THERMAL AND RHEOLOGICAL CONTROLS ON MAGMA MIGRATION IN DIKES: EXAMPLES FROM THE EAST RIFT ZONE OF KILAUEA VOLCANO, HAWAII; E.A. Parfit1, L. Wilson1,2 and H. Pinkerton2. 1Geological Sciences Department, Brown University, Providence, RI 02912, U.S.A. 2Environmental Science Div., Lancaster University, Lancaster LA1 4YQ, U.K.

Abstract: Long-lived eruptions from basaltic volcanoes involving episodic or steady activity indicate that a delicate balance has been struck between the rate of magma cooling in the dike system feeding the vent and the rate of magma supply to the dike system from a reservoir. We describe some key factors, involving the relationships between magma temperature, magma rheology and dike geometry, that control the nature of such eruptions.

Background: The two longest-lived eruptions of Kilauea volcano this century were the 1969-1974 eruption at Mauna Ulu and the 1983-1990 eruption at Pu’u ‘O’o and Kupaianaha. Both eruptions involved periods of episodic activity, in which a relatively high magma discharge rate episode would be maintained for about one day after an interval of up to about one month during which the discharge rate was very low or negligible. Both eruptions also involved periods when the discharge rate was nearly constant, but at a low rate which corresponded to the total magma mass erupted during one of the episodic cycles divided by the total duration of the cycle.

Magma flow in dikes to feed eruptions that continue for long periods can only take place when a delicate balance exists between the rate of cooling of the magma in the dike and the rate of supply of new magma to the dike from the magma reservoir. Various aspects of the cooling process have been considered by several authors, and conditions have been explored under which the mass flux of magma is likely to decrease with time as cooling through the dike walls dominates, or increase with time as heating, thermo-mechanical smoothing and possibly thermal erosion of the walls occurs or as viscous dissipation takes place [1-5]. These treatments draw a strong distinction between laminar and turbulent flow in the dike magma. Recently, it has been proposed that lateral heat transfer (due to advection caused by dike width irregularities and the presence of vertically migrating gas bubbles or crystals) can be efficient enough that a magma moving in a nominally laminar fashion in a dike may cool in a way much closer to that of a magma in turbulent motion [6]. This has strong implications for the variation, with distance from the source reservoir, of the mean magma temperature, the temperature profile across the dike, and the temperature of the interface between the magma and the dike wall.

The most elaborate calculations of this type so far have allowed only for the monotonic narrowing of a dike with distance from its magma source [6]. However, there is good evidence that the dike system feeding the long-lived Pu’u ‘O’o-Kupaianaha eruption on Kilauea was formed by the linking together, by a new intrusion, of a small number of pre-existing dike segments which represented the still partly molten remains of earlier intrusions. This would have led to significant variations, with distance from the summit reservoir, of the width of the dike, and hence to significant spatial variations of the effects of cooling on the temperature profile [7].

Temperature (and, to a lesser extent, pressure) variations in a magma cause rheological changes, directly, by changing the structure of the liquid, and indirectly, when the composition of the liquid changes as crystals form. The presence of such crystals (and of any gas bubbles which form) is an additional major source of rheological variations. The rheological properties of a magma, which can be extremely non-Newtonian and time-dependent, determine the rate at which it will deform under a given shear stress and hence the velocity profile that will develop within a dike when magma is moving in it. The fact that a magma may possess a finite yield strength means that it may not flow at all unless the pressure gradient applied to it exceeds some threshold value.

Analysis: We have used the above considerations to calculate likely variations along a dike of the lateral profile of rheological properties. We find that episodic eruptions like that at the Pu’u ‘O’o vent can be explained by a feedback system which operates as follows: Towards the end of an eruptive episode, the excess pressure in the summit reservoir becomes relatively low, due to transfer of magma from the elastically pressurised reservoir into the dike. As a result, the magma flow rate declines, and magma moving through some narrow part of the dike system near the vent end (i.e. furthest from the summit reservoir) cools sufficiently near its contact with the dike wall to develop a yield strength there. The shear stress near the wall (proportional to the pressure gradient acting along the dike and to the distance from the dike centre-line) is no longer great enough to cause shearing, and only magma in the central part of the dike is able to flow, thus reducing the total volume flux through the system.

