

# CLASTOGENESIS AS A RESULT OF REACTIVATION OF AGGLUTINATED SPATTER

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## INTRODUCTION

Hawaiian style volcanism is dominated by fissure eruptions and fire fountaining. Clasts of molten spatter erupted from these fissures and cones often accumulates on hill-slopes and can remobilize as a clastogenic lava flow under the right conditions. Quantifying the factors controlling the development of clastogenesis is critical in understanding a rather unpredictable and potentially hazardous volcanic process.

Clastogenic flows form by coalescing from accumulated spatter, but little is known about how remobilization actually occurs. Clastogenesis can occur in two ways: as a rootless flow, where clasts of very hot spatter accumulate so rapidly that they immediately coalesce and flow away, or when a pile of agglutinated spatter remobilizes under some critical height, assuming an accumulation rate fast enough that sufficient heat is retained within the cone (Rader and Geist, 2015; Sumner, 1998; Head and Wilson, 1989; Smith et al., 1999). Clastogenesis in this study will mean the latter type.

The main factors controlling the development of clastogenesis are yield strength and basal shear stress, which are dependent on accumulation rate, cooling rate, cone height, and slope. The internal temperature of a spatter cone is dependent on the accumulation rate, and the yield strength is dependent on those temperatures. Calculating the yield strength and basal shear stress of an agglutinate mound as it cools and determining the point where shear stress surpasses yield strength forms the basis for a model

of clastogenic flow. Field observations from Krafla, Iceland, geochemistry, and vesicle strain analysis supplement and support this model (Fig. 1)

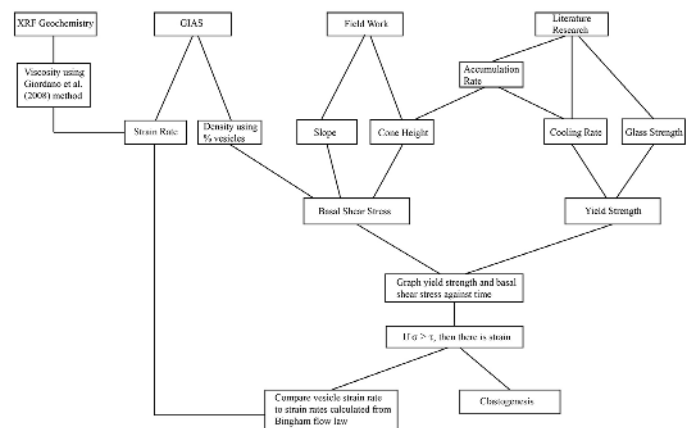


Figure 1. Chart illustrating the methods used in the model of clastogenesis, the data and measurements obtained from each method, and the way in which these results were combined to derive the critical point for clastogenic flow.

## CONTROLLING FACTORS OF CLASTOGENESIS

### The Bingham Flow Law

When spatter erupts from a fire fountain, its exterior quenches before landing, developing a glass rind while retaining a molten interior. Due to this shell, the general behavior of spatter follows the Bingham flow law (Eq. 1).

$$\sigma = \tau + \eta \dot{\epsilon}^n \quad \text{Eq. 1}$$

The basal shear stress is  $\sigma = \rho g h \sin \theta$ , and the yield

strength is  $\tau$ .  $\eta$  is the viscosity and  $\dot{\epsilon}$  is the strain rate. For Bingham substances,  $n = 1$  (Fink and Zimbleman, 1990; Griffiths, 2000). When the basal shear stress is greater than the yield strength, strain develops and flow may occur.

## Clastogenesis in the Field and Experiments

Clastogenic flows are more texturally heterogeneous than vent overflow lavas and often consist of spatter distributed across a flow of deformed and coalesced agglutinate with variable vesicularity. Such features are consistent with slippage along a fluid basal viscosity layer (Sumner, 1998; Smith et al., 1999). Clastogenic flows predominantly occur at a proximal or intermediate distance from the vent, where emplacement temperatures are highest but accumulation rates moderate, such that hot clasts are cool enough to agglutinate on impact rather than flowing away immediately (Fig. 2) (Smith et al., 1999; Head and Wilson, 1989). Once a critical height on a relatively steep slope is reached, clastogenesis may occur. Four small spatter cones at Krafla were investigated. Only one, the North Slope Cone, on the north side of the prominent Hófur Cone, exhibited convincing evidence of clastogenesis (Fig. 2). The other cones exhibited substantial compaction but no clastogenesis (South West Cone, Far North Cone, and Tube Cone).

