VOLCANICALLY-INDUCED TRANSIENT ATMOSPHERES ON THE MOON: ASSESSMENT OF DURATION AND SIGNIFICANCE. Lionel Wilson[1,2], James W. Head[2], and Ariel N. Deutsch[2] [1]Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK, l.wilson@lancaster.ac.uk, [2]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA.

Background: Needham and Kring [1] have proposed that a transient, more prominent atmosphere may have been present on the Moon at several times during its geologic history as a result of gases released in volcanic eruptions. On the basis of their analysis of the volumes and dates of lunar mare basalt eruptions, assumptions about the buried structure of mare-filled lunar impact basins, and volatile release patterns of erupted magmas, they conclude that during an interpreted peak volcanic and volatile release flux at ~3.5 Ga, "maximum atmospheric pressure at the lunar surface could have reached ~1 kPa" (~1.5 x Mars' current atmospheric surface pressure) and that the atmosphere "may have taken ~70 million years to fully dissipate." Schulze-Makuch and Crawford [2] explored the possibility of transient niches in which life could have evolved accompanying such an atmosphere. Needham and Kring [1] further explored the possibility that this transient atmosphere may have been a source for the hydrogen, presumably present as water, located in cold traps at the lunar poles, and conclude that "even if only 1% of the mare water vented during these eruptions remains in the polar regions…volcanically derived volatiles could account for all hydrogen deposits" currently observed in the lunar PSRs.

On the basis of recent work in assessing the generation, ascent and eruption of lunar basaltic magma [3,4], we adopt a more detailed approach and forward-model the production of volatiles in individual eruptions [5,6], and compare these with the results from the Needham and Kring approach [1]. We utilize our treatments [3-5] to forward-model magma emplacement and volatile release patterns and abundances, and then proceed to assess the likelihood of sufficiently abundant eruptions occurring to produce a transient atmosphere similar to that found by Needham and Kring [1].

The issues requiring examination are 1) the range (and mean value) of magma volumes in individual eruptions, 2) the masses, and hence volumes, of the various gases released in any one eruption, 3) the duration of the eruption and hence the gas release rate (possibly varying significantly as the eruption progresses), 4) the typical-time intervals between volcanic eruptions on the Moon as a function of geologic time and 5) the timescale for the dissipation of an atmosphere once one is emplaced.

Input data: Eruption volumes: Individual eruption volumes, V, of typical visible and therefore most recent lava flow deposits [3], are at least ~200-300 km^3, with some potentially up to 1000-2000 km^3 (Table 1) and we can estimate the minimum volumes of lava, ~100 km^3, needed to thermo-mechanically erode the preserved sinuous rille channels [7].

Total mare basalt erupted volumes: Using mare basins lava fill depth estimates, we have a reasonable value for the total volume, V_t, of all volcanic products erupted on the Moon over its lifetime, close to ~10^7 km^3 [8]. We do not know the absolute dates of specific eruptions but we can use crater size-frequency distribution-derived dates of units mapped from orbit, and stratigraphic relationships, to estimate the overall time span, τ_v, ~2 Ga, of the vast majority of the Moon's volcanic activity [9,3].

Number of eruptions, average rates and estimated repose periods: Using the 100-300 km^3 average eruption volume, the total erupted volume of mare basalts, and the duration, we calculate a total of ~30,000 to 100,000 eruptions in the 4-2 Ga period, and an average repose time of 20,000 to 60,000 years. Accounting for lunar thermal evolution in terms of mare mantle production rates and the evolving state and magnitude of stress in the lithosphere [3] we would predict greater volumes generated and released in earlier periods than later. Assuming that three times as much magma was erupted in the 4-3 Ga period than in the 3-2 Ga period, this suggests that the earlier eruptions could have occurred every 13,000 to 40,000 years.

Volatiles and release patterns: What volatile components were released, in what order, quantity, and in what relative abundance? We have good estimates of the mass fractions, n, a few hundred to perhaps 1500 ppm, and species, dominated by CO, water and sulfur compounds, of volatiles released from lavas and pyroclastics sampled by the Apollo missions [5,10].

Eruption durations: Analyses of the dynamics of lunar eruptions allow us to estimate the volume fluxes, F_l, of lava forming surface flows and sinuous rilles [4-6]; coupled with the erupted volumes, these give values for the typical durations, τ_e, of these eruptions.

Volatile input to the atmosphere: Multiplying the dense-rock-equivalent erupted volume V by the typical density of lunar basaltic magma, ρ_m = ~3000 kg m^{-3}, yields the magma mass erupted, and multiplying that by the released gas mass fraction n gives the total gas mass released, G. Finally dividing G by τ_e yields the gas mass input rate to the atmosphere, F_g. Table 1 summarizes these values.

