LUNAR VOLCANIC ERUPTIONS: RANGE OF ERUPTION STYLES AND IMPLICATIONS FOR MAGMA ASCENT AND EMPLACEMENT.

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Introduction: A wide variety of morphologic features representing a range of eruption styles has been documented on the Moon [e.g., 1-2]. We have characterized the nature of numerous steep-sided domes, small shields, cones, dark halo craters of internal origin, dark mantle deposits, linear rille-related deposits, and sinuous rille-related deposits on the Moon using Clementine multispectral, Apollo, and Lunar Orbiter data [2-7]. We have also shown that the main path of the ascent and eruption of magma from mantle source regions is through magma-filled cracks or dikes [2, 8-9]. We have been analyzing additional landforms and synthesizing these results into an overall assessment of the relationship between the nature of dike intrusion to shallow depths within the crust and the resulting landforms and deposits (Fig. 1). These data and this synthesis will be of importance to the general reanalysis of the models of the ascent and eruption of magma [10].

Analysis: We have revised our theoretical treatment for the penetration of magma-filled cracks (dikes) to the vicinity of the lunar surface (Fig. 1) [10], and we outline here the predicted range of tectonic and associated volcanic features and processes from our analyses [7, 9, 11]. The surface manifestation of a dike that does not actually reach the surface can take a range of forms. If the dike stalls at a sufficiently great depth, there will be some undetectably small amount of surface extension and uplift. If it penetrates to shallower depths there may still be no noticeable topographic effects at the scale of available images, but incipient failure or activation of pre-existing fractures may generate pathways along which gas (probably mainly carbon monoxide) formed by carbon-metal oxide "smelting" reactions [12-13, but see also 14] in magma in the shallowest parts of the dike can reach the surface. Still shallower penetration will lead to a larger volume of melt being exposed to the relatively low pressure environment near the surface and will encourage the generation of a greater mass of CO since the chemical reaction producing it is pressure-dependent. Subsequent loss of this gas, coupled with a magma volume decrease on solidification and cooling, may lead to collapse features (or even explosion craters) forming on the surface above the dike. Very shallow intrusion may lead to further development of a graben and will encourage the formation of small secondary intrusions and possible eruptions; we have developed criteria to distinguish between graben formed by dike emplacement and those resulting from tectonic deformation alone [15]. We have shown how the shallow stalling of a dike wide enough to allow spontaneous convection to occur during the early stages of its cooling can expose so much magma to low pressure degassing that it leads to major gas buildup and propagation of a crack to the surface, resulting in an Io-like eruption plume and the formation of a dark halo deposit ~150 km in diameter [6]. We have also assessed the deep generation of magmatic gas on the Moon and described implications for pyroclastic eruptions [16] as well as the ascent of magma feeding the steep-sided domes [7].

We have further explored the range of morphologies of volcanic vents and landforms and their implications for ascent of magma and behavior of dikes in the near surface zone, emphasizing the range of behaviors related to the four stages shown in Fig. 1. This range of behaviors appears to account for much of the diversity of eruption conditions implied by the morphologies of features seen on the lunar surface, and suggests that the following classes of morphologic features correspond to these several aspects of shallow dike emplacement behavior.

Linear rilles with associated pyroclastic cones: In some cases, a dike may propagate sufficiently near to the surface to create a graben, but still not cause significant eruption of lavas. In this situation, CO generation in the upper part of the dike may produce a region in the dike tip entirely occupied by a continuous gas pocket, behind which is an extended region of magma rich in entrained gas bubbles. As the dike ceases to propagate, the pressure gradient driving magma motion decays to zero over a time interval of a few tens of minutes and the initially low pressure in the dike tip rises to equilibrate with the ambient lithostatic load. Additional pressure and stress changes occur on time scales of tens of hours to a few days as gas bubbles migrate upward through the magma. These changes may force vesicular magma to the surface, producing initial gas venting and one or more relatively low-energy explosive events [9].

