Through Thick and Thin:
An Investigation of the Effusive Eruptions at Mt. Ngauruhoe

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Abstract. Lava flows are greatly affected by the viscosity of the magma, effusion rates and slope of the volcano. Each of these factors affects the dynamics of the flow and ultimately its structural characteristics. High viscosity, fast effusion rates and steep slopes cause greater stress on the surface crust of the lava, causing it to break and form an aa flow. The opposite will form a smooth, ropy textured pahoehoe flow. The effusive eruptions from Mt. Ngauruhoe, a stratovolcano within the Tongariro Complex, exhibit many different surface textures. To determine the control on these features, I split the flows into three categories: flows containing ogives, aa flows and a pahoehoe flow. Using x-ray fluorescence (XRF), petrography and ArcGIS, I examined the flows to determine whether the flow type is determined by viscosity, effusion rate or slope. There is no evidence showing viscosity is a control, but some data suggests effusion rate and slope may have an influence.

Introduction

Mt. Ngauruhoe is a 2,500 year old volcano, in the southern Taupo Volcanic Zone, that has shown many different eruptive characteristics in its short lifetime. Within this short amount of time, its eruptive styles have varied from effusive to sub-plinian. The effusive eruptions alone exhibit a variety of characteristics that are obvious in the field. There are many autobrecciated aa flows containing structures such as spires. In contrast, there are smoother, broader flows containing ogives and one small pahoehoe flow situated adjacent to a steeper aa flow.

Much research has been done on the transition of lava flows as they flow down the flanks of a volcano. Transitions of pahoehoe to aa occur because decreasing temperature and gas content along with increasing crystallinity lead to an increase in viscosity (Polacci et al. 1999). Studies from Mount Etna show that a transition from a steep to a gentle slope can influence the transition from lava tube flows to flows with overlapping lava tongues (Polacci & Papale 1999). These factors can also affect lava flows from eruption to eruption. Guest and Stofan (2005) state that effusion rate is recognized as the underlying factor determining flow development. Although other elements may contribute, they are easily overshadowed by effusion rate. Hobden (1997) argues that the style of lava flow eruption in the Tongariro complex is mainly driven by viscosity and yield strength of the lava although effusion rate, topographic channeling, thermal efficiency of flow process and steepness of the slope may play roles. For this paper, I made field observations to define the surface structures apparent in the Ngauruhoe lava flows in the Mangatepopo Valley. I then used petrography, XRF data and ArcGIS to determine the controls on the type of lava erupted.

Methods

I mapped the area of the Mangatepopo Valley in February 2010 with the aid of aerial photos. I drew initial lava flows on the aerial photos, then used field observations to confirm or retract the original map. Relative ages were assigned based on lava emplacement and vegetation. An 1800 year old Taupo ignimbrite and a 600-700 year old Taupo ashfall were also used as age markers. After the map was complete, I took 15 samples from a wide range of effusive lava flows that contain a variety of surface structures.

Based on the variety of surface structures observed in the field, I split the lava flows into three categories. The first group contained all lavas with ogives (Doom 2, 3, 14, 16 and 19). Doom 2, 3, 16 and 19 lie within the four oldest mapped flows. Doom 14 is the youngest of the ogive flows and flowed through marginal levees. The next group contained all aa flows (Doom 4-6, 8-11, 15 and 18). Although many of the aa flows have different characteristics, such as levees, spires, and tumuli, they were not split into subcategories because there were not enough examples taken of each flow structure. The final group was made up of the pahoehoe flow (Doom 17). I also used the silica content from the XRF data to split the lavas into two groups, basaltic andesite (<55% SiO_2) and andesite (>55% SiO_2). These different groups were compared against each other to find a common control on viscosity.

I used XRF data to create Harker diagrams. Graphs separating the surface structures as well as the silica content were created to see if composition of the flows was a control.

