THE SHAPE OF DIKES EMPLACED LATERALLY WITHIN VOLCANIC EDIFICES;

Elisabeth A. Parfitt, Department of Geological Sciences, Brown University, Providence, RI 02912.

Many volcanoes possess shallow magma chambers which form at density traps within the surrounding country rocks (1). The pressure distribution within such a magma chamber can be shown to cause dike emplacement to preferentially occur laterally rather than vertically. Using a physical model of the dike emplacement process developed from theory derived by Rubin and Pollard (2), the lateral emplacement of dikes was simulated for a range of different starting conditions. These simulations show that the shape of the resulting dikes can be complex and this complexity can influence the nature of intrusive and eruptive activity that occurs.

Dike shape

A number of factors control the final shape of a laterally emplaced dike; these factors can be divided into two basic types, those which influence the overall shape of a dike and those which affect the shape of only certain sections of a dike. Taking the controls on the overall shape of the dike first, two factors are important - the lithostatic load on the dike and the slope of the dike centreline. If a dike is emplaced horizontally within an edifice which has minimal along-strike slope (a situation that applies to certain Icelandic volcanoes such as Krafla) then there is no along-strike variation in either the lithostatic load acting on the dike or the magma pressure head acting on the dike tip as the length of the dike increases. The resulting dike therefore has the same centreline driving pressure at all points along it and as a result has the same final half-height and width along its entire length, i.e., the dike geometry is uniform. However, if a dike grows within an edifice which has even a small amount of along-strike topographic relief (e.g., Kilauea volcano which has flank slopes of ~1.3^{o}) and/or the centreline of the dike slopes upwards or downwards (rather than being horizontal), the resulting dike <u>will always</u> have a non-uniform geometry. This is because the pressure distribution within the dike varies systematically with position along the dike. Such dikes take on a classic 'teardrop' shape (3) with the end of the dike closest to the magma chamber having a small half-height and width, the width and half-height increasing with distance from the magma chamber; the longer the dike, the greater the non-uniformity of the dike geometry.

In addition to these basic controls on the shape of a dike, the geometry of the dike may be modified by a number of other factors. These include non-uniformity in the compressive stress within the country rocks, structural complexity producing areas of inelastic mechanical response at certain points within the edifice, and the presence within the edifice of pre-existing pockets of unsolidified magma. All three factors may modify the basic shape of the dike by producing sections of dike, superimposed on the basic dike shape, in which the width is unusually wide or narrow. Non-uniformity of both types can play an important role in governing the intrusive and eruptive behaviour of a volcano.

Influence of dike geometry on intrusive and eruptive style

For a dike having a uniform geometry, the behaviour during both intrusive and eruptive activity is expected to be simple. During an initial dike emplacement event the final length of the dike is limited only by loss of driving pressure. Following cessation of growth the magma in the dike will begin to cool and, due to the uniform geometry of the dike, cooling will occur at the same rate at all points along it. If, following the intrusion, the driving pressure in the magma chamber rises rapidly, a new intrusion will begin before the previous dike has solidified and the intrusion will occur by reusing the previous dike - essentially it is the continuation of the same intrusive event punctuated by a brief period of summit reinflation. If the time gap between intrusions is longer, the previous dike will have solidified in the intervening period and the next intrusion will occur as a wholly new event. The non-uniformity of the geometry of a dike can modify and complicate this basic pattern because the rate of cooling and solidification of the magma in the dike varies according to the dike width, cooling being maximised in the narrowest sections of dike (4,5). Following the shutdown of an initial emplacement event cooling will begin throughout the dike as before but will occur most rapidly at the narrowest section(s). Initially the magma in these narrow sections will develop a yield strength. If the rate of reinflation of the magma chamber is high, the pressure may rise sufficiently to overcome this yield strength after a relatively small gap in time. The cooled magma is then forced out of the narrow dike sections into the wider sections of dike where it is less effective in resisting magma motion. The

extra pressure generated to overcome the yield strength then enables some new propagation of the dike to occur, but reduction in the driving pressure associated with growth quickly causes propagation to stop again and the whole process of cooling and reinflation is then repeated. Alternatively, if the pressure rise following intrusion is not as high, the magma at the narrow parts of the dike will solidify during the inflation period. Renewed propagation then occurs when a new dike fractures through the solidified narrow section and causes the connection of the new dike to wider sections of dike that have not already solidified. Patterns of intrusion consistent with this behaviour are found to occur commonly in Hawai'i (6).

