes preliminary findings.
EXPERIMENTAL CHALLENGES

Since Fall 2015 preliminary experiments have been conducted at the Syracuse University Lava Project laboratory. While preliminary experiments were conducted, several obstacles were encountered including inaccurate thickness measurements, thermocouple equilibration lag time (Figure 10), and measuring internal lava temperatures.

Methods to overcome the obstacles encountered are:

- Inaccurate thickness measurements: Currently, thickness is carefully measured upon dissection, after flow solidification. Measurement of thickness during flow can be accomplished by profile-view photography, and by placing markings in the steel trough to indicate flow depth during active flow.

- Thermocouple equilibration lag-time: This challenge can be overcome by using a smaller diameter thermocouple to reduce equilibration time, and by pre-heating the thermocouples to elevated temperatures before the flow comes in contact with the probe.

- Measuring internal lava temperatures: Internal temperature of the lava can be measured and approximated. The temperature can be measured directly by inserting a thermocouple directly into the lava by hand, or by suspending a thermocouple ~1 cm above the flow slope. Internal temperature may also be numerically modeled using the surface and basal temperatures of the lava.
Figures

Figure 1 - Natural pahoehoe morphologies. (a) Sheet flow from Krafla volcano, Iceland, consisting of a mostly-flat surface with small hummocks, and pahoehoe ropes in the left-hand side of the image. (b) Skylight in a lava tube from Kilauea volcano, Hawaii. Photo from the Hawaiian Volcano Observatory (https://hvo.wr.usgs.gov/). (c) Inflated pahoehoe flow. Note the thickness of the lava, using the street sign for scale (Hon et al., 1994). (d) Shelly pahoehoe from a 1984 flow at Krafla volcano, Iceland, with a broken shelly bubble or tube in the foreground. Note camera case for scale (Rossi, 1997). (e) Pahoehoe ropes as drawn by Dana (1890) in (Harris et al., 2017). (f) Pahoehoe ropes from the 1974 Keanakakoi Crater flow. Width of photo is about 10 m, with flow direction from left to right (Fink and Fletcher, 1978). (g) Fresh pahoehoe toe flowing over older broken up flow. Photo from Hawaiian Volcano Observatory (https://hvo.wr.usgs.gov/).
Figure 2 - Submarine lava morphologies. (a) Collapsed lava lake with lava pillars topped by lobate lavas (Clague et al., 2014). (b) Pillow lava on the Galapagos Rift, 2005. Note the parallel striations on the surface of the bulbous pillow lava. Photo from NOAA Ocean Explorer (http://oceanexplorer.noaa.gov/explorations/05galapagosrift/media/687A2327.html). (c) Pillow lava. (d) Lobate lava. (e) Sheet flow. Images c, d, and e from Niños eruption at the Galapagos Spreading Center (McClinton and White, 2015).
Figure 3 - PEG wax morphologies showing (a) pillowed flow, (b) rifted flow, (c) folded flow, and (d) leveed flow. Figure from Gregg and Fink (2000).

Figure 4 - Variation in viscosity at different temperatures for different composition melts (McBirney and Murase, 1984).
Figure 5 - Laboratory setup of the Syracuse University Lava Project, with tilting furnace pouring molten basalt onto the flow slope, and student measuring the temperature of the lava.

Figure 6 - Temperature-viscosity data from Giordano (2008) viscosity model, and shows that the lavas created at the Syracuse University Lava Project should behave as other basaltic melts. Compositional data Etnian basalt (grey) was obtained from Giordano (2003). Mount Saint Helens (light blue) compositional data was obtained from Rutherford and others (1985). Chengwataana basalt (purple) compositional data was obtained from Wirth and others (1997). SU Melt data obtained from Jeff Karson (personal communication).
Figure 7 - Various morphologies of lava flows created at the Syracuse University Lava Project (Karson and Wysocki, 2017).

Figure 8 - Preliminary experiment data with variation in temperature, effusion rate, and slope angle. Despite variation in all eruption parameters, a decent correlation between calculated psi values, slope angle, and final morphology is shown. With more stringent experimental control, greater correlation is expected.
Figure 9 - Two separate lava flows from the Syracuse University Lava Project. Images A-H show lava experiment 140705-2 flowing normally and then slipping down slope, with timing of slip displayed in corner of each image. Flows I-L show lava flowing downslope by viscous flow, with no slip observed.
Figure 10 - Equilibration time of thermocouples versus instantaneous FLIR surface temperature readings with respect to time during the flow. Measurements taken from thermocouple underneath flow 65 cm from top of ramp from experiment 160401.
Tables

<table>
<thead>
<tr>
<th>Subaerial Morphology</th>
<th>Submarine Morphology</th>
<th>Wax Laboratory Morphology</th>
<th>Syracuse Laboratory Morphology</th>
<th>Cooling Rate</th>
<th>Slope</th>
<th>Flow Rate</th>
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<tbody>
<tr>
<td>Toey pahoehoe</td>
<td>Pillows 2-8</td>
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Table 1 - Equivalent morphology types in their respective environments, and their relation to calculated Ψ value, cooling rate, slope, and flow rate. Note that relationships for submarine morphologies are inferred because a mid-ocean ridge eruption has never been witnessed. Modified from Gregg and Fink (2000).

<table>
<thead>
<tr>
<th>Temp C</th>
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<tbody>
<tr>
<td>Morphology</td>
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Table 2 - Experimental matrix for morphology transitions with respect to temperature variation. Constant parameters are slope angle (15°), effusion rate (250 cm³/s), and substrate material (planar dry sand bed).

<table>
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<th>Slope (degrees)</th>
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<td>Ropy</td>
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<tr>
<td>Sheet</td>
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<tr>
<td>Channel</td>
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</tbody>
</table>

Table 3 - Experimental matrix for morphology transitions with respect to slope variation. Constant parameters in this experiment set are temperature (1150° C), effusion rate (250 cm³/s), and substrate material (planar dry sand bed).

<table>
<thead>
<tr>
<th>Effusion (cm³/sec)</th>
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<td>Sheet</td>
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<td>Channel</td>
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</table>

Table 4 - Experimental matrix for morphology transitions with respect to variation in effusion rate. Constant parameters in this experiment set are temperature (1150° C), slope angle (15° C), and substrate material (planar dry sand bed).
<table>
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<tr>
<td>Clay</td>
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Table 5 - Preliminary data for lava slip experiments. Three documented slip events fit within the experimental family, loosely constraining the critical angle at which slip occurs. Other slip events have no record of slope angle.
References


