Lunar mare basalt flow units: Thicknesses determined from crater size-frequency distributions

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[1] Accurate lava flow unit thicknesses estimates are necessary to place constraints on volcanic flux estimates. We refine the technique of using the shape of crater size-frequency distribution (CSFD) curves to estimate the thickness of individual lunar mare flow units. We find that a characteristic knee often observed in CSFD curves is reasonably interpreted to represent the presence of two lava flow units separated in time, and that the diameter at which this knee occurs is related to the thickness of the overlying flow unit. Examination of 58 curves with this characteristic knee in several lunar nearside basins (Oceanus Procellarum, Imbrium, Tranquillitatis, Humorum, Cognitum, Nubium, and Insularum) allowed us to identify flow units that have not been detected in low-sun images. We found that the range of flow unit thickness is ~20–220 m and the average is ~30–60 m. This technique expands considerably the ability to assess lava flow unit thicknesses and volumes on the Moon and planets. *INDEX TERMS:* 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 5470 Planetology: Solid Surface Planets: Surface materials and properties; 5464 Planetology: Solid Surface Planets: Remote sensing; 5480 Planetology: Solid Surface Planets: Volcanism (8450); 6250 Planetology: Solar System Objects: Moon (1221)

1. Introduction

[2] Establishing the volume of mare basalts emplaced on the surface as a function of time (the flux) is an important goal in setting constraints on the petrogenesis of lunar mare basalts and their relation to the thermal evolution of the Moon [*Head and Wilson*, 1992]. Early work focused on estimating the total thickness of mare basalt fill in the mare basins [e.g., *DeHon*, 1974; *DeHon and Waskom*, 1976; *Hörz*, 1978, *DeHon*, 1979], and a variety of techniques were used, as summarized in *Head* [1982]. Studies by *DeHon and Waskom* [1976] yielded total thickness values of up to 2 km, with 200–400 m on average. Reviewing the assumptions that underlie the thickness estimates of *DeHon and Waskom* [1976], *Hörz* [1978] concluded such values were overestimates.

[3] In order to refine the flux of lunar mare basalt volcanism we need to know the thicknesses of individual mare flow units. Thus, another approach was to measure the thickness of individual mare basalt flow units and use this information in conjunction with areal extent to obtain volumes of the uppermost flow unit, and then combine this with crater count ages or returned sample geochronology. Measurements of flow unit thicknesses are made difficult by (1) the limited availability of high-resolution topography and near-terminator images necessary for the recognition of flow fronts, (2) regolith formation processes, i.e. impact cratering, which can obliterate flow fronts of up to 15 m [*Head*, 1976], and (3) the composition and the eruption style of lunar lavas which are thought to be responsible for the sparseness of mare flow features [*Schultz et al.*, 1976; *Head*, 1976].

[4] The thicknesses of individual flow units have been investigated using a variety of techniques, including: (1) shadow measurements in high-resolution images obtained under low-sun conditions [e.g., *Schaber*, 1973; *Schaber et al.*, 1976; *Gifford and El-Baz*, 1978, 1981]; (2) in situ observations of flow units by the Apollo astronauts, e.g. within the walls of Hadley Rille at the Apollo 15 landing site [*Howard et al.*, 1972], and (3) studies of the chemical kinetic aspects of lava emplacement and cooling [*Brett*, 1975]. Using Apollo 14 and 15 near-terminator images, *Lloyd and Head* [1972] measured a flow front height of 3–5 m for a single flow unit southeast of the crater Kunowsky. *Gifford and El-Baz* [1981] reported on a much larger number of units and found flow heights of 1–96 m with an average thickness of ~21 m, similar to values of 10–20 m observed in the wall of Hadley Rille [*Howard et al.*, 1972]. *Gifford and El-Baz* [1981] argued that the actual thickness of a few flow units may be even larger (>100 m) because only the shadowed portions of the flow fronts were measured. The average thickness of the Eratosthenian flows in Mare Imbrium studied by *Schaber* [1973] is 30–35 m. However, these latter units were interpreted as atypical because their thickness (10–63 m) is much larger compared to other lunar flow fronts that could be identified in imaging data (5–10 m) [*Schaber et al.*, 1976]. Chemical kinetic considerations based on Apollo samples suggest that lunar lava flow units are no thicker than ~8–10 m at the Apollo 11, 12 and 15 sites [*Brett*, 1975].

