Beginning and end of lunar mare volcanism

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Mare volcanism on the Moon is commonly attributed to an important but relatively short-lived epoch of internal heating after 3,900 Myr BP but before about 2,500 Myr BP (refs 1, 2). Although some studies suggested that mare volcanism had started earlier3–8 than times indicated by dated lunar samples, only recently have photogeological, spectral, and geochemical data9,10 documented the importance of a pre-4,000 Myr BP epoch. Similarly, early Earth-based geological mapping revealed a bright-rayed crater (Lichtenberg) superposed by mare units2, thereby indicating that mare volcanism must have extended to times significantly more recent than 3,100 Myr BP. Lunar orbital photography confirmed this inferred stratigraphical relationship5, but crater statistics indicated that the youngest units were at least twice the age of Copernicus, or between 1,700 and 2,000 Myr BP (refs 11–13). We present here the inferred distribution and style of the early phases of mare volcanism based on current evidence and conclude that certain regions of the Moon underwent two distinct pulses of igneous activity. We then examine crater statistics for the post-Lichtenberg mare unit and other selected units that conclude and that mare volcanism extended to a time comparable with that of the Copernicus impact, or ~1 Myr BP. These reassessments of the oldest and youngest maria provide new constraints on geophysical models of the internal thermal history of the Moon. Direct evidence for the existence of ancient lunar volcanism is found in a variety of sample investigations. Numerous mare basalt fragments are found as clasts in breccias that were assembled before 3,900 Myr BP (refs 14, 15). Many of these breccias appear to be related to major basins, suggesting that volcanic flows constituted at least part of the target for these impacts. Such volcanics could have existed either as lava flows covering the basin impact site or subsurface magma reservoirs ejected and subsequently included in basin deposits. Mixing model studies of highland soils (see ref. 16) require substantial admixture of a mare basalt component at a level significantly higher than that expected from post-mare lateral mixing by impacts17. This suggests the presence of a mare component within the highlands, either buried by and included within highlands megaregolith or deposited as basin ejecta.

The very early stages of mare volcanism are believed to be indicated by dark-haloed impact craters which have excavated ancient mare units from below light-coloured ejecta deposits9. More than 100 such craters larger than 1 km in diameter have been identified on the Moon. Apollo orbital geochemical data8,18 and recent Earth-based spectral data7 confirm the proposed mafic component in these ejecta. The distribution of dark-haloed impact craters provides a basis for mapping buried mare basalt plains in order to understand the areal extent and the source regions. Figure 1 illustrates a conservative estimate of ancient mare deposits and reveals a close association with very old impact basins identified in refs 4 and 18. Although early analysis11 of old impact basins led to the suggestion that such structures may have been filled with dark lavas whose surface lightened with age, dark-haloed impact craters were not cited as specific indicators of the nature and extent of this early phase of volcanism. The most extensive deposits are found in the eastern hemisphere: within the heavily degraded basin Lomonosov–Fleming and partly encircling Smythii, Crisium, Milne, and Balmer basins. Additionally, dark-haloed craters indicate buried mare surfaces around the Schiller–Zucchius basin where thermal IR maps9 clearly indicate a relative excess of blocks comparable with that of more recent unblanketed mare surfaces and in contrast with adjacent highlands.

The apparent absence of buried mare surfaces on the nearside (near 0°) and western hemispheres (270°) is believed to reflect masking by Imbrium and Orientale ejecta deposits. Although dark-haloed impact craters and geochemical signatures in these regions may indicate buried maria6, their occurrences are too isolated for defining significant contiguous plains. Poor photographic coverage may account for the absence of inferred buried maria between 180° and 270° and in the polar regions. Nevertheless, the total estimated areal extent of these ancient mare deposits exceeds 7.5 x 10⁶ km² or ~12% of the visible Imbrian and younger maria. This value should be viewed as a minimum since ponded lavas within craters and thin flows are difficult to recognize. Moreover, recent identification of a mafic anomaly in the region of the crater Firsow (4° N, 112° E) suggests the presence of a mare volcanic flow whose surface expression

