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

During the past 20 years considerable advances have been made in modelling the behaviour of lava flows. Earlier models were based on the assumption that the rheological properties of lava flows could be approximated by a newtonian model (1-3). While this assumption may be valid for the growth of silicic domes (4), it is clearly not valid for the thinner flows whose dimensions are strongly influenced by their non-newtonian properties (5, 6). The development of isothermal Bingham flow models (7,8) has proved to be useful in understanding the factors which control the width and thickness of lava flows. However, the isothermal assumption has been questioned, and a number of models have been developed which calculate the heat loss and the hence the resulting dimensions of lava flows (9-13). However, the factors which control flow length are still not fully understood.

The initial assumption that flow length was mainly influenced by viscosity was contested by Walker (14) who proposed that the length of a lava flow was dependent on the mean effusion rate. Malin (15), 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. A study of recent flows on Mount Etna and on Hawaii has confirmed that some flows (e.g., the high-effusion rate 1981 flow on Mount Etna) are limited by erupted volume, whereas the lengths of many individual flows are limited by cooling of the flow margins, which is in turn a function of effusion rate (16, 17). A re-analysis of Malin's (15) data has shown that those hawaiian lava flows which are longer than predicted using Walker's (14) relationship were fed by mature tubes, whereas those which are shorter than predicted were fed for less than two days. If, following Walker (14), we omit, from Malin's (15) data set, the low-duration flows and if, in addition, we omit the mature tube-fed flows because they cool less rapidly and hence have the potential to flow further than channel-fed flows (18) then all of Malin's data fit within Walker's limits (Fig. 1).

The apparent conflict between the empirical effusion rate (14) and volume (15) flow length models is therefore resolved. But confirmation that the effusion rate relationship (14) holds for only channel-fed flows with durations greater than 2 days restricts its usefulness. Also, using the effusion rate relationship (14), the length of a flow can, for a given effusion rate, vary by a factor of 7. An alternative method of determining flow length is therefore required.

Factors other than effusion rate are therefore clearly important in controlling the lengths of lava flows. Although the erupted volume is an important parameter which controls the lengths of flows, many flow fronts stop advancing even though lava is still being erupted from the vent. In some of these flows, the main channel may have become blocked by portions of the solidified channel wall which become dislodged and subsequently dam the main channel. Lava then spills over the levees and, in cases where the blockage becomes total and permanent, a new flow is formed. This process has been reported on Etna (17) and Hawaii (19). However, not all breaches are the result of channel blockage. Some flows stop advancing because the strength of the cooled margins exceeds the stresses generated at the base of the flow. Lava from the relatively uncooled interior can then break through the sides of the flow forming a new flow or lobe (16, 17, 19). We can therefore distinguish between 3 types of lava flow: volume-limited flows, whose lengths are functions of the erupted volume; breached flows with lengths which are dependent on the accidental blockage of the main channel; and cooling-limited lava flows which have lengths which are controlled by the amount of cooling which the flows have experienced.

It has been shown (12, 16, 20) that the maximum lengths of cooling-limited flows are dependent on the conductive heat loss of a flow. This can be calculated using the dimensionless Gratz number:

$$G_{Z} = \left(\frac{n^{2} \cdot E \cdot d}{\kappa \cdot W_{c} \cdot L}\right)$$

where \(n\) is the ratio of equivalent diameter (21) to flow depth; \(E\) is the mean effusion rate; \(d\) is the mean flow depth; \(\kappa\) is the thermal diffusivity; and \(L\) is the flow length. The theoretical channel width, \(W_{c}\), can be calculated if lava behaves as a Bingham fluid (12, 22). The maximum theoretical length is then:

$$L_{\text{max}} = \left[\frac{n^{2} \cdot E^{2/3} \cdot (\gamma \cdot \eta)^{1/3}}{\kappa \cdot W_{c} \cdot L}\right]$$

where \(\tau\) is the yield strength of the distal part of a lava flow; \(\eta\) is its Bingham viscosity; \(\gamma\) is the mean gradient; and \(G_{Z_{\text{crit}}}\) is the critical Gratz number of the flow when it stops advancing. Observation of cooling-limited flows on Etna and Hawaii suggest that the critical Gratz number is 300. Available field measurements (5, 6, 23, 24) suggest that the value of \((\gamma \cdot \eta)^{1/3}\) ranges from about 0.6 at the vent to about 0.2 at the front of basaltic flows. A value of 0.2 has also been found for recent proximal andesitic flows on Arenal, Costa Rica (25).

In addition, the relationship between mean flow depth and flow length can either be calculated (11) or it can be established using measurements of the depths of compositionally similar flows which flow down similar gradients (26). Equation (2) can therefore be used to predict the maximum cooling-limited length of a lava flow given only the mean effusion rate and the mean gradient of the ground over which the flow will advance.

Similarly, the lengths, \(L_{\nu}\), of volume-limited lava flows can be estimated (12) using the following equation:

$$L_{\nu} = \left[\frac{\alpha^{2} \cdot E^{2/3} \cdot (\gamma \cdot \eta)^{1/3}}{\kappa \cdot W_{c} \cdot L}\right]$$
Applying this equation to data from the 1983-84 Pu‘u ‘O‘o eruptions (26, 27) gives reasonable agreement (Fig. 2), and when equation (3) is modified to take into account the changing rheological properties of the flows as they advance, the resulting non-isothermal equation improves the correlation between calculated and measured lengths:

\[ L_C = 0.0082 n \alpha^{2/3} E^{2/3} (\tau_0)_{\frac{1}{2}} \]

Differences between observed and calculated flow lengths are attributed to (i) fluctuations in effusion rate (10, 28); (ii) variations in slope and (iii) topographic channeling which prevents flows from attaining their predicted width (29). To improve the model, these changes should be taken into account. A cumulative conductive cooling model has been developed (17), permitting the maximum lengths of cooling limited flows to be calculated more accurately than is possible using mean flow properties. Similar methods can be developed to improve equation (4), though more refined methods are clearly less useful as predictive tools than equations based on estimated mean effusion rates and gradients.

Although the method has been developed for basaltic lavas, it can also be applied to andesitic and possibly to rhyolitic lava flows. Measurements of the viscosities and yield strengths of andesitic lava flows on Arenal, Costa Rica (25) confirm the usefulness of a Bingham model for these flows, and they suggest that, although viscosity and yield strength of the distal flows are several orders of magnitude higher than for basaltic flows, the ratio of yield strength to viscosity is comparable. The cooling limited lengths of the 1974-80 flows on Arenal are calculated to lie in the range 1.1 to 2.4 km, compared with measured lengths (30) of 1.0 to 2.5 km. More generally, the model correctly predicts that, while the more siliceous lava flows advance at generally slower rates than basaltic flows, their maximum flow lengths, for a given effusion rate, will be greater than for basaltic lava flows.