At Syracuse University, we attempted to recreate spatter and clastogenesis using remelted basalt poured from a gas-fired tilt furnace. Ground slope was set at  $5^\circ$ . Surface temperature was measured with a FLIR camera. No clastogenesis occurred; future experiments at higher slope angles are needed to replicate field conditions. However, samples from the pile do show evidence of small scale melt mobilization in the form of glassy bands.

## Slope and Agglutinate Mound Height

Due to the influence of gravity, greater spatter cone height and steeper basal slopes increase the basal shear stress. As the cone grows, the layers of spatter begin to compact at the base and weld into foliated agglutinate, a feature observed in clastogenic lavas at Izu-Oshima Volcano, Japan, Vulcan Cone, Albuquerque Volcanoes, NM, and spatter cones at Krafla (Grunder and Russell, 2005; Sumner, 1998; Smith et al., 1999). Slope and cone height of the four spatter cones at Krafla are summarized in Table 1.

## Geochemistry and Viscosity

Geochemical XRF analysis of samples taken from the four spatter cones reveals no significant difference in major, minor, or trace element concentrations between cones with clastogenesis and those without.

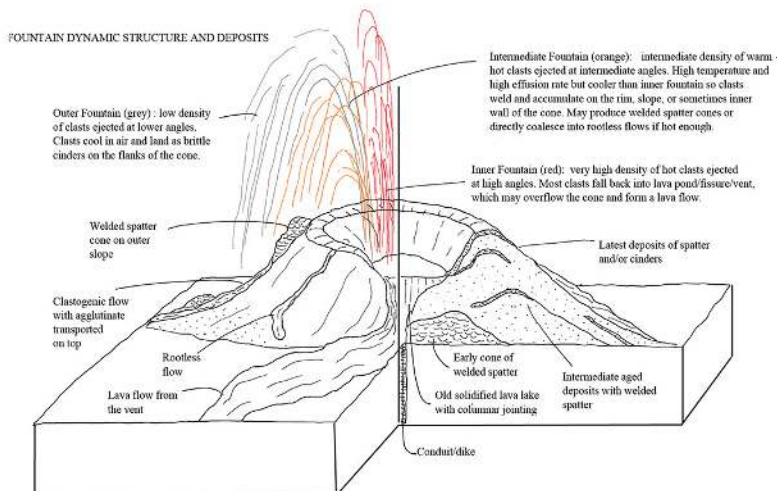


Figure 2. Diagram: Hawaiian style fire fountain illustrating the various types of spatter deposits and where they occur in proximity to the vent. The left side of the diagram shows modern surface volcanics and processes. The right side shows older volcanics and the interior structure of the larger cone (Modified from Head and Wilson, 1989 and Smith et al., 1999). This generalized diagram is remarkably similar to the actual Hófur cone at Krafla. Photograph: North Slope Cone at Krafla. The red line shows the direction of the clastogenic flow from the base of the cone. The white circle outlines a large piece of the cone/agglutinate that was transported by the clastogenic flow. The purple line shows a possible rootless flow, much like in the diagram to the left.

| Spatter Cone     | Compaction? | Clastogenesis?  | Slope      | Height        |
|------------------|-------------|-----------------|------------|---------------|
| North Slope Cone | Yes         | Yes             | 30°- 40°   | ~ 3.5 – 4 m   |
| South West Cone  | Yes         | Rudimentary     | ~ 10°- 24° | ~ 1.1 – 2.5 m |
| Tube Cone        | Minor       | No (vent flows) | ~ 30°      | 1.1 m         |
| Far North Cone   | Yes         | Rudimentary     | ~ 5°       | ~ 1.5 – 3.9 m |

*Table 1. Summary of flow types, slope, and cone height at each of the four spatter cones observed at Krafla. Rudimentary means there was welding and compaction and/or evidence of melt mobilization or deformation within the cone but no convincing evidence of flow.*

However, using Giordano et al.'s (2008) method, major oxide data was used to calculate the viscosity of the agglutinate as a function of temperature. This viscosity was averaged across all the samples from each individual cone to construct a general viscosity curve for Krafla lava. These viscosities are important for estimating strain rates and in applications of the Bingham Flow Law.

