LUNAR REGIONAL PYROCLASTIC DEPOSITS: EVIDENCE FOR ERUPTION FROM DIKES EMPLACED INTO THE NEAR-SURFACE CRUST.

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Introduction: Lunar pyroclastic deposits can be subdivided into several modes of occurrence [1], suggesting different modes of emplacement. For example, some smaller pyroclastic deposits have been interpreted to have erupted during strombolian/hawaiian activity [2], while others are linked to vulcanian activity related to dike and sill emplacement below crater floors [3,4]. The largest pyroclastic deposits (Orientale dark ring, Aristarchus Plateau, Sinus Aestuum, Rima Bode, Mare Vaporum, Sulpicius Gallus, and Taurus Littrow) cover regions >1000 km^2 [1], and their mode of emplacement has been less clear than that of the smaller, more isolated deposits. In the case of the Aristarchus Plateau pyroclastic deposits, very high effusion rate eruptions leading to sinuous rilles [5] and associated pyroclastic emplacement have been implicated. The location of specific vents, and thus eruption styles, has been less clear for the remainder of the large deposits, partly due to burial and obscuration by post-pyroclastic deposit effusive volcanism [6]. Important evidence related to candidate modes of emplacement comes from analysis of the Orientale dark ring, a 154 km diameter pyroclastic deposit that was shown to emanate from a linear depression interpreted to be the remains of an elongated vent at the top of a dike [7]. In this interpretation, a wide dike stalled just below the surface, and the low-pressure environment led to gas buildup along the top of the dike, ultimately leading to the eruption of an Io-like pyroclastic plume to produce the dark pyroclastic ring. The central elongate depression thus represents evidence of this shallow dike emplacement-related activity. Additional evidence for the association of pyroclastics with dike-emplacement activity comes from comes from the analysis of the ascent and eruption of magma [8], where it was shown that the low-pressure environment associated with dike tip propagation could enhance formation of volatiles *during* dike ascent so that the dike could arrive at the surface with the top of the dike already saturated with magmatic foam, and not requiring secondary buildup as in the vulcanian [3] or the Orientale dark halo [7] cases. Could this mechanism, arrival of volatile magmatic foam-laden dikes to the shallow subsurface [8], perhaps combined with further shallow crustal gas formation [8] subsequent to stalling, lead to the penetration of foams to the surface and eruption of magmatic foams to produce regional pyroclastic deposits?

Distribution and Characteristics of Linear Features: The association of linear rilles (interpreted to be the surface manifestation of stress fields associated with shallow dike emplacement [9]) with some of these deposits (e.g., Rima Bode, Sulpicius Gallus) motivated us to use new Lunar Reconnaissance Orbiter Laser Altimeter (LOLA) and camera (LROC) data to analyze the lengths, orientations and associations of linear rilles, fissures and crater chains in the Sinus Aestuum and Rima Bode regional pyroclastic deposits (Fig. 1), and to use these data to assess whether eruptions of magmatic foam-laden dikes [8] from these candidate vents could help to explain the nature and distribution of these regional pyroclastic deposits. Maps of the Sulpicius Gallus and Rima Bode regions and the distribution and orientation of linear features are shown in Fig. 1. These data suggest the presence of numerous linear dikes of varying orientations in and adjacent to these deposits. Mantling deposits could also cover additional linear dikes. We use these data to analyze the dispersal and emplacement of regional pyroclastics from shallowly intruded dikes and magmatic foams.

Dispersal of pyroclasts: The observed spatial relationships between linear rilles and dark mantle deposits suggest that pyroclast ranges are commonly up to 100 km. The maximum range, R, that can be reached by a clast ejected at speed v when the acceleration due to gravity is g is

$$R = v^2 / g \qquad (1)$$

which implies that v is up to $[(100 \times 10^3 \times 1.622)^{1/2} =]$ 403 m s^{-1}. The corresponding time of flight is ~350 s, a value consistent with the cooling rates and cooling times estimated by Saal et al. [10] for lunar volcanic glass beads: 2-3 K s^{-1} over intervals of 2-5 minutes, i.e. 120-300 s. If we assume a larger range (200 km) then v = 570 m s^{-1} and the time of flight is 497 s.

Volatile issues: A reasonable way of linking the released magmatic volatile mass fraction, n, to the final gas speed at the end of complete gas expansion, v, is to assume that the gas expands adiabatically and that the pyroclasts acquire all of the gas speed. In that case

$$v = \{[2\, n\, Q\, T\, \gamma] / [m\, (\gamma - 1)]\}^{1/2} \qquad (2)$$

where Q is the universal gas constant, 8314 J K^{-1} kmol^{-1}, T is the magmatic temperature, γ is the ratio of the specific heats of the gas at constant pressure and constant temperature, and m is the molecular mass of the gas. In practice some heat is transferred from pyroclasts to gas early in the expansion, maintaining the gas temperature near-magmatic for a while and thus increasing the gas speed and hence the pyroclast range. However, pyroclasts must eventually decouple from the gas when the gas expansion becomes so large that the system enters the Knudsen regime, and this reduces the potential range. Using eq. (2) as a compromise between the over- and under-estimates, and rearranging:

