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Lunar volcanism produced a transient atmosphere around the ancient Moon

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ABSTRACT

Studies of the lunar atmosphere have shown it to be a stable, low-density surface boundary exosphere for the last 3 billion years. However, substantial volcanic activity on the Moon prior to 3 Ga may have released sufficient volatiles to form a transient, more prominent atmosphere. Here, we calculate the volume of mare basalt emplaced as a function of time, then estimate the corresponding production of volatiles released during the mare basalt-forming eruptions. Results indicate that during peak mare emplacement and volatile release ∼3.5 Ga, the maximum atmospheric pressure at the lunar surface could have reached ∼1 kPa, or ∼1.5 times higher than Mars' current atmospheric surface pressure. This lunar atmosphere may have taken ∼70 million years to fully dissipate. Most of the volatiles released by mare basalts would have been lost to space, but some may have been sequestered in permanently shadowed regions on the lunar surface. If only 0.1% of the mare water vented during these eruptions remains in the polar regions of the Moon, volcanically-derived volatiles could account for all hydrogen deposits – suspected to be water – currently observed in the Moon's permanently shadowed regions. Future missions to such locations may encounter evidence of not only asteroidal, cometary, and solar wind-derived volatiles, but also volatiles vented from the interior of the Moon.

1. Introduction

The lunar atmosphere was first detected by ion and charged particle experiments installed during Apollo (Johnson et al., 1972; Hodges, 1973; Hoffman et al., 1973). The present atmosphere is low density and, thus, is designated a surface boundary exosphere (SBE). Similar exospheres, in which atoms and molecules removed from the surface have only a small probability of suffering a collision before escaping to space, have also been detected around Mercury, Io, Europa, and Callisto. Sources for the lunar atmosphere (e.g., Stern, 1999) include thermal, sputtering, and chemical processes that affect grains at the uppermost surface of the Moon, releasing ions and molecules from the surface into the exosphere. Additionally, meteoritic collisions onto the lunar surface produce impact-generated vapor and melted material that outgasses to the surrounding environment. Furthermore, other processes that release volatiles, including seismically induced seepage of volatiles from the lunar interior and volcanism, could contribute to the development of the exosphere. Although the lunar atmosphere has likely been a SBE for the past 3 Ga, enhanced volcanic activity early in lunar history may have facilitated development of a more substantial collisional atmosphere around the ancient Moon.

2. Methods

2.1. Lunar mare basalt volume over time

We investigated the volume of mare basalt and the mass of volatiles released from the Moon as a function of time to determine how the lunar atmosphere may have been affected by more intense volcanic activity early in lunar history. Volumes of mare basalts erupted into each basin (Table 1) vary as a function of basin size and thermal evolution of the lunar interior. Mare basalt thicknesses may also be uncertain, which affect estimated volumes (e.g., from ∼5×10^5 km^3, Williams and Zuber, 1998; Hiesinger et al., 2011, to 10^6 km^3, Bratt et al., 1985, in Crisium). In general, initial attempts to estimate mare basalt volumes (Solomon and Head, 1980; Bratt et al., 1985) overestimated those volumes by factors of ∼2 (Williams and Zuber, 1998; Dibb and Kiefer, 2015). In contrast, estimates of mare basalt thicknesses based on analyses of lunar basin depths (De Hon, 1974, 1976, 1977, 1979) augmented with Clementine altimetry data (Williams and Zuber, 1998) are

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Table 1
Estimated total volume of mare basalt fill in lunar basins.

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

[a] Williams and Zuber (1998).
[b] Whitten et al. (2011).
[c] Hörz (1978).
[d] Yingst and Head (1997).

generally consistent with more recent estimates using Lunar Orbiter Laser Altimeter (LOLA) topography data (Dibb and Kiefer, 2015) and Gravity Recovery and Interior Laboratory (GRAIL) data (Evans et al., 2016). Specifically, these newer estimates place an upper bound on the thickness of all nearside mare basalts of ∼7 km (Evans et al., 2016). Recently reported basin-specific thickness estimates for the nearside mare basalt-filled basins with the greatest fill volumes (Serenitatis and Imbrium) are <15% different (Dibb and Kiefer, 2015) when compared with the work of Williams and Zuber (1998). Because Williams and Zuber (1998) analyzed the majority of lunar mare basalt-filled basins and reported thicknesses that are consistent with new topography and gravity data, we used these thicknesses to calculate the volume of mare basalt in lunar basins, including Crisium, Grimaldi, Humorum, Imbrium, Nectaris, Serenitatis, and Smythii. More recently reported mare basalt thicknesses were included for Orientale (Whitten et al., 2011) and other minor basins (Hiesinger et al., 2011), and mare volumes within Tranquillitatis, Oceanus Procellarum (Hörz, 1978), and South Pole – Aitken (SPA; Yingst and Head, 1997) were also included where more recent volume estimates were not available (Tables S1, S2).