[5] A fourth approach was discussed by *Neukum and Horn* [1975]. Their work showed that endogenic lava flow processes could be identified by their characteristic effects on CSFDs without necessarily being able to recognize individual flows in the images. This is an important result because photogeologic and morphologic recognition of individual flow fronts on the Moon is difficult and is mostly restricted to thicker flows and areas where low-sun images or samples were obtained, as discussed above. Making use of deflections (knees) in CSFD curves, *Neukum and Horn* [1975] found that Imbrian-aged flow units in Mare Imbrium are on the order of 200 m thick, and Eratosthenian flows are about 60 m thick, the later value being consistent with photogeologic estimates of the same flow units [*Schaber*, 1973; *Schaber et al.*, 1976; *Gifford and El-Baz*, 1981]. In this paper we develop in more detail the technique described by *Neukum and Horn* [1975] and apply it to numerous mare basins using recently obtained impact crater size-frequency distribution data.

2. Technique

[6] Over the last five years we performed crater counts for ~220 spectrally and morphologically defined basalt units in several nearside basins [e.g., *Hiesinger et al.*, 2000, 2001]. Many of these crater counts show evidence for resurfacing events in form

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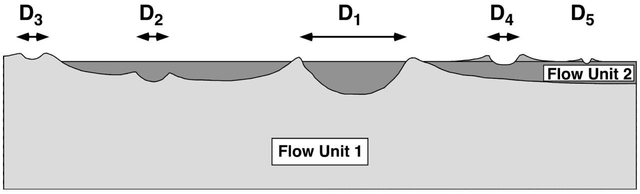


Figure 1. Schematic cross-section illustrating various effects of lava flooding on crater size-frequency distributions.

of characteristic knees in the measured CSFDs. Some of the units show knees that are obvious enough that in our previous studies we assigned two different ages to this unit, an older age that indicates the age of the first recognizable geologic event and a younger age that reflects the resurfacing event. For the majority of units the knees in the CSFD were more subtle, and we did not assign a second age to these units. Nevertheless, in many cases, the deviations of the measured CSFD from a primary production function are strong enough to be recognized in the log-log plots of cumulative crater frequency versus crater diameter.

[7] First, let us consider how in the case of volcanic resurfacing a lava flow that is deposited on top of an older flow unit surface influences crater size-frequency distributions (Figure 1). After the emplacement of a fresh unit (flow unit 1 in Figure 1), the surface is exposed to impact cratering and accumulates more and more craters with time (craters D1, D2, D3). The undisturbed crater population that forms on this surface defines at any given time the primary production size-frequency (Figure 2, curve a). A subsequent resurfacing event (flow unit 2 in Figure 1) preferentially covers smaller craters of the older flow unit (e.g., D2), while larger craters (crater D1) remain detectable after the emplacement of the younger flow unit. Continued impact cratering then forms a new crater population on top of the younger flow unit 2 (e.g., D4, D5). The selective covering of smaller craters on the older flow unit (e.g., D2) results in characteristic deflections of the CSFD of this resurfaced region (Figure 2) [*Neukum and Horn*, 1975]. These deflections occur at two distinctive crater diameters.

[8] The first deflection occurs at a diameter where the crater counts abruptly deviate from the primary production function due to the extinction of smaller craters. The second deflection occurs at smaller diameters where the crater counts asymptotically approach the post-flooding production function [*Neukum and Horn*, 1975]. The crater diameters where these deflections occur can thus be used to estimate the thickness of the second flow unit; the larger diameter is used to estimate the maximum flow unit height, and the smaller diameter is used to estimate the minimum flow unit height. Because the knees occur at diameters well below 10 km, the flow unit height is estimated by the rim height/diameter relationship of *Pike* [1980]:

$$\mathrm{Re} = 0.036\mathrm{Dr}^{1.014} \qquad \mathrm{D} < 15\ \mathrm{km} \qquad (1)$$

where Re is the rim height (km) and Dr is the crater diameter (km). The standard error of this relationship, based on 124 craters <15 km, is +0.0075/−0.0062 [*Pike*, 1980]. This standard error was used to estimate the error of our measurements.

