EXPLOSIVE VOLCANISM ON ATMOSPHERE-LESS BODIES - A COMPARISON OF THE MOON, MERCURY AND IO.

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Introduction: There is abundant observational evidence of explosive volcanism on all three of the large airless silicate-dominated bodies, the Moon [1], Mercury [2] and Io [3]. The lack of atmospheres makes analysis of explosive activity relatively simple. We combine the results of earlier analyses of explosive volcanism to draw inferences about the geologic circumstances of explosive activity on these three bodies and the amounts of volatiles driving the eruptions.

Theoretical development: In steady eruptions, classified as Hawaiian or Plinian, most of the energy release driving the eruption speed, and hence vacuum range, of pyroclasts occurs as gases expand from the magma fragmentation pressure, P_f, to the pyroclast decoupling pressure, P_d. P_f is the pressure at which exsolved gas bubbles are close-packed so that they collapse to convert the magmatic foam to a gas stream entraining pyroclastic droplets. If the foam collapses at a gas bubble volume fraction f then for gases obeying the perfect gas law P_f is easily shown to be

$$P_f = [(1 - f)\, n\, Q\, T\, \rho] / [f\,(1 - n)\, m] \quad (1)$$

where n is the free gas mass fraction, Q is the universal gas constant, T is the magma temperature, ρ is the magma liquid density and m is the molecular mass of the gas. P_d, is the pressure at which the mean free path of the gas molecules becomes about 50% greater than the typical pyroclast size, d, and is given by [4] as

$$P_d = (2^{1/2}\, Q\, T) / (3\, \pi\, \phi^2\, N\, d) \quad (2)$$

where ϕ is the diameter of the gas molecules and N is Avogadro's number.

With good thermal coupling between clasts and gas, the steady eruption speed, U, of the gas and small pyroclasts is given by

$$U^2/2 = [(n\, Q\, T) / m] \ln(P_f / P_d) \quad (3)$$

If the thermal coupling is poor, the eruption speed is given instead by

$$U^2/2 = [(n\, Q\, T)/m][\gamma/(\gamma-1)][1-(P_d/P_f)^{\{(\gamma-1)/\gamma\}}] \quad (4)$$

Here γ is the effective ratio of specific heats of the pseudo-gas given by

$$\gamma = (n\, s_p + (1 - n)\, s_r) / (n\, s_v + (1 - n)\, s_r) \quad (5)$$

where s_r is the specific heat of the magma, and s_p and s_v are the specific heats at constant pressure and volume, respectively, of the gas. In practice, whichever is the smaller U from eqs. (3) and (4) is the appropriate eruption speed.

Not all explosive eruptions are steady. The main types of transient activity are Strombolian, where coalescence of many small gas bubbles causes large gas bubbles to emerge intermittently at the surface of a lava lake, and Vulcanian, where a gas pocket accumulates under a rigid plug that eventually fails. A third transient style, termed here Foam-Collapse, is due to the spontaneous coalescence of gas bubbles that have accumulated as a foam at the top of a magmatic intrusion when a pathway to the surface opens as a result of the rising pressure. Strombolian activity ejects mainly coarse clots of hot magma and Vulcanian activity ejects mainly coarse blocks of cold country rock and chilled magma, whereas Foam-Collapse ejects a spray of hot, sub-mm magma droplets [5].

Practical applications: Most physical parameters in the above equations do not vary by more than ~20% between mafic eruptions on the atmosphere-less terrestrial planets and typical values can be adopted (e.g. T = 1450 K, ρ = 3000 kg m^{-3}, $\phi = 3.5 \times 10^{-10}$ m, d = 300 μm [5]). The greatest variability lies in the magmatic volatile composition and hence the value of m, ranging by more than a factor of 2 from 28 kg/kmol for CO, which dominated eruptions on the Moon [6] to 64 kg/kmol for SO_2 or S_2 dominating eruptions on Io [7]. The dominant volatile on Mercury is still in doubt [8], though sulfur is implicated by remote sensing observations [9] and is assumed here based on [10]. Using these values, Table 1 presents eruption speeds, U, and corresponding maximum pyroclast ranges, R, for a wide range of volatile mass fractions, n.