Crater chains with no linear rilles: At least some of the crater chains on the Moon which are not associated with linear rilles may be due to the more extensive degassing of dikes too deep to produce near-surface stress fields capable of creating graben, but shallow enough to allow gas production in the magma and venting of gas to the surface to form crater chains (Fig. 1). The pressures at which chemical reactions forming CO operate efficiently range up to ~10-15 MPa, corresponding to lithostatic pressures at depths in the Moon of about 3 km. These data would then suggest that, on average, dikes emplaced to depths between 2 and 3 km below the surface would be too deep to create surface deformation and graben, but shallow enough to allow gas production. Venting of gas to the surface would then form pit craters aligned along the strike of the dike. We have recently examined quantitatively the gas buildup behavior in large near-surface dikes [6]. A key issue in wide dikes is that spontaneous thermal convection can occur for a considerable length of time before cooling causes the dike to become too narrow for the Rayleigh-Taylor instability to operate. Magma reaching the top of the convection cell is exposed to the low ambient pressure and produces bubbles of CO gas. These drift upward through the magma at a speed dictated by their size and density contrast with the melt. The time available for them to segregate into a continuous gas pocket above the liquid surface depends on the circulation speed of the convecting magma, which will decrease with time. Thus potential scenarios exist in which the gas accumulation rate is initially low (magma flow speed too fast for gas bubble segregation), increases for a time (magma circulation speed decreases) and then decreases again (most of the magma has already been exposed to low pressure and has completed all possible chemical reactions). The Mendeleev crater chain is a candidate example of this eruption type.

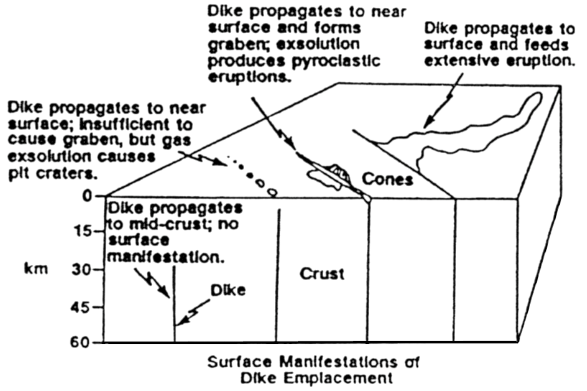

Figure 1. Geometry of shallow dike intrusion and aftermath.

Linear rilles with associated crater chains: The crater Hyginus and the two rilles leading away from it contain pits that are centrally located along the 3-4 km wide linear rilles; some pits appear to have no rims and are interpreted to be collapse craters, but others appear to have partly raised rims and may be explosion craters. The size of the crater Hyginus (9 km) makes it one of the few candidates observed on the Moon for a caldera-like structure associated with a shallow magma reservoir [2]. This is of particular importance because of the general lack of evidence for mare basalt magma stalling in the shallow crust to form reservoirs [17], and the critical nature of such evidence in distinguishing between models of magma ascent and eruption. Thus the radiating graben could be evidence of lateral dike emplacement from a shallow reservoir along a rift zone. Graben width suggests that the depth to the top of the dike is ~1.5-2.0 km, a value within the range of depths where CO gas formation would be expected to occur. Thus the production and explosive venting of the volatiles, with subsequent collapse, may explain the range of features seen here.

Domes and cones: Where these occur in isolation, or in small groups, they represent additional types of features that suggest the presence of unusual conditions giving rise to low effusion rates. We are examining representatives of the full range of domes and cones. The Gruithuisen and Mairan domes are one end member that is spectrally distinct and may be affiliated with early mare deposits or be a candidate for non-mare basalts [5]. We have completed regional multispectral analyses of the domes and their relationship to mare units [5, 18], have established a stratigraphic sequence and obtained crater size-frequency distribution ages [18] and have modeled the ascent and eruption of candidate materials along dikes to produce these features [7]. Variations in magma composition, and hence rheology, are as important as variations in dike geometry in controlling the formation of these features. Small lunar domes and cones (e.g., Marius Hills, Grace and Diana shield volcanoes [3, 4]) represent a range of features involving both effusive and explosive eruptions and we show how fine tuning of dike widths and intrusion depths can lead to the variety observed in these features.

Summary: The range of volcanic eruption features observed on the Moon can be reasonably interpreted in terms of predictions of the consequences of the penetration of magma-filled cracks (dikes) to the vicinity of the lunar surface. Placing these in the context of large-volume, high eruption-rate effusive eruptions [2] provides a much improved picture of the range of characteristics of eruptions and shallow intrusions in the upper lunar crust. The nature and frequency distribution of dike widths, eruption rates, and near-surface intrusions help to distinguish between models in which simple buoyancy forces drive magma to the surface (e.g., [19]) and those in which other driving forces play a role (e.g., [11, 20]).

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