

LUNAR MAGMATISM AND VOLCANISM: THEORY OF MAGMA GENERATION, ASCENT, INTRUSION AND ERUPTION. L. Wilson¹ and J. W. Head², ¹Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK (L.Wilson@Lancaster.ac.uk), ²Dept. of Geological Sciences, Brown University, Box 1846, Providence RI 02912, USA (James_Head@Brown.edu).

Introduction: Given the impending enormous increase in volume and in spatial and spectroscopic resolution of spacecraft data for the Moon, we have reassessed the current understanding of lunar volcanic processes to pinpoint key issues requiring both theoretical and observational investigation. Major topics include the relationships between effusive and explosive eruptions; the reasons why some effusive eruptions generate normal surface lava flows whereas others produce narrow flows that thermo-mechanically erode their substrates to form sinuous rille channels; the extent to which shallow intrusions produce diagnostic surface features; and the extent to which the cumulative effects of intrusions at all depths in the lithosphere have controlled changes in surface volcanic activity over lunar history.

Influence of lunar structure on volcanism: Ideas on the relative importance of magma buoyancy and magma source pressure have evolved considerably with improvements in values for the density and thickness of the lunar crust and for the liquidus densities of the erupted magmas [1, 2]. It is clear that virtually all mafic melts reaching the surface that were derived by partial melting of the mantle were positively buoyant relative to their mantle source rocks. However, by no means all of these melts were positively buoyant at all levels in the crust. The recognition of this trend in early modeling of lunar volcanism was taken to imply that in some, possibly many, cases an excess pressure in the magma source region was required to enable melts to erupt at the surface, irrespective of whether those melts traveled directly from source to surface in a single event [3, 4] or were temporarily stored in a reservoir at some intermediate depth [5]. It is now clear that not all mantle melts require assistance of this kind in ascending at least most of the way through the crust.

However, if a column of magma with Newtonian rheology, i.e. no yield strength, extends continuously through a mantle source region and out of that source region into a dike, then there is *inevitably* an effective excess pressure in the magma at the top of the dike equal to the integral over the vertical path length of the product of the acceleration due to gravity and the density difference between host rocks and magma. Incremental contributions to this integral will be positive everywhere in the mantle as long as the melt is less dense than the mantle rocks, as seems likely. If the

magma becomes denser than the host rocks somewhere in the crust, then contributions to the integral will become negative. If the integral goes to zero before the surface is reached, the magma intrudes at some level in the crust. If the integral is still positive when the dike tip reaches the surface, the residual effective excess pressure is used to drive the magma motion against wall friction and is the quantity that determines the magma flow speed through a dike of a given width.

The dike width is itself determined by the vertical distribution of stress across the dike walls and, since this is related to the magma pressure, the problem of magma flow and dike shape is coupled. Analytical solutions to the coupled problem of dike propagation have been obtained in a few special cases [6 - 8], but none of these correspond exactly to real configurations of volcanism in the lunar lithosphere. Analytical models of long-distance vertical dike penetration through planetary lithospheres [6, 7] are forced to inappropriately assume a constant density difference between host rocks and magma; additionally the model of vertical intrusion and extensive lateral spreading of a dike at a neutral buoyancy level in the crust [6], as employed for the Moon by [1], neglects the inevitable excess center-line pressure that such a dike will have as long as it is connected to its mantle source, and thus underestimates how close to the surface the upper tip of such a dike can approach. We have used a variety of approximate methods to obtain estimates of dike widths and magma flow rates for dikes transferring magma directly from lunar mantle source regions, and also from shallower depths, to the surface, and we have used a suitably modified version of the shallow rift-zone dike intrusion treatment of [9] to model the giant dike intrusions in the lunar crust that we infer are responsible for producing some of the larger-scale linear rille graben [10, 11].

Results: To summarize our major findings:

(a) *Eruptions feeding mare lava flows.* Analyses utilizing the measured thicknesses and widths of mare lava flows and the slopes of the surfaces on which they were emplaced imply that typical eruptions conditions involved surface fissures ~20 to 30 km long fed by dikes ~2 to 3 m wide at shallow depth, erupting magma at a volume flux of 10^5 to 10^6 m³ s⁻¹ for durations of 10 to 20 hours. Flows were turbulent, and their lengths imply that they were not limited by cool-

ing, but instead reflect the volumes of magma (~ 200 to 300 km^3) available to be erupted in a single event.