Table 1: For a range of values of the volatile mass fraction, n, in explosion products (given as ppm and mass %), values are given for the speed, U, and maximum range, R, of sub-mm pyroclasts.

		Moon		Io		Mercury	
n	n	U	R	U	R	U	R
ppm	%	m/s	km	m/s	km	m/s	km
100	0.01	23	0.32	14	0.11	14	0.05
300	0.03	43	1.13	27	0.39	27	0.19
1,000	0.1	84	4.38	53	1.55	53	0.76
3,000	0.3	155	14.7	98	5.30	98	2.58
10,000	1	294	53.2	187	19.4	187	9.44
30,000	3	505	157	324	58.2	324	28.3
100,000	10	822	417	534	158	534	77.1
300,000	30	1161	832	763	323	763	157
500,000	50	1361	1145	898	448	898	218

Interpretations: We now examine the pyroclastic deposits seen on the surfaces of the Moon, Io and Mercury in terms of the results in Table 1.

Moon. Kerber et al. [11] combined the distribution of pyroclastic deposit radii on the Moon [12] and Mercury [11] (Fig. 1). Lunar deposits with radii up to ~15 km are consistent with total magmatic volatile contents of up to 3000 ppm [6] (CO plus small amounts of H_2O and other species) and encompass dark halo deposits such as those in the floor-fractured craters Alphonsus and Schrödinger [13, 14]. Similar, purely magmatic volatile contents are implied [5] for the depressions at the sources of sinuous rilles, interpreted as lava ponds deepened by thermal erosion of their floors during long-lasting relatively steady eruptions [15].

All larger deposits on the Moon, expecially the dark mantle deposits with radii in excess of 50 km, must imply the accumulation of volatiles in the upper parts of intrusions, leading to volatile contents in the explosion products enhanced by a factor of at least 10 over magmatic values [16]. Examples have been described in Mare Orientale [17] and at Rima Hyginus [18].

Io. The presence of plumes and their deposits with radii up to ~500 km [3] imply volatile contents in explosion products of up to as much as 50%, at least an order of magnitude greater than any geochemically possible dissolved magmatic volatile content. The observation that these eruptions are maintained for long periods (days to months) is not consistent with volatile accumulation in shallow intrusions, which would be exhausted in at most hours unless they were sills with very great lateral extents. Instead, these eruptions can be explained by dikes cutting through the crust and encountering "aquifers" containing liquid sulfur or SO_2. The liquids form when the corresponding solids, deposited on the surface from plumes along with silicate pyroclasts, are buried to depths of order 15-20 km [19].

Mercury. Imaging resolution issues may play a part in the apparent absence of pyroclastic deposits with radii less than ~7 km on Mercury (Fig. 1). The observed deposits with radii of ~10 km require volatile amounts of ~1 mass % in explosive eruptions, a value that might be consistent with dissolved magmatic volatiles in mafic or ultramafic magmas. However, deposits with radii greater than 30 km would require at least 3 mass %, a value that would generally be regarded as geochemically improbable, and so almost certainly imply volatile accumulation in shallow intrusions [20].

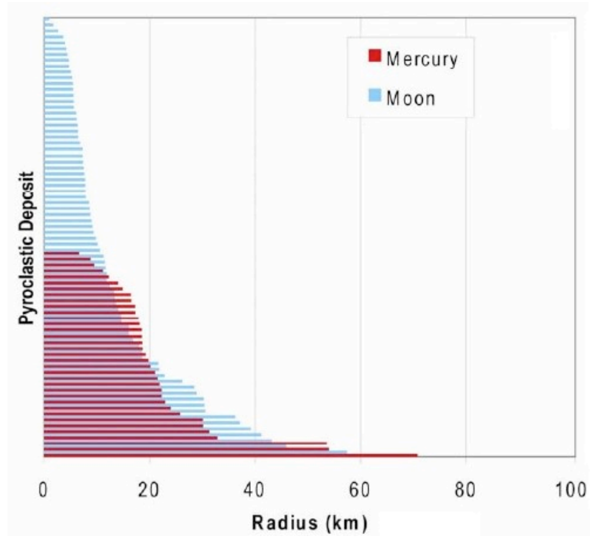

Figure 1: The distribution of the radii of pyroclastic deposits mapped on the Moon and Mercury, adapted from data in [11] and [12].

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