I analyzed the crystallinity of the lava flows under thin section, focusing on plagioclase. A study conducted by Hiroaki Sato (1994) compared a pahoehoe flow to an older aa flow from the Izu-Oshima volcano, Japan. The pahoehoe flow contained plagioclase that was coarser grained but much less abundant than the aa flow. Linear cooling experiments as well as isothermal cooling experiments determined that the difference in crystallization between the two flows was due to undercooling. Degassing of the magma increased the equilibrium liquidus temperature, which promoted crystallization in the aa. The pahoehoe on the other hand was less undercooled before erupting and did not crystallize as many plagioclase crystals (Sato, 1994). Using this data, I looked at size and abundance of plagioclase crystals within each group to see if a similar pattern existed amongst the lava flows.

Harris et al. (2007) examined satellite-based techniques as a method to calculate lava effusion rates. The equations used to do this indicate that there is a linear relationship between time-averaged discharge rate and the area of the active lava flow. Data comparing ground-based discharge rates with satellite-based discharge rates show a close correlation. I applied this theory and used ArcGIS to calculate the areas of each flow. Because most of the flows have been overlain by younger flows, the area of the flow must be inferred. I used the character of the exposed flow to speculate the flow field. I also used typical flow characteristics to deduce the area, for example aa flows tend to widen, not lengthen over time (Sigurdsson 2000). Flows that are not well exposed were not extrapolated and their areas were not determined. The area of the pahoehoe flow was not calculated either because it may have been produce by an adjacent aa flow.

Results

Composition

The Harker diagrams separated by surface structures comparing silica with MgO and Fe_2O_3 showed no correlation (Fig. 1). The aa flows were grouped fairly well in the silica vs. Fe_2O_3 plot. Beyond this minor correlation, the data for the aa and ogive flows was scattered. The only consistent pattern within the plot was the extreme differentiation of the pahoehoe flow with the rest of the samples. The pahoehoe lies adjacent to a steeper aa ridge, and it is possible that it is not an independent flow but was produced by another aa flow. The plot that separates the flows into basaltic andesite and andesite has a very interesting correlation. The two types of flows split into two separate linear trends with the exception of one andesite flow.

Crystallinity

The crystal abundance of each sample did not significantly vary. It ranged from 30 to 40%. In each flow plagioclase was the most common phenocryst followed by orthopyroxene, clinopyroxene, and olivine, respectively. Within the ogive flows there is variation in phenocryst size (Fig. 2). Doom 2 and 3 both contain a high quantity of small crystals, averaging 1.1 mm. The other two ogive flows have a much higher abundance of large crystals although there is a mixture of large and small phenocrysts. Doom 14 has an average plagioclase crystal size of 2.3 mm. Most of the aa flows have similar phenocryst sizes to Doom 14 and 19. The one exception is Doom 15, which has much smaller phenocrysts than the other aa flows (Fig. 2).

Effusion rates as a function of area

Three of the ogive flows were measured to have the largest areas, Doom 2, 3 and 19. All of the aa flows had smaller flow areas. The Doom 14 ogive flow has a smaller area than the Doom 15 flow area but is larger than the other aa flows (Fig. 3).

Discussion

Viscosity

The XRF data did not show any correlation between the aa and ogive flows (Fig. 1), implying that composition does not have an effect on the surface texture of a flow. It is interesting that the pahoehoe flow was an outlier in all plots. It is extremely rare for a basaltic andesite or andesite lava to form a pahoehoe flow (Francis 2004). From field observations, it seems as though the pahoehoe flow was the result of hot internal lava draining from an aa flow because it is emplaced directly against the higher aa flow where doom 18 was taken. This aa flow contains a hornito, which is created by expansion of gas within the flow. This same process could have created the small pahoehoe flow because pahoehoe flows typically contain gas that is actively expanding while the flow congeals (MacDonald 1972). Internal lava with a high quantity of expanding gas could cause the aa crust to break and form a small pahoehoe flow. Thin sections and hand samples show that the pahoehoe flow (Doom 17) has a much higher percentage of vesicles than Doom 18. Doom 17 contains about 20% vesicles that are much larger than the vesicles in Doom 18, which has about 10% vesicularity.

There was no significant pattern detected in the abundance or size of the phenocrysts (Fig. 2), suggesting that crystallinity is not a control. If crystallinity were the controlling factor, data would most likely show that the aa flows contain a higher abundance of crystals because it increases viscosity. Polydispersity of crystals within a flow can also decrease its viscosity. Both the aa and ogive flows had a wide range of crystal sizes, showing that it did not affect the structure of flow even if it did control viscosity. Therefore, there is no evidence for crystallinity being the controlling factor.

