VOLATILES RELEASED DURING EMPLACEMENT OF MARE BASALTS: IMPLICATIONS FOR A LUNAR ATMOSPHERE.

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Introduction: The lunar atmosphere currently has an extremely low density and, thus, is designated a surface boundary exosphere (SBE). Although the lunar environment has most likely been a relatively stable SBE for the past 3 Gyr, enhanced impact and volcanic activity early in lunar history may have contributed to an ancient, thicker collisional atmosphere around the Moon [1]. To determine how the lunar environment may have been affected by more intense volcanic activity early in its history, this study investigates the volume of mare eruptions and the associated mass of volatiles released on the Moon as a function of time.

Methodology and Results:

Mare Volume over Time: The mare volume in each basin varies widely, reflecting both the basin sizes and the thermal evolution of the lunar interior. We use primarily mare thickness estimates in [2], which are in line with recent estimates using Lunar Orbiter Laser Altimeter (LOLA) topography data [3] and Gravity Recovery and Interior Laboratory (GRAIL) data [4], to determine the total mare volume in several lunar basins (Table 1). Less certain estimates of mare volumes in Tranquillitatis, Oceanus Procellarum [5], and South Pole – Aitken (SPA) basin [6] were also included to be complete, but may need to be revised in future studies.

To deduce a production function for volatiles, the timing of mare eruptions is needed. Analyses of Lunar Orbiter IV and Clementine images [7] and of Lunar Reconnaissance Orbiter Wide Angle Camera (LROC WAC) images and Moon Mineralogy Mapper (M^3) spectral data [8] indicate mare unit ages range from ~3.9 Ga to ~1.1 Ga. Observations of specific mare flows within Serenitatis and Oceanus Procellarum indicate an average flow thickness of ~250 m [9]; this thickness is taken as the average flow thickness for all surface mare units in the absence of other thickness measurements (*e.g.*, in Orientale [8] and in SPA [6]). These units represent the final stages of mare emplacement and, thus, are interpreted to post-date any underlying mare. We estimate the volume of the underlying mare as the difference between the total mare for a given basin and the volume of the mapped surface flows. Although the ages of these underlying basalts are not known, they are at least as old as the oldest surface unit.

Table 1: Volume of mare in lunar basins

Basin	Area (km^2)	Thickness (m)	Volume (km^3)
Crisium [8]	156,103	2,940	458,943
Grimaldi [8]	15,359	3,460	53,142
Humorum [8]	101,554	3,610	366,611
Imbrium [8]	1,010,400	5,240	5,294,497
Nectaris [8]	64,277	840	53,993
Orientale [4]	75,975	88	13,294
Procellarum [19]	1,757,799	325	571,285
Serenitatis [8]	342,716	4,300	1,473,679
Smythii [8]	28,075	1,280	35,937
SPA [20]	206,430	varied	153,240
Tranquillitatis [19]	371,257	350	129,940

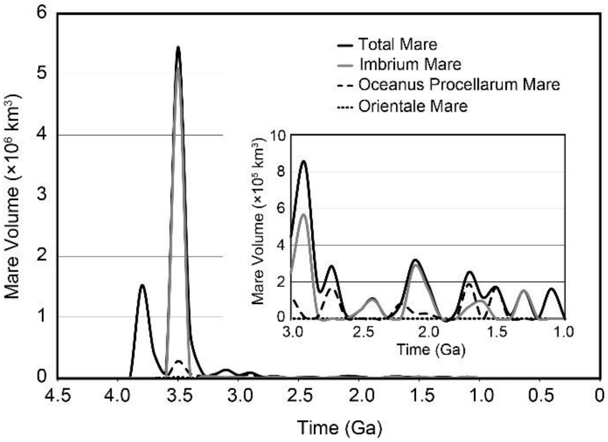

Fig. 1: Volume of erupted mare basalts as a function of time. The inset zooms in on 3–1 Ga to show the continuation of less voluminous lunar eruptions into more recent lunar history. The peak in mare volume at 3.8 Ga is primarily due to eruptions in the Serenitatis basin.

We use these observations to calculate mare volume as a function of time (Fig. 1). Most mare was emplaced between 3.1 Ga and 3.8 Ga, with the largest volumes emitted ~3.5 Gyrs ago. The largest contributors to the erupted volumes include basalts emplaced within Serenitatis basin (peak at 3.8 Ga), Imbrium, and Oceanus Procellarum basins (peaks at 3.5 Ga).

Mass of Volatiles over Time: Estimates of volatile masses released during these eruptions may lead to a better idea of how thick the lunar atmosphere may have been ~3.5 Gyrs ago. Volatile abundances in lunar pyroclastic deposits were directly measured in Apollo 15 and 17 volcanic glasses (*e.g.*, [10-12]). Volatiles released during mare eruptions have lower concentrations than those released during pyroclastic eruptions: CO (100% liberated from parent magma, 80 – 750 ppm, [13]), H_2 (100% liberated, 0.007 – 45 ppm, [14]), H_2O/OH (85 – 99% liberated, 1.98 – 9.9 ppm, [15]), and S (90% liberated, 90 – 540 ppm, [16]).