### GIAS and Vesicle Strain Analysis

Pure shear from compaction should be evident in samples from the base of the cone, where vesicles should have deformed from spherical to ellipsoidal. Using MATLAB, Geological Image Analysis Software (GIAS) processes binary photomicrographs of thinsections, conducts a spatial distribution pattern (SDP) analysis of the vesicles, and provides geometric measurements of the vesicles (Beggan and Hamilton, 2010). These measurements, along with the calculated viscosities, can then be used to estimate strain rate (Rust et al., 2003).

At Izu-Oshima Volcano, Japan, Sumner (1998) did not observe a consistent increase in strain ratio or a decrease in porosity in the more densely welded layers, which were often excessively vesiculated with both spherical and deformed vesicles. Such observations are consistent with the Krafla study. Even though there is visible flattening of vesicles in thinsection, there is no quantitatively consistent increase in strain towards the bottom of the cone according to GIAS. However, there may be some error in the software's ability to measure the vesicles, and the sample size of only four thinsections per cone may not be sufficient to identify statistically significant changes in strain. After porosity has been reduced by about 5%, vesicle compaction may not record evidence of further strain. Nevertheless, strain may be

accommodated by deformation via viscous flow within the deposit or by the whole deposit (Grunder and Russell, 2005). Thus, the degree of strain in vesicles is a first order indication of the strain required to initiate melt mobilization.

There is a clear relationship between strain rate and viscosity. On the assumption that heat is insulated uniformly throughout the mound, we can average the strain rates as a function of viscosity from each sample to develop a general strain rate vs. viscosity curve for each cone (Fig. 3). The cones that did not produce clastogenic flows actually have slightly higher strain rates for given viscosities than the cone that did produce clastogenic flows. However, lower recorded strain in the North Slope Cone thinsections may actually imply that it underwent greater strain due to strain rate's dependency on bubble size, which is a function of surface tension. If the strain was great enough to break bubbles into chains of smaller bubbles, the strain signature could be reset. This scenario requires future investigation and experimentation.

### Accumulation Rate and Cooling Rate

Accumulation rate controls the degree to which the spatter is insulated, with a greater number of clasts landing per unit time allowing for greater heat retention. Rader and Geist (2015) cite agglutinate cooling rates ranging from 7 °C/min to as low as 0.0028 °C/min and accumulation rates capable of producing clastogenic flows between 10 and 36 m/hr. There is a linear relationship between the natural logs of cooling rate and accumulation rate, determined from experimental data (Figure 4a) (Rader and Geist, 2015). Accumulation rates and their corresponding cooling rates will be tested in a model of yield strength and basal shear stress versus time.



