LUNAR VOLCANIC ERUPTIONS: ESTIMATES OF MAGMA VOLATILE CONTENTS, VOLUMES AND ERUPTION RATES.

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Introduction: We have no direct information on the eruption conditions, e.g., volume eruption rates and exsolved volatile mass fractions, that emplaced the ancient mare basalts. However, we can measure various morphological properties of their deposits, including the lengths, widths and volumes of lava flows; the lengths, widths and depths of sinuous rille channels and their source depressions; the radial extents of pyroclastic deposits; and we can analyze returned samples. Also, theoretical physical models can predict eruptive behavior under lunar environmental conditions. Here we focus on estimating magma volatile contents.

Theory: The absence of a significant atmosphere on the Moon simplifies modelling explosive volcanic eruptions [1]. The maximum ranges of pyroclasts ejected in steady hawaiian-style explosive eruptions in a vacuum are proportional to the sum of the quantities (n_i/m_i) where n_i and m_i are the mass fractions and molecular masses of the i_{th} gas species released [2] . Estimates of the total mass fractions of volatiles released in lunar eruptions vary, and opinions differ on the dominant species. We use the estimates given by [3], [4] and [5] to derive a most likely value of $\Sigma(n_i/m_i) = 1.02 \times 10^{-4}$ kmol/kg. Applied to explosions producing monodisperse pyroclast size distributions, this implies that the maximum range of pyroclasts, R, is related to the total released volatile mass fraction, N, by $N = 0.25\ R$ with N in ppm by mass and R in meters. For bidisperse or more generally polydisperse distributions the relationship is more complex, because pyroclasts with different sizes decouple from the expanding gas stream at different gas pressures and different distances from the vent to start their purely ballistic paths to the surface [6]. This can significantly increase the ranges of intermediate-sized clasts.

Magma volatile amounts: The above relationships have been applied to predict the released magma volatile fractions for magmas whose explosive eruption led to the formation of more than 100 dark halo and dark mantle deposits documented by [7] and [8]. About 80% of these deposits can be readily explained by magmas releasing a mixture of CO, H_2O and S compounds in the amount, a total of 3400 ppm, and proportions predicted by [3] for the Apollo 17 orange glass bead magma. Other gas compositions would require similar mass fractions. The remaining 20% of deposits require either greater magma volatile contents or a mechanism such as strombolian-style activity that concentrates gas into the part of the magma that erupts.

A second class of lunar pyroclastic "deposits" exists: the source depressions of sinuous rilles. Models of sinuous rille formation by thermomechanical erosion predict that the circular to oval depressions forming the sources of the rilles are the drained remains of the lava ponds filled with turbulent lava that surrounded the vent during the eruption [9]. The depression radii are therefore a measure of the maximum ranges of the pyroclasts in the eruption's fire fountain [10, 11, 12]. The relationship shown above between N and R, applies in this case also, though R is now the depression/pond radius. Hurwitz et al. [13] cataloged morphometric properties of 194 sinuous rille channels and 78 source depressions. Figure 1 shows a histogram of the distribution of source pond radii and corresponding total released magma volatile mass fractions. Most eruptions forming sinuous rilles involved magmas releasing 100-800 ppm volatiles, though values up to 1200 ppm are implied.

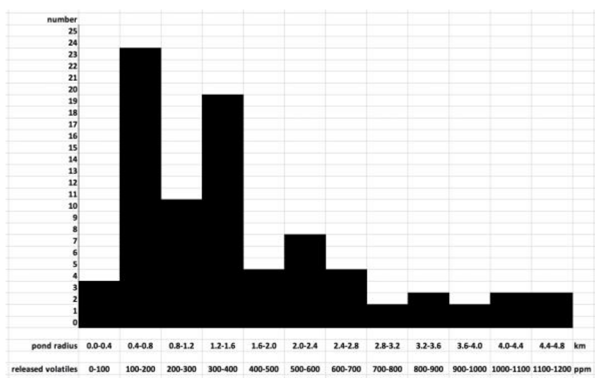

Figure 1: Distribution of rille source pond radii in km and released magma volatile mass fractions in ppm.

Rille-forming eruption durations: The catalog of [13] gives source pond depths, D, for 78 rilles. A plausible total (thermal plus mechanical) erosion rate, E, for the beds of sinuous rille channels and ponds is ~20 microns/s [14, 15]. Dividing the pond depth, D, by the erosion rate gives the duration of the eruption, τ. Figure 2 shows a histogram of the source pond depths and corresponding eruption durations. Possible post-eruption drainage of the shallow parts of dikes feeding ponds means that the larger pond depths and eruption durations may be over-estimates. Most rille-forming eruptions lasted significantly less than one year.