[9] Several additional effects of lava flow flooding on CSFDs are described by *Neukum and Horn* [1975]. They found that incomplete resurfacing of the surface and several successive flows have similar effects on the CSFD as single flow events. A unit that has been resurfaced multiple times is characterized by several knees in its CSFD. However, it has to be kept in mind that the latest resurfacing event not only changes the CSFD of the next older flow unit but potentially also the CSFD of all previously emplaced surfaces. For this reason only the thickness of the latest resurfacing Mflow unit can be estimated with this technique. We now apply this technique to the new CSFD data we have obtained [e.g., *Hiesinger et al.*, 2000, 2001].

3. Results

[10] In our data set of 154 mare flow units recognized and defined on the basis of remote sensing data in Oceanus Procellarum, Imbrium, Tranquillitatis, Humorum, Cognitum, Nubium, and Insularum [e.g., *Hiesinger et al.*, 2000, 2001], we found ~58 mare units whose crater counts show characteristic deflections from an undisturbed production function. From our study we excluded Mare Australe and Mare Humboldtianum because there is a distinct possibility that resurfacing is dominated by impact processes, i.e. ejecta emplacement rather then lava flooding. We also excluded from our study units in the vicinity of large fresh impact craters such as Dawes and units that were influenced by dark mantle deposits.

[11] On the basis of the relationships outlined in Figures 1 and 2 we determined a minimum and a maximum thickness for each of the flow units analyzed (Figure 3a). We then estimated an upper and a lower error for each thickness estimate, based on the data of *Pike* [1980]. Our results reveal that the range of minimum flow

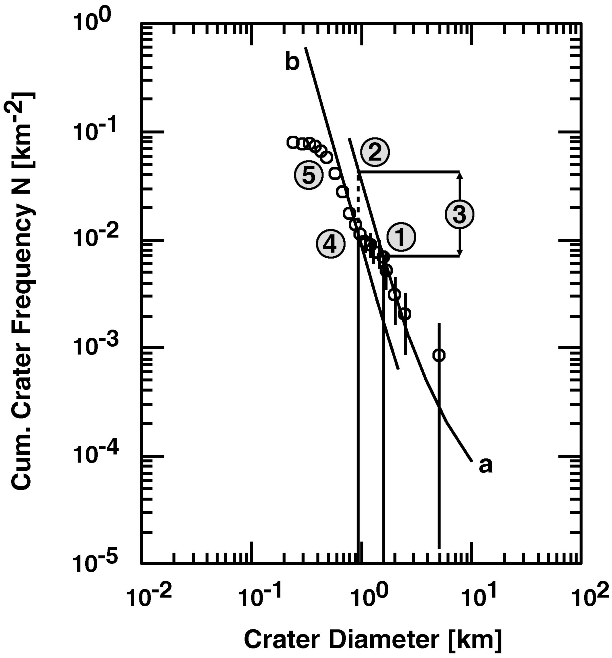
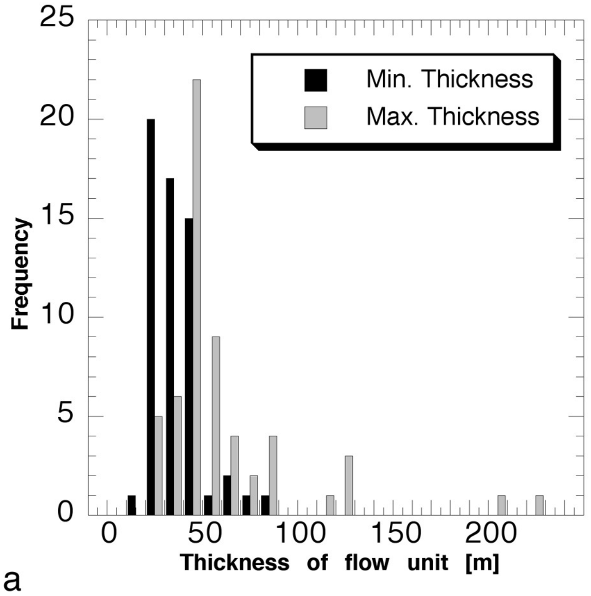