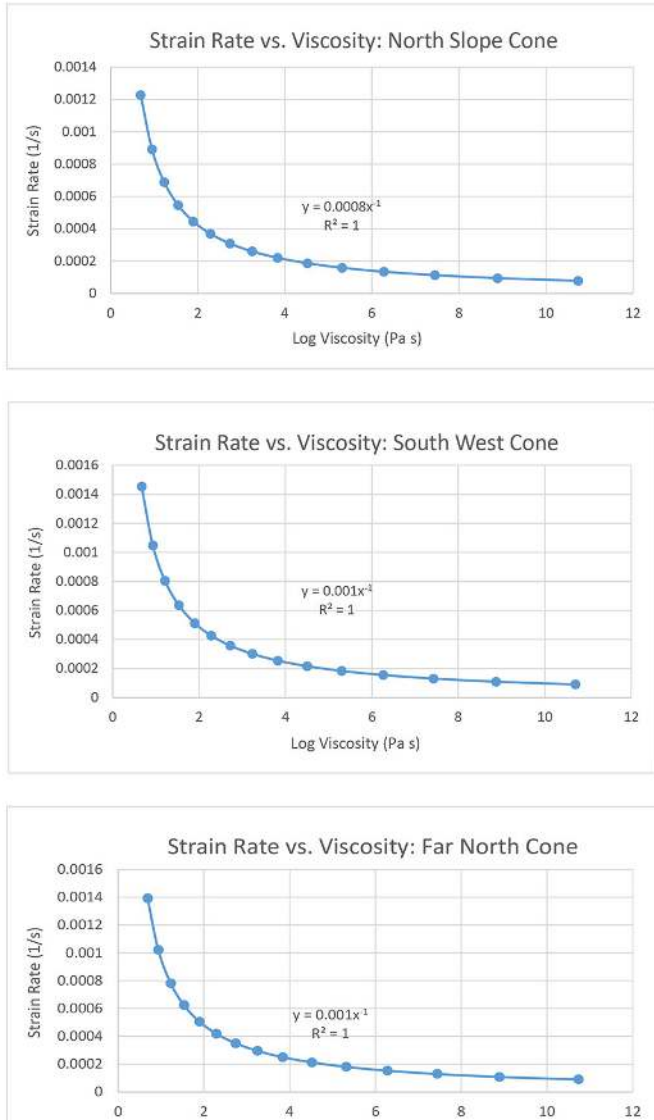


Figure 3. Plots of the average strain rate as a function of viscosity for the NS Cone, SW Cone, and FN Cone. Note that the two cones that did not produce clastogenic flow (SW Cone and FN Cone) generally have a higher strain rate for a given viscosity than the NS Cone, which did produce a clastogenic flow.

## Yield Strength

Yield strength quantifies when clastogenesis will occur and is defined mainly by cooling rate. Dragoni (1989) developed an equation describing the relationship between the yield strength of lavas and temperature, where strength increases exponentially below the liquidus temperature ( $T_L$ ). Because spatter cools in the air, the clasts are bound by a thin glassy rind, which forms a vitreous interclastic framework within the cone. The glass provides sufficient structure that despite the high internal temperature of the mound, the spatter can pile up and agglutinate prior

to remobilizing. Van Otterloo et al. (2015) estimate that the tensile strength of volcanic glasses is on the order of 30 MPa. Due to impurities such as vesicles and the thinness of the rinds, this can be reduced to an estimate of ~30 kPa (Eq. 2). Given a sufficient accumulation rate, enough heat should be retained within the agglutinate mound's structure to eventually melt through this glassy matrix. If such melt migration occurs in conjunction with a high enough basal shear stress, then the cone or pieces of it will destabilize and become a clastogenic flow.

$$\tau(T) = \tau_0 [e^{b(T_L - T)} - 1] + 30,000 \quad \text{Eq. 2}$$

In Equation 2,  $\tau_0$  (0.01 Pa) and  $b$  (0.08 1/°C) are experimentally determined parameters from Dragoni (1989), and the 30,000 accounts for the glass strength. For modeling purposes, temperature is given as the initial clast temperature (1130°C) minus cooling rate times time.

## CLASTOGENIC MODEL AND CONCLUSIONS

Ultimately, the onset of clastogenic flow occurs where basal shear stress exceeds yield strength. Density (1017 kg/m<sup>3</sup>) is a weighted average of melt density; gas density, given the high vesicularity (average 89%) obtained from GIAS; and glass density, from the rinds around the clasts. Accumulation rate determines height. These parameters determine basal shear stress. Different accumulation rates and their corresponding cooling rates are tested in the model of clastogenesis to determine when clastogenesis will occur, in terms of the accumulation rates necessary and at what time and height the agglutinate will yield. In a model set for an initial slope of 40°, accumulation rates greater than or equal to 11 m/hr are sufficient to produce clastogenic flows. At 11 m/hr, clastogenesis occurs after about 26 min of eruptive activity but only lasts for about 10.5 minutes, since yield strength again rises above the basal stress (Fig. 4b). The predicted failure height for these conditions is 4.8 m. The higher the accumulation rate, the earlier the point of failure and the longer the duration of clastogenic activity.