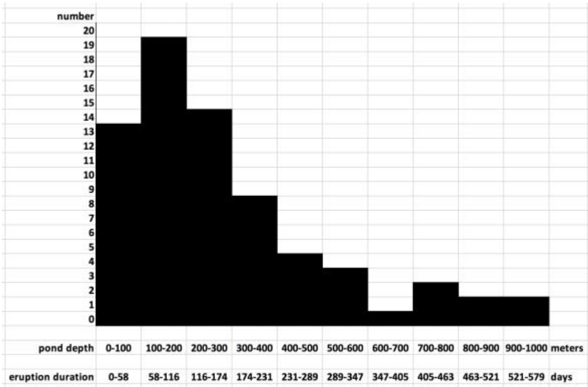

Figure 2: Distribution of rille source pond depths in meters and eruption durations in days.

Rille-forming eruption magma volumes: During an eruption, the dike in the crust shrinks, both because it is erupting and because magma is chilling against its walls as heat is lost. The thickness, T, of the chill layer on each wall equals $2\ (\kappa\ \tau)^{1/2}$ where κ is the thermal diffusivity of the magma, $\sim 3 \times 10^{-7}\ m^2\ s^{-1}$. Thus, the final dike width W_f is the ($2\ T$) magma thickness that never erupts. The volume of residual magma can be estimated by assuming that, in order for magma to reach the surface through a crust in which it is negatively buoyant, the dike transferring it must have extended into the mantle by a distance Z that was at least as large as the vertical distance that the dike occupied in the crust, ~30 km on the lunar near-side [1]. Assuming a penny shape, the residual dike magma volume was thus $V_r = \sim 2\ \pi\ Z^2\ T$ with $Z = 30$ km. We estimate the erupted magma volume in rille-forming eruptions from the eruption duration and our predictions [1, 16] of the erupted volume flux, F, during rille-forming eruptions, $\sim 10^4\ m^3\ s^{-1}$, consistent with the magma in the dike having only slight positive net buoyancy. The erupted volume is thus $V_e = F\ \tau$. The total volume of magma involved in the eruption, V_t, is the sum of the erupted and residual volumes, $V_t = V_e + V_r$. The mean width of the precursor penny-shaped dike W_i can be found from $\pi\ Z^2\ W_i = V_t$. Finally, the erupted magma must of course form a deposit at the end of the eroded channel, e.g., by ponding in a topographic low. Depths of lava units in the lunar maria are variously estimated as several tens of meters. If we assume a $Y = 50$ m deep circular mare lava deposit, its diameter $X = [(4\ V_t)/(\pi\ Y)]^{1/2}$. Table 1 shows the implied values. Note that the erupted lava volumes, mostly less than 400 km^3, are consistent with theoretical predictions [1, 17], and are similar to those of the Mare Imbrium flows, ~100-500 km^3 [18, 19], and to an estimate for the Rima Prinz rille, 160-270 km^3 [15].

Table 1: Values of lava pond diameter range, D, in meters; number of occurrences, *no.*; eruption duration, τ, in days; final dike width, W_f, in meters; residual dike magma volume, V_r, in km^3; erupted magma volume, V_e, in km^3; initial dike width, W_i, in meters; fraction of dike magma erupted, *%*; and diameter of erupted mare lava sheet if assumed to be 50 m deep, X.

D	*no.*	τ	W_f	V_r	V_e	W_i	*%*	X
0-100	13	29	3.5	10	25	12	72	25
100-200	19	87	6.0	17	75	33	82	44
200-300	14	145	7.7	22	125	52	85	56
300-400	8	203	9.2	26	175	71	87	67
400-500	4	260	10.4	29	225	90	88	76
500-600	3	318	11.5	32	275	109	89	84
600-700	0	376	12.5	35	325	127	90	91
700-800	2	434	13.4	38	375	146	91	98
800-900	1	492	14.3	40	425	165	91	104
900-1000	1	550	15.1	43	475	183	92	110

Results: (a) 80% of dark halo and dark mantle deposits can be explained by magmas releasing up to 3400 ppm of volatiles, the amounts predicted by [3] for the Apollo 17 orange glass bead magma. 20% of deposits require either greater magma volatile contents or a gas concentration mechanism. (b) Eruptions creating sinuous rilles appear to involve smaller amounts of magma volatiles, up to 800 or at most 1200 ppm. (c) Sinuous rille-forming eruptions typically lasted for 3-12 months and erupted similar volumes of lava to eruptions forming large mare lava flows, but at much lower volume eruption rates.

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