Fig. 1 Distribution of mare plains younger than 3,900 Myr (black) and buried mare plains (striped) inferred from the clustering of dark-haloed impact craters and orbital geochemical data. Buried mare units are probably more widespread but their signature has been masked through vertical and lateral mixing by impact cratering including the formation of the large multi-ringed basins. Such ancient mare surfaces are localized within very old impact basins in patterns similar to younger mare deposits. Abbreviations represent the following selected multi-ring basins (after refs 4, 18, and 38): O, Orientale; H, Humorum; S2, Schiller–Zucchius; I, Imbrium; N, Nectaris; C, Crisium; B, Balmer; S, Smythii; LF, Lomonosov–Fleming; AK, Al-Khwarizmi-King; TS, TsaoKolovsky-Stark; M, Milne; MS, Moscovien.
Figure 1 shows that several impact basins have undergone at least two separate stages of volcanic activity. Dark-haloed craters near Mare Smythii occur in smooth plains-filled craters within a very ill defined outer ring outside the principal boundary scarp containing floor-fractured craters and mare units. Crater statistics (see ref. 12) indicate that mare units in the interior of Smythii are very young, yet the buried, crater-contained units peripheral to the inner ring are very old. Apollo orbital geochemical data\(^8\) support the interpretation that these peripheral units are volcanic in origin. Similarly, dark-haloed craters peripheral to Mare Crisium occur in low-lying concentric valleys with inferred ages much older than that of the mare plains. Recent high spatial resolution Mg/Al maps of this region reveal relatively high Mg/Al values in certain areas, some of which correlate with the occurrence of small dark-haloed craters\(^1^).\

Certain models\(^2\) suggest that late-stage volcanic activity occurred principally near the edge of the mare basins owing to tensional stresses from the load of the volcanic fill. The observations here do not negate this basic idea, but indicate in addition that the basin may undergo a period of resurgent activity concentrated along an interior ring\(^2,23,24\). Such volcano-tectonic resurgence can re-establish a battered circular outline (for example, for Smythii and Humorum) corresponding to deep-seated, impact-related fractures. Thus, concentric pools of lava (as inferred form dark-haloed craters and geochemical signatures) outside the principal rings of Smythii and Crisium may be remnants of a very early stage of volcanism. Such a two-stage model of mare flooding may reflect the relatively rapid isostatic adjustment of impact basins formed before \(\sim 4,000\) Myr BP. As the lithosphere gained strength, deep-seated fractures along the inner rings of certain old basins provided conduits for later mare basalts. The subsequent outward migration of vents to the outer rings, however, may have ceased due to insufficient reloading of the basin interior, more limited magma reservoirs or deepening of the magma-source regions.

At the other end of the lunar time scale, current interpretations date the last stages of widespread lava flooding \(\sim 2,500 \pm 500\) Myr BP (ref. 25) with the youngest eruptions occurring around \(1,700 \pm 2,000\) Myr BP (refs 11, 13), about twice the estimated age of Copernicus\(^2\). However, the young mare units superposing the Lichtenberg ray system (Fig. 2) poses a contradiction in such interpretations. Bright-ray patterns from impact craters gradually disappear with time at a rate that increases with decreasing crater size\(^25,26\). Correlations between crater densities and the rate of crater ray removal\(^28\) indicate that a crater the size of Lichtenberg (20 km in diameter) would lose its bright rays if it were older than Copernicus (100 km). If Copernicus was formed at about 900 Myr BP (ref. 26), then the flow units superposing Lichtenberg should have erupted at a similar time.