$$n = [v^2\, m\, (\gamma - 1) / [2\, Q\, T\, \gamma] \qquad (3)$$

Measurements of the volatile chemistry of erupted lunar basalts allow the amounts of volatiles released during explosive eruptions to be estimated. An oxidation-reduction reaction between graphite and various metal oxides at pressures less than ~40 MPa commonly produced up to 2000 ppm CO [11,12]. Saal et al. [10] estimated that in addition up to 700 ppm H_2O, 325 ppm S, 15 ppm F and 0.5 ppm Cl could be released by exsolution. The amount of energy per unit mass available from the expansion of volatiles is inversely proportional to their molecular mass. As CO, with molecular mass m = 28 kg kmol^{-1}, is the dominant volatile, it is appropriate to scale the amounts of other volatiles to CO, so that their equivalent amounts become [(28/18) × 700 =] 1089 ppm H_2O, [(28/64) × (325/2) =] 71 ppm S_2, [(28/19) × (15/2) =] 11 ppm F_2 and [(28/35.45) × (0.5/2) =] 0.2 ppm Cl_2. The total is ~3170 ppm of equivalent m = 28 kg kmol^{-1}. At magmatic temperatures, say T = 1600 K, the value of γ for CO is very close to 1.3; the value for H_2O is ~1.25 and since the other species are present in small amounts it suffices to use a weighted average of γ = 1.28. Equation (2) then implies that the maximum speed at which pyroclasts are likely to be ejected on the Moon in purely magmatic explosive activity is $\{[2 \times 3170 \times 10^{-6} \times 8314 \times 1600 \times 1.28] / [28 \times 0.28]\}^{1/2} = 117$ m s^{-1}, corresponding to a range of 8.5 km.

This range is very much less than the observed value of ~100 km, implying greater ejection speeds and hence greater gas mass fractions in the eruption products. Equation (3) shows that if v is the 403 m s^{-1} needed to reach 100 km, n must be at least $\{[403^2 \times 28 \times 0.28] / [2 \times 8314 \times 1600 \times 1.28] =\}$ 0.037, i.e., 3.7 mass % or 37000 ppm. Thus the amount of released gas needed to eject pyroclasts to a range of 100 km is ~10 times greater than the total available from a typical lunar magma, ~ 3000 ppm. If the range is 200 km, so that v = 566 m s^{-1}, then the value of n that is needed is ~74000 ppm, ~25 times more than is available.

Volatile concentration: The low pressure always present in the propagating tip of a dike means that as dikes approach the lunar surface their upper tips will consist of a cavity containing gas underlain by a region where gas bubbles concentrate into a foam [8]. If the dike fails to break through to the surface, gas bubbles migrate up through the foam to increase the size of, and pressure in, the gas cavity. Additional foam is generated beneath the gas cavity if the dike is wide enough to allow convection to occur because this brings magma from depth to shallow enough levels for additional pressure-dependent gas release. Head et al. [7] showed that these processes acting in a ~500 m wide dike produced an ~25-fold gas concentration leading to an explosive eruption emplacing a ~150 km diameter circular pyroclastic deposit in Mare Orientale. Wilson et al. [13] found that a 4-fold gas concentration led to the ~30 km radius pyroclastic deposits around Hyginus crater as gas migrated to the active vent system from the outer margins of the dike whose injection induced the associated Rima Hyginus graben; additional local gas venting caused multiple collapse craters to form along the graben [13].

A generic example of this process based on Head et al. [7] and Wilson et al. [13] would involve a 100 km long linear rille graben induced by a 300 m wide dike making the horizontal cross-sectional area of the dike 3×10^7 m^2. Magmatic foam would occupy the upper ~ 8 km of the dike where the pressure was less than 40 MPa. If the foam evolved to 80% gas volume fraction, close to the upper limit for foam stability [14], then at an average pressure of 20 MPa and a magmatic temperature of 1750 K the average density of the m = 28 kg kmol^{-1} gas would be 40 kg m^{-3} and this would contribute a partial density of [(40 × 0.8) =] 32 kg m^{-3}. If the remaining 20% of the foam consisted of magma with density 3000 kg m^{-3} this would contribute a partial density of [(3000 × 0.2) =] 600 kg m^{-3}. The gas would then represent a mass fraction of [32/(600 + 32) =] 0.0506, i.e., ~5 mass % or ~50000 ppm. Using eq. (2), release of this foam would produce an eruption speed of 487 m s^{-1} ejecting pyroclasts to ~147 km. The mass of magma in the foam would be its partial density, 600 kg m^{-3}, multiplied by the volume of foam, [(3×10^7 m^2 area × 8000 m depth) =] 2.4×10^{11} m^3, i.e. 1.44×10^{14} kg. If this magma were deposited as pyroclasts over an area of 100 km (the rille length) × 147 km (the maximum range) with a bulk density on landing of 2000 kg m^{-3}, the resulting deposit thickness would be 4.9 m. We infer that essentially all of the observed dark mantle regional pyroclastic deposits on the Moon can be explained by minor variations on this scenario.

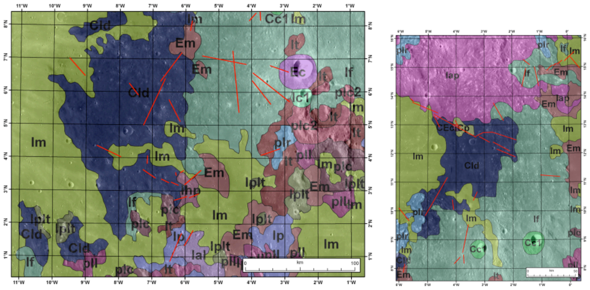

Fig. 1. Linear graben, crater chains and fissures (red lines) mapped in Sulpicius Gallus (left) and Rima Bode (right). Dark blue areas are mapped as pyroclastics on USGS maps [e.g., 15].

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