Figure 2. Example of a CSFD measurement that shows a distinctive deflection in the distribution of crater sizes. The measured CSFD of an undisturbed surface (such as flow unit 1 in Figure 1) follows the production function along curve "a". Resurfacing of this unit (by a unit such as flow unit 2 in Figure 1) destroyed craters smaller than the diameter D1 (in Figure 1) at point 1 on curve "a" (Figure 2). If no resurfacing occurred, 2 would show the frequency of smaller craters with diameter less that D1. Due to the covering of smaller craters with the lava flow unit, a certain number of craters are lost (the area in the interval 3) and the actual frequency of craters of this diameter that is measured on the new surface is shown at 4. Continued impact cratering produces a new crater population on the new surface (e.g., craters D4 and D5) that follows the production function along curve "b". The frequencies of craters with sizes close to or below the limit of image resolution (D5) are systematically underestimated which is reflected in flattening of the measured CSFD at 5.



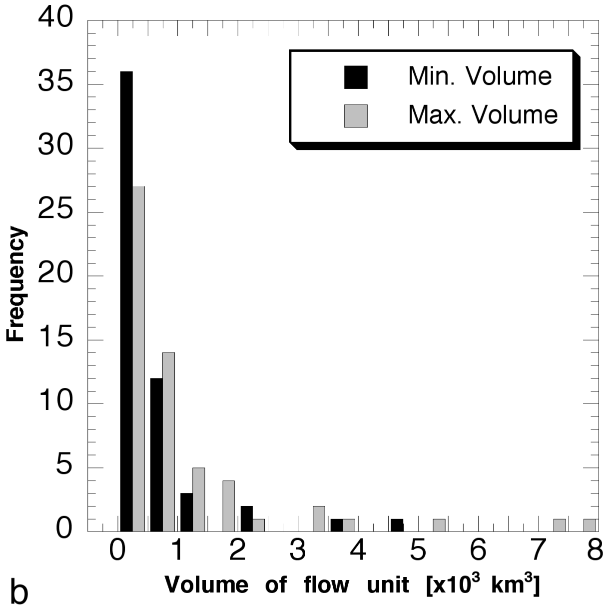


Figure 3. Histograms of the frequency distributions of flow unit thickness (a) and volumes (b). Black bars show minimum estimates, gray bars show maximum estimates.

heights of all units investigated is 19–81 m, and that the average minimum flow unit thickness is about 34 m (+7/−6 m). The range of maximum flow heights of all units investigated is 25–221 m and the average maximum flow unit height is about 53 m (+9/−9 m). These estimates are in good agreement with previously published values that were derived from shadow measurements in low-sun high-resolution images [e.g., *Schaber*, 1973, *Gifford and El-Baz*, 1978, 1981]. On average the thinnest flow units were detected for units in Mare Insularum, Cognitum, and Nubium, and the thickest flow units are seen in Mare Tranquillitatis and Humorum. In Oceanus Procellarum and Mare Imbrium, average flow unit thicknesses are larger than in Insularum, Cognitum, and Nubium, but smaller than in Tranquillitatis and Humorum.

[12] Specifically, in Mare Insularum two units show evidence for resurfacing and these flow units are on average ~27–38 m thick (+8/−4 m). In Mare Cognitum we identified only one unit that has been resurfaced, with a flow unit thickness of ~29–43 m (+9/−5 m). Resurfacing is found for six units in Mare Nubium with average minimum/maximum flow unit thicknesses of ~30 m and 43 m respectively (+9/−5 m). The twenty-six flow units detected in Oceanus Procellarum are between ~32 and ~51 m thick (+10/−6 m) and are basically identical in average flow unit thicknesses to flows in Mare Imbrium. In Mare Imbrium we found six units which showed evidence for resurfacing; flow units there average ~32–50 m (+11/−5 m). *Schaber* [1973] and *Schaber et al.* [1976] investigated the Eratosthenian flow units in Mare Imbrium and reported an average thickness of 30–35 m (range 10–63 m) for his phase-III flow. Our data indicate a thickness of 32–50 m (+11/−5 m) for this particular flow unit which is in excellent agreement with Schaber's values. For the twelve units studied in Mare Tranquillitatis we found the average flow unit thickness to be on the order of ~43–65 m (+14/−7 m). The five flow units in Mare Humorum are on average ~43–78 m thick (+17/−9 m). In summary, these thicknesses are commonly greater than those typical of terrestrial basaltic lava flows and more comparable to those of terrestrial flood basalts, a correlation consistent with evidence for high effusion rates and volumes for basalt eruptions in the lunar environment [*Head and Wilson*, 1992].