We use these mare volatile concentrations to determine the production function of volatiles released over lunar history. Following the recent approach for quantifying volatile production in lunar pyroclastic eruptions [17], the mass of erupted lava was calculated by multiplying the estimated mare volume by the bulk density of typical mare basalt (~3.00 g/cm^3, [18]). This mass was then multiplied by the minimum and maximum contents of each mare volatile species to

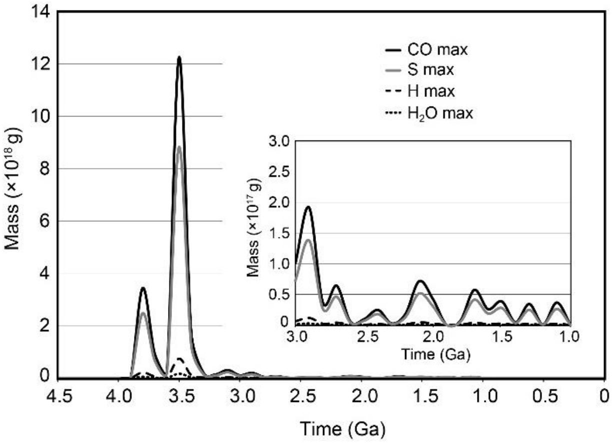

Fig. 2: Volatile mass from all mare eruptions as a function of time. The most prevalent volatile released is CO, followed by S, H, and H_2O.

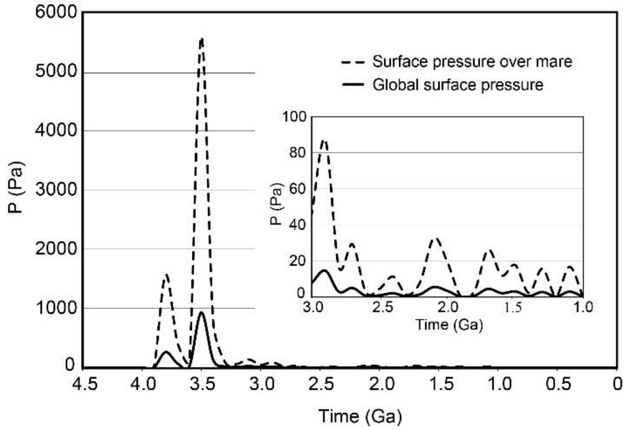

Fig. 3: Local and global lunar surface pressure as a function of time. If the mare volatiles had a local distribution above the source region, the surface pressure would be much higher (~6% Earth's surface pressure) than if the volatiles were distributed more diffusely around the entire Moon (~1% Earth's surface pressure).

determine the mass range of each volatile released (Fig. 2). Peak volatile releases coincide with the largest eruption events of 3.8 Ga and 3.5 Ga.

The most prevalent volatile species released are CO (0.2 – 2.0 × 10^{19} g total) and S (0.5 – 1.4 × 10^{19} g total); H_2O is the third-most prevalent volatile released (0.5 – 2.6 × 10^{17} g total). Contents of F and Cl in mare basalts have not yet been explicitly reported and are, therefore, assumed to have been released in amounts smaller than anticipated for pyroclastic deposits (*e.g.*, less than 2 – 9 × 10^{14} g of F and 0 – 4 × 10^{13} g of Cl).

Discussion and Implications: The maximum volatile masses released during the emplacement of mare basalts (Fig. 2) can be used to estimate the maximum surface pressure of an atmosphere that might be expected to develop as a result of these eruptions (Fig. 3). Assuming a homogeneous distribution of volatiles around the Moon, the maximum global surface pressure during the peak epoch of 3.5 Ga would have been ~1 kPa, or 0.01 atm (Fig. 3, solid line). This pressure is ~1% of Earth's current surface pressure and ~1.5 times higher than Mars' current surface pressure. If the erupted volatile-derived atmosphere was more heavily concentrated over the mare source region (area of 6.3 × 10^6 km^2, [19]), the more localized surface pressure immediately after the 3.5 Ga pulse in volcanic activity would have been 5,600 Pa (0.06 atm) or ~6% of Earth's surface pressure (Fig. 3, dashed line).

Released volatiles may have formed an atmosphere that lingered around the Moon. The current lunar atmospheric loss rate is estimated to be ~10 g/s [1]; however, the loss rate changes significantly when the atmospheric mass exceeds 10^8 kg [20], at which point a much higher loss rate on the order of 10^4 g/s is expected [1]. At the peak of lunar volcanic activity ~3.5 Ga, the total mass of particles released into the atmosphere was on the order of 10^{16} kg and, at a loss rate of 10^4 g/s, this thicker lunar atmosphere would have required ~70 million years to dissipate. The actual loss time may be longer than this estimate because the loss rate is expected to have decreased as the atmosphere thinned.

After erupting, the volatiles would have been susceptible to migration towards the poles [21,22], where they would have been trapped in permanently shadowed regions (PSRs). If 0.1% of the total vented mare water (calculated above to be ~10^{17} g) is trapped in PSRs, volcanically-derived volatiles could account for all of the water currently observed in PSRs (*e.g.*, 10^{14} g, [23]). The relative contributions of indigenous and exogenous sources are still uncertain, but these results suggest transport models need to account for periods with higher indigenous fluences of volatiles to properly evaluate their contribution to PSR volatile deposits. As indigenous volatiles will have a distinct isotopic signature [*e.g.*, 24], those model calculations can be tested with future lunar surface missions, such as the upcoming Resource Prospector mission.

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