Crater statistics support the very young age of the basalt flows east of Lichtenberg. Figure 3 and Table 1 permit comparison of the number of craters larger than 0.5 km in diameter found on this unit that can be calibrated with lunar sample ages from Apollo 12 and Apollo 15 (ref. 29) and the inferred absolute ages of Copernicus\(^2\) and Tycho\(^2\) The reference crater size of 0.5 km is large enough to avoid irregularities observed for crater statistics at small sizes\(^31\) but small enough to obtain meaningful statistics for small counting areas. The number of superposed craters on the flows overlapping Lichtenberg approximates values for Copernicus. These statistics are based on enhanced near-terminator Apollo panoramic photographs that probably produce an overestimated age based on low-Sun corrections noted in (ref. 32). For comparison, Figure 3 shows the four mare age classes in (ref. 12) that extend to \(\sim 2,000\) Myr BP. The youngest units previously cited include a region 400 km south-east of Lichtenberg whose inferred age is 1,800 \(\pm 200\) Myr BP (ref. 13) and the late Imbrium flows whose inferred age is 1,700 Myr BP. Our inferred age estimates are in agreement with previous studies, but in addition, we find several regions in Oceanus Procellarum having significantly

Fig. 2 a. The bright-rayed crater Lichtenberg (31.5°N, 67°W) in Oceanus Procellarum, embayed by younger mare units. The rate of crater ray removal for a crater of this size and the crater frequency on the mare units indicate a time of about \(900 \pm 300\) Myr for mare eruption. The box corresponds to the area shown in b. Scale bar, 10 km. Lunar Orbiter IV-170-H1. A, A low-Sun, high-resolution view near Lichtenberg where mare units have embayed the ejecta deposits (arrow A) and covered the bright ray pattern. Arrow B identifies the contact between this young mare unit and older (but still relatively young) mare units of Oceanus Procellarum. Scale bar, 5 km. Apollo 15 Panoramic Photos 369 and 370.

has been totally obliterated by saturation impact cratering within the proposed Al-Khwarizmi–King basin\(^5\). Thus numerous farside basins that appear to have no mare fill on the basis of albedo or surface features, may have undergone early mare flooding. The high cratering rates during the pre-Nectarian and Nectarian periods gardened and masked these units with the highlands megaregolith.
young ages. Moreover, very young mare flows are not confined strictly to the Oceanus Procellarum region as is commonly cited (see, for example, ref. 33). Table 1 and Figure 3 show that Mare Smythii is only slightly older than a large cluster of young maria in the Procellarum region (uppermost Eratosthenian). Older ages for the same units cited in ref. 12 reflect the use of techniques that integrate statistics from broad areas and different horizons, thereby combining and overestimating the age of the youngest units. Table 1 shows that statistics for craters >0.5 km in similarly broad regions (>10^5 km^2) result in inferred relative ages consistent with those derived in ref. 12.

We suggest, therefore, that the end of mare volcanism extended to around the time of Copernicus or ~1,000 Myr Bp. The total areal extent of these last gasps of mare volcanism is impossible to determine from available image resolution. The very young units indicated in Fig. 3 and Table 1 all have retained very fine-scale (20-30m) flow textures characteristic of thin lava flows and appear to correlate with spectrally distinct blue mare units in Oceanus Procellarum. Such units cover a combined area of the order of 10^7 km^2.

We conclude that lunar volcanism has been a relatively continuous process beginning perhaps as early as 4,300 Myr (the time when more basalt source regions became isotopically closed) and gradually terminating around 1,000 Myr. The beginning of mare flooding was concentrated in old impact basins much in the style of post 4,000 Myr volcanism as suggested in ref. 1. Inactive activity ceased in numerous basins, perhaps reflecting isostatic adjustment during early lunar history; however, volcano-tectonic resurgence occurred within the inner rings of several basins well after 4,000 Myr. Volcanism extended to 1,000 Myr with possible minor eruptions postdating the Copernicus impact. This revised scenario is more consistent with theoretical thermal models where the lunar interior gradually cools without a sudden termination.