Conditions of eruption

Two of the mechanisms of modification of the basic dike width - non-uniform compressive stress and reconnection with existing dike sections - can also modify behaviour by increasing the likelihood that eruption will occur. In general it is extremely difficult to generate laterally-emplaced dikes which intersect the surface (and therefore erupt): this is because the magma density in the upper half of the dike is higher than that of the surrounding country rocks and the magma is thus negatively buoyant. To produce eruptive dikes the density of the magma near the top of the dike must be reduced sufficiently for the magma to become buoyant. The factors modifying dike width achieve this situation in differing ways. In the case of dikes whose shape has been modified by encountering areas of locally high compressive stress, the dike width within the high compressive stress region is unusually small. As a result this region of the dike will tend to solidify rapidly between intrusions and, due to the locally high compressive stress, which means that a high driving pressure is required to cause fracture, it is difficult for the next dike section to grow laterally through it. This results in enhanced vertical growth of the dike and causes the upper surface of the dike to reach shallower levels within the country rocks than would otherwise be possible. When a sufficiently shallow level is reached the reduced lithostatic load on the dike enables gas exsolution to occur, lowering the magma density and aiding continued vertical growth to even shallower levels and ultimately to the surface. The other situation involves a dike which grows laterally and intersects sections of older dikes which contain magma that has not totally solidified, but which has been stored for sufficiently long that it has crystallised and differentiated. Crystallisation will cause gas exsolution, again lowering the density of the magma and aiding vertical propagation, increasing the likelihood that eruption will occur. A number of recent eruptions of Kilauea Volcano in Hawai'i can be linked to the presence of stored magma within its East Rift Zone (7-10, while other eruptions can be linked to the presence of compressive or barrier regions - for example, the November 1979 eruption of Kilauea (6).

In addition to altering the pattern of intrusion and the likelihood of eruption, the shape of a dike can also affect the nature of activity during individual eruptions. A prime example of this is the Pu'u 'O'o eruption of Kilauea during which activity occurred episodically as a direct result of the interplay between dike geometry and magma cooling. The details of this interplay have already been discussed elsewhere (11) and thus are not given here.

References

(1) Wilson, L and Head, J.W. (1990) LPSC XXI, 1343. (2) Rubin, A.M. and Pollard, D.D. (1987) Chapter 53 in U.S.G.S. Prof. Paper 1350. (3) Pollard D.D. and Muller, O.H. (1976) J.G.R. **81:** 975-984. (4) Delaney, P.T. and Pollard, D.D. (1982) American Journal of Science, **282:** 856-885. (5) Bruce, P.M. and Huppert, H.E. (1989) Nature, **342:** 665-667. (6) Klein, F.W., Koyanagi, R.Y., Nakata, J.S. and Tanigawa, W.R. (1987) Chapter 43 in U.S.G.S. Prof. Paper 1350. (7) Moore, R.B., Helz, R.T., Dzurisin, D., Eaton, G.P., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P. and Puniwai, G.S. (1980) J. Volcanol. Geotherm. Res., **7:** 189-210. (8) Dzurisin, D., Koyanagi, R.Y. and English, T.T. (1984) J. Volcanol. geotherm. Res., **21,** 177-206. (9) Wolfe, E.W., Garcia, M.O., Jackson, D.B., Koyanagi, R.Y., Neal, C.A. and Okamura, A.T. (1987) Chapter 17 in U.S.G.S. Prof. Paper 1350. (10) Garcia, M.O., Ho, R.A., Rhodes, J.M., and Wolfe, E.W. (1989) Bull. Volcanol., **52:** 81-96. (11) Parfitt, E.A. and Wilson, L. (1988) LPSC XIX: 903-904.