Given that the predicted failure height is very similar to the actual height of the North Slope Cone measured in the field, this clastogenic model is consistent with field observations. Moreover, while the duration of the

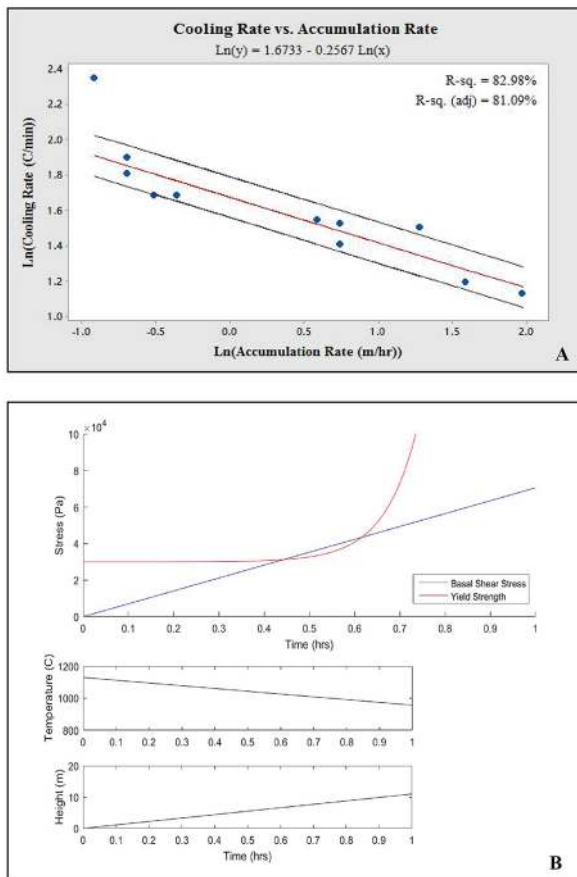


Figure 4. a) Linear regression model of the relationship between accumulation rate and cooling rate of 5 cm clasts from experimental data from Rader and Geist (2015). Other statistical tests show that the linear model is appropriate for these data, and based on the  $R^2$  value there seems to be a rather strong correlation. Accumulation rates ranging between 2 m/hr and 36 m/hr and their associated cooling rates were tested in the clastogenic model. b) General model for the critical point of clastogenesis on a 40° slope and with an accumulation rate of 11 m/hr. Clastogenesis begins after 26.4 minutes of continuous eruptive activity and ceases after 10.5 minutes. Failure temperature is 1054°C and failure height is 4.8 m, similar to the actual height of the North Slope Cone measured in the field.

flow seems short, the extent of the clastogenic flow at the North Slope Cone was minor, so this may have been just enough time to detach some agglutinate and send it downslope on a fluidized layer. It is also logical to assume that the cone prior to remobilization was a bit taller than it is now due to cone material being removed during the process of clastogenesis and due to subsequent weathering and erosion.

From the Bingham flow law, the difference between shear stress and yield strength when  $\sigma > \tau$  equals the viscosity times the strain rate. Using the maximum

differences in shear stress and yield strength during clastogenesis from the 40° slope model and the viscosities of the agglutinate at those points of maximum stress difference, the maximum predicted strain rates range from 1.39 1/s to 36.16 1/s for accumulation rates between 11 m/hr and 36 m/hr, respectively. Based on the strain rates for each of these viscosities at the North Slope Cone, determined from GIAS (Figure 3), the vesicles appear to accommodate a maximum of only ~0.017% of the total predicted strain.

This model assumes a constant accumulation rate and constant linear cooling rate; however, real rates are likely not constant or linear. The cone will cool as a function of time, height, and accumulation rate, and the accumulation of material may occur episodically and still be high enough to generate clastogenesis. Future work on this model should address variations in these rates. Modeling the heat diffusion out of the individual clasts and how it can potentially remelt the glassy skins is also key to understanding the stability of a spatter cone and should be investigated in future studies. The general model presented here is consistent with field observations. Overall, at high slopes, clastogenesis is possible at accumulation rates of 11 m/hr or higher. On lower slopes, higher accumulation rates are needed.

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