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**Table 1**

<table>
<thead>
<tr>
<th>Region</th>
<th>Lat.</th>
<th>Long.</th>
<th>Photograph no.</th>
<th>D_A (km)</th>
<th>N_/A</th>
<th>A_1 (km^2)</th>
<th>A_2 (km^2)</th>
<th>Ref.</th>
<th>Absolute age (Myr)</th>
<th>Ref.</th>
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<tr>
<td>Apollo 15</td>
<td>15.3°N</td>
<td>2.8°E</td>
<td>LV-O-101-M</td>
<td>270±15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.0±1.0</td>
<td>373</td>
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<tr>
<td>Apollo 12</td>
<td>31.7°S</td>
<td>2.3°W</td>
<td>LV-O-128-154</td>
<td>210±20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.8±1.0</td>
<td>351</td>
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<tr>
<td>Late Imbrian</td>
<td>26.5°N</td>
<td>8.7°W</td>
<td>A15M-1009</td>
<td>165±25</td>
<td>3.0±0.4</td>
<td>1735</td>
<td>3.7±0.7</td>
<td>685</td>
<td>(2,000±500)</td>
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<td>Mare Smythii (MS)</td>
<td>1.3°N</td>
<td>9.1°E</td>
<td>L0-I-15</td>
<td>165±25</td>
<td>2.6±0.5</td>
<td>915</td>
<td>2.8±0.9</td>
<td>352</td>
<td>(1,800±300)</td>
<td></td>
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<td>South-west of Maestlini (SMW)</td>
<td>1.8°N</td>
<td>4.1°W</td>
<td>L0-II-201</td>
<td>165±25</td>
<td>.0±0.4</td>
<td>1,243</td>
<td>.8±0.7</td>
<td>392</td>
<td>(1,200±400)</td>
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<td>Letronne mare (LM)</td>
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<td>4.5°W</td>
<td>L0-A16-2996</td>
<td>225±14</td>
<td>-</td>
<td>2.3±0.3</td>
<td>1,800</td>
<td></td>
<td>(1,100±300)</td>
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<td>Gruithuesken mare (GM)</td>
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<td>4.7°W</td>
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<td>225±15</td>
<td>-</td>
<td>2.3±0.3</td>
<td>1,800</td>
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<td>(1,100±300)</td>
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<td>Flamsteed Ring mare (FRM)</td>
<td>2.1°N</td>
<td>4.2°W</td>
<td>L0-III-187</td>
<td>165±25</td>
<td>-</td>
<td>2.3±0.4</td>
<td>1,770</td>
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<td>(900±400)</td>
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<td>South-east of Lichtenberg (SEL)</td>
<td>31.8°N</td>
<td>6.6°W</td>
<td>A15P-366-370</td>
<td>165±25</td>
<td>2.0±0.2</td>
<td>4,950</td>
<td>1.5±0.3</td>
<td>2,134</td>
<td>(300±300)</td>
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<td>Copernicus (ejecta)</td>
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<td>18°W</td>
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<td>100±12</td>
<td>1.4±0.18</td>
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<td>1.6±0.3</td>
<td>2,140</td>
<td>850±100</td>
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<td>Tycho (ejecta)</td>
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<td>47.3°W</td>
<td>L0-V-201</td>
<td>-</td>
<td>0.44±0.13</td>
<td>4,347</td>
<td>400</td>
<td>96±5</td>
<td>30</td>
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</table>

N/A represents the number of craters larger than 0.5 km in diameter per km^2. Subscripts refer to nested counting areas. Large areas (subscript 1) result in counts larger than counts for small areas (subscript 2) for very young surfaces but comparable counts for old surfaces owing to the effect of secondary impact craters.

D_A is a limiting crater diameter for degradation as described in ref. 11.

Absolute ages in parentheses indicate ages inferred from Fig. 3.

* Region used in ref. 13.

Values will be slightly larger than values in mape owing to target strength differences.

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**Fig. 3**

Number density of craters larger than 0.5 km on selected units versus absolute age as calibrated by four dated lunar events (circled). Actual values plotted are given in Table 1. Note pronounced cluster of inferred ages for mare units in the late Eratosthenian and early Copernican where time stratigraphical boundaries (top of graph) have been determined in ref. 38. Age groupings (I, II, III, and IV) at the bottom of the graph are from ref. 12. Abbreviations for selected mare units are given in Table 1.