Mare basalt provinces were emplaced from ∼3.9 Ga to as recently as ∼1.1 Ga (Figs. 1, 2a), as indicated by mare unit boundary mapping and crater size frequency analyses of Lunar Orbiter IV and Clementine data for SPA (Yingst and Head, 1997) and for nearly all other basins included in these analyses (Hiesinger et al., 2011; Table S1). Mare basalt unit boundaries and associated model ages for Orientale were determined using data from Lunar Reconnaissance Orbiter Narrow and Wide Angle Camera (LROC NAC, WAC) images and Moon Mineralogy Mapper (M^3) spectral data (Whitten et al., 2011). Observations of specific mare eruptive units indicate an average mare unit thickness of ∼250 m (Weider et al., 2010) within Serenitatis and Oceanus Procellarum. This thickness is expected to incorporate an integrated sequence of thinner flows such as those observed in exposed walls of mare pits (Robinson et al., 2012), and is assumed to be the average thickness for all surface mare units in the absence of other thickness measurements (e.g., in Orientale (Whitten et al., 2011) and in SPA (Yingst and Head, 1997), Table S1).

We use observed mare basalt properties to calculate the volume of surface mare basalts across the Moon as a function of time (Fig. 2a and Table S2). The surface mare units represent the final stages of mare emplacement and, thus, are interpreted to post-date underlying mare units. We assume that the underlying flows were emplaced as older surface flows that were embayed by younger surface flows, such that the mare units are stacks of superposed lava units emplaced via effusive surface eruptions. Although ages of underlying basalts, with volumes taken as the difference between the total mare basalt for a given basin and the volume of the mapped surface flows, are not identified directly, these deposits are at least as old as the oldest surface unit (noted in italics in Table S1).

Mare volcanism peaked between 3.8 Ga and 3.1 Ga, with the largest volumes erupted ∼3.5 Gyrs ago (Figs. 1 and 2a). Most mare basalts were emplaced within Serenitatis at 3.8 Ga, and within Imbrium and Oceanus Procellarum basins at 3.5 Ga. After those voluminous effusions of mare basalt, mare emplacement waned to near zero. Additional volumes of maria or cryptomaria that predate Orientale may not be included in our analyses, but would further contribute to the early release of volatiles.

2.2. Production of lunar volatiles over time

Measurable volatile abundances associated with lunar basalt eruptions [H, C, N, F, S, and Cl], began to emerge with direct measurements of Apollo 15 and 17 volcanic glasses (Saal et al., 2008,

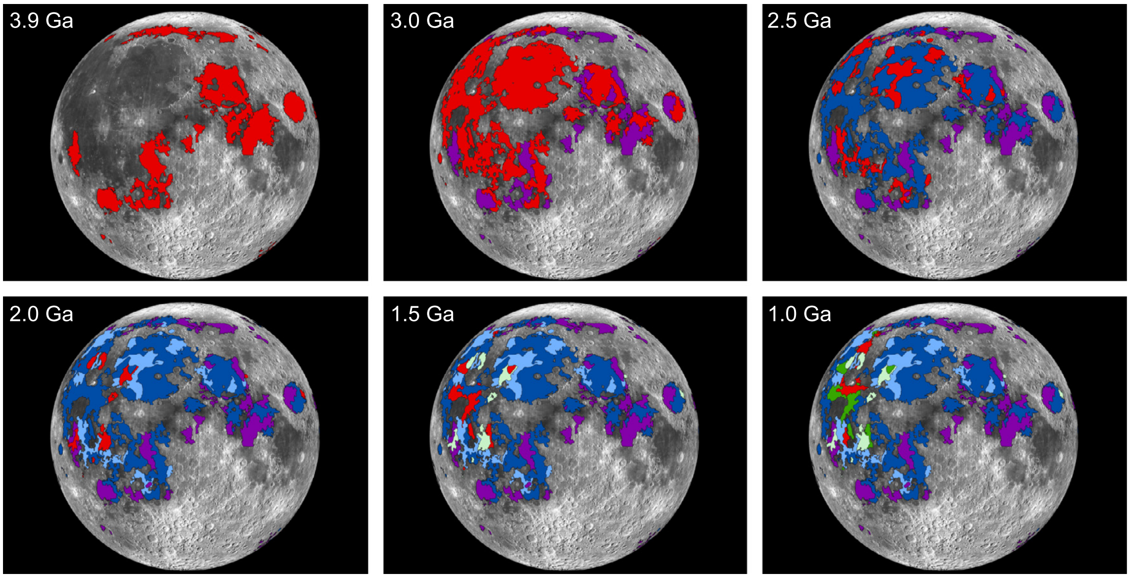

Fig. 1. A time sequence of lunar mare basalt emplacement in 0.5 Ga time increments, with red areas in each time step denoting the most recently emplaced basalts. Ages of mare basalt units are from Hiesinger et al. (2011).