Approximate solutions of the coupled dike geometry-magma flow problem suggest that the smallest volume flux likely to be associated with a long-lived voluminous eruption of buoyant magma from a deep ($\geq \sim 200 \text{ km}$) source within the Moon is of order $3 \times 10^4 \text{ m}^3 \text{ s}^{-1}$, consistent with the 10^5 to $10^6 \text{ m}^3 \text{ s}^{-1}$ eruption rates deduced from the surface flow morphologies. Eruption rates much less than $1 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ from very deep sources are forbidden by cooling constraints. Only if buoyant magma erupts from a reservoir at a depth very much less than 100 km (e.g. a magma reservoir at the base of the crust) is an eruption at a much smaller discharge rate likely to be possible.

The upper limit on magma volume fluxes is hard to predict, being set by the physics of melt extraction from the source region. If the source is within the mantle, the key issue is the efficiency of the melt migration process within the partial melt source zone. If the source is in the elastic lithosphere, the controls are the excess pressure in the magma reservoir, the reservoir volume, and the stress and pressure conditions holding the dike open.

(b) *Eruptions forming sinuous rille channels.* Using thermal erosion models [12 - 14] to relate rille channel lengths to magma discharge rates we find that the implied eruption rates are 10^3 to $10^5 \text{ m}^3 \text{ s}^{-1}$. Predicted erosion rates of ~ 5 to $35 \mu\text{m s}^{-1}$ coupled with measured rille channel depths imply durations of ~ 50 to 500 days. The lava flows that develop into sinuous rilles are much narrower than typical mare basin lavas, and this appears to be a result of a combination of relatively smaller (by a factor of typically ~ 10) eruption rates and relatively steeper (again by a factor of typically ~ 10) substrate slopes. The smallest inferred magma eruption rates are not consistent with magma sources deep in the mantle, and may require that sub-crustal reservoirs existed. Geochemical and petrological implications of this result need to be explored. The large magma volumes erupted, tens to thousands of km^3 , imply that these reservoirs must have been very large.

(c) *Dikes that do not erupt.* For realistic ranges of magma density, crust and mantle densities, and magma source depths, many dikes that do not erupt should extend to shallow depths, ranging from tens of meters to $\sim 5 \text{ km}$ below the surface. These may readily cause visible features such as graben [10] more than 100 km long. The typical widths of such dikes will be in the range ~ 10 to 100 m , consistent with graben geometries [11], with the widest dikes being those that extend closest to the surface. Minor effusive or explosive activity may follow emplacement of such intrusions as they reach equilibrium. Shallow intrusions of this kind into the breccia lenses under impact craters can initiate

sills growing into laccolithic bodies raising crater floors [15, 16].

(d) *Explosive activity.* The source depressions feeding sinuous rilles are interpreted to be the result of thermal erosion of the bases of lava ponds fed by optically dense fire fountains. The lateral sizes of the ponds then reflect the ranges of pyroclasts, and the required eruption speeds imply magma volatile contents of ~ 500 to 1500 ppm . This is consistent with the expectation that the main lunar magma volatile was up to 2000 ppm CO formed in smelting reactions [17 - 20].

Lunar fire fountains from steady magma discharge are likely to eject pyroclastic droplets with sizes in the range $100 \mu\text{m}$ to 1 mm to distances of up to 10 km , consistent with the sizes of rille source depressions and the inferred opacities of their fire fountains. If a wider range of pyroclast sizes is present, a circumstance encouraged by intermittent rather than steady eruptive activity, coarser clasts will accumulate closer to the vent, possibly forming detectable near-vent constructs, and the smaller mass loading of the expanding gases will allow smaller clasts will be transported to ranges up to 30 to 40 km .

Transient conditions at the onset of eruptions due to the discharge of gas that has been concentrated by dynamic processes into the upper tip of the propagating dike have the potential to generate greater speeds and ranges, but will not involve large amounts of magma.

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