Another control on viscosity is volatile content within the magma. The high percentage of plagioclase crystals implies a water content less than 2-5 wt% because plagioclase stability decreases with higher water contents (Hobden 1997). This limited fluctuation in water content could imply that volatiles did not control viscosity and therefore surface structure in the magma. On the other hand, it has been found that an increase in wt% H_2O in a magma with a low water content has larger effects on viscosity than a magma with an already high water content (Richet et al. 1996). Water content could have caused changes in viscosity, since there is not evidence in from the data, it is undetermined whether or not it had an effect on the type of lava flow.

Effusion Rate

With the exception of Doom 15, the ogive flows have higher areas than the aa flows (Fig. 3), suggesting the ogive flows had a higher effusion rate and could be a controlling factor. Typically, aa flows have higher effusion rates than pahoehoe flows, which contrasts the data from this study. This result needs to be investigated at closer detail due to the possible error. Although a linear relationship between effusion rate and flow area has proven to be accurate in comparison with ground measurements, the model assumes the flow area is mainly controlled by heat loss and neglects volume and topography (Harris et al. 2007). If a flow was not temperature limited, the linear relationship does not stand true. It is possible that the flows from Ngauruhoe are strongly influenced by topography because previously formed glacier features and other Tongariro vents determined the flow paths. There is also probable error in the calculations of the lava flow areas because the only fully exposed flows are from the historical eruptions.

Slope

Changes in slope encountered by a single lava flow can easily alter the rheology and flow structures of the existing flow. At Mt. Etna, steep slopes are characteristic of long lava tubes or channels, and a transition to a flatter slope creates ephemeral vents and overlapping lava tongues (Polacci and Papale 1999). It is possible that variations in slope as Ngauruhoe developed altered the types of flows. Four of the ogive flows in Mangatepopo Valley are the oldest flows. A shallow slope of a young volcano could create the surface features seen on the lava. As that volcano grew and became steeper, the velocity of the erupted lava increased. This creates more stress on the crust causing it to break and form a rubbly, aa surface. Hobden (1997) argues that the steep slope of the volcano created the surface features of the 1870 flow (Doom 11) by breaking up the flow into loose blocks. As Polacci and Papale stated, a steep slope easily forms long tubes or channels, and some of the younger flows exhibit these characteristics, Doom 11 and Doom 14. Doom 14 also contains ogives from the flows between marginal levees where the sample was taken. On Mount Etna, flows with pahoehoe or toothpaste morphologies commonly occur within the margins of aa flows due to a decrease in discharge rate (Calvari & Pinkerton 1999). This could be the case for the levees channeling an ogive flow, if the discharge rate slowed toward the end of the eruption.

Conclusion

I found that slope is the most probable control on lava surface structures. The older flows have a morphology typical of a shallow slope, and the younger flows are more characteristic of steep slopes. Viscosity did not prove to control textures through crystallinity or composition although the pahoehoe was anomalous in terms of composition. Volatile content may be a factor but conclusions cannot be made based on the current data. Effusion rates did correlate with the type of lava flow, but they were not characteristic of each flow. Typically, aa flows have higher effusion rates, but data showed that the ogive flows had the higher effusion rates. Because Ngauruhoe has exhibited such a wide range of eruptions, understanding the controls on its effusive eruptions can help us understand the character of lava flows in future eruptions, which has great implications for hazard management.

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Captions

Figure 1. Harker diagram plotting SiO_2 vs. MgO. Points are split into aa flows, ogive flows and the pahoehoe flow. Vertical line represents transition from basaltic andesite to andesite.

Figure 2. Thin section photos of Doom 3, 4, 15 and 19 showing differences and similarities in plagioclase crystal size and abundance between ogive and aa flows. The white scale bar is 500μm, and all thin sections are magnified to 4X.

Figure 3. A theoretical linear curve when area of flow vs. the effusion rate is plotted. The calculated areas of each flow were plotted to fit the curve to compare the ogive flows and aa flows.

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