Further decline in summit reservoir pressure causes the widths of the stagnant zones at the dike walls to increase, and enhanced cooling of the stationary magma causes its yield strength to increase and the boundaries between stationary and flowing magma to migrate even closer to the dike centre. Eventually the volume flow rate either
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vanishes (if cooling causes a finite yield strength to exist everywhere across the narrow dike section), or becomes extremely small (if some magma motion still occurs in the warmest region around the middle of the dike); at this point, lava eruption at the vent ceases and a repose period begins.

The supply rate to the summit reservoir from the mantle now exceeds the magma loss rate into the dike. The summit reservoir pressure rises as it inflates, and the pressure gradient applied to the cooling magma in the narrow dike section also increases. This means that the shear stress increases at all points across the dike. The profile of this shear stress is linear, varying from a value of zero at the dike centre to a maximum value at the dike wall. The profile of the magma yield strength, however, will be very non-linear, increasing more rapidly near the wall than near the centre of the dike. As a result, shearing will first begin again, to start a new eruptive episode, at some intermediate point between the dike centre and edge. The rate at which the volume flux increases at the start of the episode may be very great, especially if the magma in the dike system has become completely stationary during the repose period. During this repose period, cooling of the unsheared magma will result in the formation of a thixotropic melt. However, once movement begins, field and laboratory measurements confirm that the static yield strength and high viscosities decrease rapidly. In addition, crystalline magmas are pseudoplastic. Consequently, their yield strengths and apparent viscosities decrease as the rate of shear increases. This will lead to an increase in velocity and volume flow rate with time even though the applied stress remains essentially constant (though in fact the onset of significant magma flow through the dike will rapidly reverse the trend of summit reservoir inflation into one of deflation as the new episode proceeds).

As fresh magma feeds through the narrow dike section, displacing the central part of the cooled magma which had developed a yield strength into an adjacent wider dike section, the still-stagnant magma nearest the dike wall will be reheated somewhat, and the boundary between flowing and stationary magma will migrate towards the dike wall. This, together with the fact that the displaced cool magma will now be moving through a wider dike section so that its yield strength will have a smaller effect on controlling the flow speed, means that the volume flux of magma through the system increases with time at first, even though removal of magma from the summit reservoir is decreasing the driving pressure gradient. Eventually, however, the declining summit reservoir pressure becomes the dominant factor; flow rate decreases, cooling in the narrow dike section becomes important again, a yield strength begins to develop near the dike wall, and the new eruptive cycle ends.

This process can be repeated many times (47 in the case of Pu'u 'O'o) before a combination of thermal and mechanical effects tends to increase preferentially the width of the narrowest section of the dike to the point where cooling, and the development of a yield strength near the wall, are no longer enough to cause magma flow to cease when the summit reservoir has deflated to the point where inflow from the mantle is matched by outflow into the dike. At this point, the eruptive character changes to steady-state flow of magma through the system at a rate equal to that of the mantle supply: in the current Kilauea activity this corresponded to the movement of the eruption site to the Kupaianaha vent.

This steady-state condition may also persist for a long time; however, the progress of the Mauna Ulu eruption (and the most recent change of style of the current activity, coincident with the move of the eruption site from Kupaianaha to a location on the flank of the original Pu'u 'O'o cone) shows that it is possible for the eruption style to change back from steady-state to episodic. We infer that this is most likely to be triggered by a small decrease in the mantle supply rate.

**Summary:** the above scenario has been presented in qualitative terms. However, we have used it to model numerically a number of cycles of the Pu'u 'O'o activity, and find that the observed behaviour is reproduced well with dike section geometries that are consistent with geophysical evidence and with magma rheological parameters that are consistent with the measured properties of hawaiian basalts as a function of temperature. This work is currently being prepared for publication.

**References.**