Analysis: For each of the released gas masses in Table 1 we can find the properties of the lunar atmosphere that would be created if the gas release rate from the erupted magma was much greater than the total loss rate of the atmosphere into space by whatever mechanisms were relevant (which we shall show shortly is the case). Based on [5] we assume that the volcanic gas consists of CO, H_2O, sulfur compounds and traces of halogens [10] such that the mean molecular mass is m = ~25 kg/kmol. We then find the scale height of the resulting atmosphere, $H = (Q\ T) / (m\ g)$ where Q is the universal gas constant, 8.314 kJ kmol^{-1} K^{-1}, T is the mean lunar surface temperature, ~235 K, and g is the acceleration due to gravity at the lunar surface, 1.62 m s^{-2}. These values give H = 48 km. The surface density of the atmosphere, ρ_s, is equal to its mass, M, from Table 1, divided by the volume equivalent to the surface area of the Moon multiplied by the scale height, i.e. $\rho_s = M/(4\ \pi\ R^2\ H)$ where R is the lunar radius, 1738 km. Finally the surface pressure is $P_s = \rho_s\ g\ H$. Table 2 lists the values of ρ_s and P_s corresponding to eruption types in Table 1.

Table 1. Parameters of various types of lunar eruption. Cobra Head is the source of Vallis Schroeteri [3] and FFC is a typical floor-fractured crater [11-12]. Released volatiles assumed to be dominated by CO and to form n = 1000 ppm by mass of a magma that has a liquid density ρ_m = 3000 kg m^{-3}. V = lava volume; F_l = lava volume eruption rate; τ_e = eruption duration; M = total gas mass released; F_g = gas mass release rate. Typical values for parameters are quoted but individual eruption values may vary by a factor of at least 2 to 3.

Feature	V/km^3	F_l/(m^3 s^{-1})	τ_e/days	M/kg	F_g/(kg s^{-1})
Cobra Head	2000	1.4×10^5	165	6×10^{12}	4×10^5
FFC	1000	$\sim10^5$	115	3×10^{12}	3×10^5
long flow	300	10^6-10^4	30	9×10^{11}	3×10^6
small flow	200	10^5-10^3	100	6×10^{11}	3×10^5
sinuous rille	100	$\sim3\times10^4$	50	3×10^{11}	10^5

Table 2. Initial values of the surface density, ρ_s, and surface pressure, P_s, in a transient atmosphere produced by the five types of volcanic activity listed in Table 1. The maximum duration of the atmosphere, τ_d, is indicated.

Feature	ρ_s/(kg m^{-3})	P_s/Pa	τ_d/years
Cobra Head	3.3×10^{-6}	0.26	19,000
FFC	1.6×10^{-6}	0.13	9,500
long flow	4.9×10^{-7}	3.8×10^{-2}	2,900
small flow	3.3×10^{-7}	2.6×10^{-2}	1,900
sinuous rille	1.6×10^{-7}	1.3×10^{-2}	950

Discussion: The implied atmospheric gas masses due to typical types of lunar volcanic activity (see Table 1) are of order a few times 10^{11} to a few times 10^{12} kg. As part of an extensive review of three possible types of lunar atmosphere, Stern [13, his section 5.2.2] treats a hypothetical volcanically-induced atmosphere, and with some prescience chooses a total gas mass of 10^{14} g, i.e., 10^{11} kg, for his illustration, the same order of magnitude as the smallest value that we predict. We therefore follow his arguments about the rate at which such a collisionally dominated atmosphere would be lost to space, and like him we adopt the loss rate calculated by Vondrak [14] of 10^4 g s^{-1}, i.e., 10 kg s^{-1}. This leads to the timescales for atmospheric decay, τ_d, shown in Table 2, between ~1,000 and ~20,000 years. These are likely maximum atmosphere durations because as the density becomes very small, other loss mechanisms come into play. These values need to be compared with the likely intervals between eruptions on the Moon. With a total volume of volcanics of $V_t = 10^7$ km^3 [1, 5], a typical erupted volume of 200 ± 100 km^3 (Table 1), and a total duration of volcanism of τ_v = ~2 Ga, the average interval is 20,000 to 60,000 years. Assigning higher eruptions fluxes to the early part of the mare volcanism era does not change this conclusion greatly.

Conclusions: The implied intervals between typical lunar eruptions, ~20,000 to 60,000 years, are an order of magnitude greater than the likely durations of the vast majority of individual transient atmospheres, between ~1,000 and 3,000 years, though for some floor-fractured crater events and the extreme example of Schroeter's Valley the time scales are comparable. Otherwise, only if all of the Moon's ~10^7 km^3 of basaltic volcanism were to have taken place within a 200 Ma interval would the time scales be comparable. We therefore think it unlikely that the Moon had a semi-permanent (as long as ~70 Ma) volcanically-driven atmosphere as proposed by Needham and Kring [1]. We attribute the differences between our estimates and those of Needham and Kring [1] to their use of maximum impact basin depths as average depths, and assignment of all excess volumes below datable units to one age (e.g., 5.9 x 10^6 km^3 assigned to 3.5 Ga in the case of Imbrium).

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