THE DYNAMICS OF CHANNEL-FED LAVA FLOWS. Harry Pinkerton and Lionel Wilson, Institute of Environmental & Biological Sciences, University of Lancaster, Lancaster LA1 4YQ, U.K.

The factors which control lava flow length are still not fully understood. The initial assumption that flow length was mainly influenced by viscosity was contested by Walker (1) who proposed that the length of a lava flow was dependent on the mean effusion rate. Malin (2), on the other hand, found a poor relationship between length and effusion rate for 84 Hawaiian flows and he concluded that flow length was dependent on erupted volume. We argued previously (3) that these differences arose because Walker tried to restrict his data set to flows which cease to advance because of cooling, whereas Malin included many immature flows whose lengths were limited by the volume of lava erupted. These flows are referred to respectively as cooling-limited and volume-limited flows (3, 4). We also recognise that many flows are channelled down pre-existing depressions; these channelled flows will be thicker and hence cool more slowly than unconfined flows. Other types of flows which have the potential to flow further than unconfined channel flows are tube fed flows which are fed by established lava tubes. By contrast, some flows do not travel as far as expected. These breached flows escape from their well-established channels, normally because of blockages of the channel by collapsed levee material.

A reanalysis of Malin's data has shown that those Hawaiian lava flows which are longer than predicted using Walker's relationship were tube fed flows, whereas those which are shorter than predicted were immature volume-limited flows which were fed for less than two days. The remaining high duration channel-fed flows fit within Walker's limits. Thus, while Walker's relationship has been confirmed for all mature, channel-fed flows that we have analysed, it predicts flow lengths only to within a factor of 7. Factors other than effusion rate are therefore important in controlling the lengths of lava flows.

In order to assess the relative importance of the factors which influence flow length, we have analysed the very comprehensive set of data for the recent Pu'u 'O'o Episode 1 to 48 flows erupted from the eastern rift zone of Kilauea (5). The best fit equation between their length and effusion rate is: \( L=2290E^{0.12} \) (correlation coefficient, \( C_C=0.19 \)). The relationship between length and volume, given by \( L=0.6V^{0.57} \) (\( C_C=0.75 \)), is improved when we investigate the relationship between length, effusion rate and time (\( L=0.66E^{0.50}T^{0.80} \); \( C_C=0.83 \)). When we add the effects of slope, the best fit equation becomes \( L=2.75E^{0.43s0.64}T^{0.53} \) (\( C_C=0.88 \)) and when we calculate the conductive heat loss from the flows by including the dimensionless Grätz number, the improved relationship is \( L=5.2E^{0.48s0.50}T^{0.50}G^{0.26} \) (\( C_C=0.90 \)). The correlation coefficients increase to a maximum value of 0.97 if we also take into account the differing rheological properties of Episode 1 to 10 flows compared with the Episode 11 to 20 and 21 to 48 flows (6) by analysing each batch independently. From this analysis, it is clear that the majority of Pu'u 'O'o flows are volume-limited. If we restrict our analysis to those which are cooling limited, the relationship between effusion rate and length improves, as predicted by our earlier analysis (3), and the relationship is given by \( L=1230E^{0.46} \) (correlation coefficient, \( C_C=0.76 \)). Thus, using this simple statistical analysis, we have developed equations which are considerably better predictors of flow length for recent Hawaiian flows than published treatments. However, the equations presented here, in common with those presented by Malin (1980), are not dimensionless and they have been tested only on flows from Hawaii. We therefore require an alternative method of determining flow dimensions which can be used both as a predictive tool in volcanic hazard studies and retrospectively to determine the eruption dynamics of terrestrial or planetary flows.

While an assumption of isothermal flow behaviour (7, 8) may be appropriate for unconfined, high effusion rate, low duration flows, we argue that, for all other flows, cooling of the flow margins will influence the dimensions and rates of advance of the flows. Evidence in support of this can readily be obtained by observing active basaltic flows, some of which experience breakout of relatively uncooled lava from the flow fronts. The relatively rapid advance rate of the new front, together with the concomitant reduction in channel height behind the old front, confirms that the lava in channels behind established flow fronts has a height which is greater than would be achieved by an isothermal, unconfined flow (9). Thus realistic models of lava flows must incorporate cooling of lava and rheological changes in the distal regions of the channel and front. The amount of cooling controls the rheological properties of the front, and this in turn is one of the main factors controlling the thickness and advance rates of the rest of the flow.

Our model is based on an isothermal Bingham flow model (7, 8), but differs significantly from it. It calculates conductive heat loss form the flow, and this is used to calculate the changing channel and levee dimensions and flow front velocities as the flow advances. In addition, unlike previous models, it does not assume that the thickness of flows is everywhere equal to the thickness dictated by a unique yield strength of the flow, since, as we
argued previously, flow thickness is dependent on topographic channelling as well as the properties of the active flow front. Available field measurements (11,12) suggest that the ratio of yield strength to viscosity varies systematically from the vent to the front of a lava flow. The relationship between mean flow depth and flow length for any flow can either be calculated (12,13), or it can be established using measurements of the depths of compositionally similar flows which flow down similar gradients. Using the computed cumulative Grätz numbers (GZ), the variations in widths of channel (wc), levee (wb) and total width as a function of cooling, and hence distance from the vent, can be calculated for any combination of effusion rate (E), slope (α) and flow depth (d):

\[ w_c = \left( \frac{244 E^4}{[\alpha^7 d (0.5(GZ/2.105)^0.09)]^1/11} \right) \] ...........................................(1)

or \[ w_c = \frac{241}{E^{1/3}} \left( \frac{1}{\alpha^{2/3}} \cdot d \right) \left( 0 < w_c/w_b < 1 \right) \] ..................................................(2)

and \[ w_b = \frac{d}{2\alpha} \] .........................................................(3)

Flow lengths (L_cum) can now be calculated from:

\[ L_{cum} = \Sigma(E\Delta t/(w_c+w_b)) \] ..............................................(4)

In order to test the validity of this approach, we have applied the method to Mauna Loa Flow 1A which was erupted in 1984 and which we argue, using the field description in (13), is cooling-limited. Using the published channel dimensions and velocities (10,13), the cumulative Grätz number of lava in the channel is readily calculated (see 4). The cumulative Grätz number construction in Fig. 1 demonstrates that, when the lava achieved its maximum length of 27 km, the Grätz number had dropped to 290. Observation of cooling-limited flows on Etna (9) and Hawaii (3) indicates that the critical Grätz number is ~300. Flow 1A is therefore confirmed as a cooling-limited flow. Calculated and measured advance rates are compared in Fig. 2, where it can be seen that there is very good agreement. We therefore have a working model which can determine the dimensions, advance rates and dynamics of planetary flows erupted at different effusion rate (shown in \( m^3/s \)) down a slope of 5.5°.