[13] *Schaber* [1973] estimated the total volume of the three Eratosthenian eruptive phases in Mare Imbrium to be $\sim 4 \times 10^4$ km^3, but the lack of thickness data and distinctively areally defined units in other areas precluded more refined estimates. More recent studies, however, used Galileo and Clementine remote sensing data to define distinctive areal units [e.g., *Hiesinger et al.*, 2000, 2001], and these data provide important new information to combine with the thickness data to obtain volumes of flow units.

[14] On the basis of the known area of exposure of each of our 58 flow units, and their minimum and maximum average thickness, we estimated their volumes (Figure 3b). The measured areas include both the basic resurfaced flow unit and the resurfacing unit (flow units 1 and 2 in Figure 1), and thus are overestimates of the resurfacing unit volume. The thickness of the overlying unit is very likely to be less than that of the underlying unit, so the volume estimates are minimum values for the whole unit. Nonetheless, these values serve as useful estimates for comparison with values derived from other techniques. In ongoing analyses we are assessing these estimates in more detail, also taking into consideration stratigraphic relationships in the volume estimates. With these caveats in mind, we found that the range of volumes is 30–7700 km^3. The minimum average volume of all investigated flow units is ~590 km^3 and the maximum average volume is ~940 km^3.

[15] *Yingst and Head* [1998] investigated individual isolated lava ponds in Mare Smythii and Mare Marginis and, on the basis of morphologic evidence, concluded that they were emplaced during a single eruptive phase. They found that pond volumes in both maria range from 15 km^3 to 1045 km^3. The mean pond volume in Mare Smythii is ~190 km^3 and about ~270 km^3 in Mare Marginis. Ponds in the South Pole-Aitken basin that were interpreted to be single eruptive phases have volumes ranging from 35 to 8745 km^3 and average 860 km^3 [*Yingst and Head*, 1997]. Ponds in the Mare Orientale/Mendel-Rydberg basins interpreted to have been filled by a single eruptive episode have volumes of 10 to 1280 km^3 and a mean value of 240 km^3 [*Yingst and Head*, 1997]. From this comparison we conclude that our volume estimates are comparable to volumes of lava ponds that are interpreted to have been filled during a single eruptive episode.

[16] On the basis of their investigation of high-resolution low-sun images *Gifford and El-Baz* [1981] found that flow

scarps are concentrated in the northwestern parts of the lunar nearside. Their map indicates that flow fronts have not been identified in Mare Serenitatis and Mare Tranquillitatis with the exception of one location at the northern margin of Mare Tranquillitatis. Using the method outlined here, we were also unable to identify individual resurfacing events for units in Mare Serenitatis. In contrast to their findings, however, we found abundant evidence for individual resurfacing events in Mare Tranquillitatis. The greater abundance of flow fronts, and units with evidence of resurfacing, in the shallow non-mascon maria and in the younger units in Imbrium may be related to two factors. First, mascon mare tend to undergo subsidence and lava units are more likely to pond and have greater thicknesses. Secondly, later flows are emplaced when topography is smoothed by earlier events, thus causing lateral spreading, rather than ponding, of lava units. Serenitatis, for example, is a mascon mare and is not characterized by abundant late-stage mare units. Imbrium, also a mascon mare, is characterized by abundant late-stage mare units and flow fronts.

[17] The difference between curves a and b in Figure 2 not only provides information about the thickness of a flow unit but also provides information about the separation time between eruption phases and maximum estimates for the total duration of emplacement of distinctive spectral units. For example, initial analyses indicate that the range of separation ages between the 26 units analyzed is 100–2000 m.y. with a mean value of ~700 million years. These values imply mineralogically similar long-lived or repetitively active source regions at depth.

4. Conclusions

[18] We have quantified a CSFD method to assess the thickness of lava flow resurfacing events first described by *Neukum and Horn* [1975]. We conclude that (1) crater size frequency distribution measurements are a valuable tool for estimating the thickness of flow units, (2) this approach allows one to obtain thicknesses and volumes for additional flow units that have not been detected in low-sun images, (3) analyzed basalt flow units exposed within the nearside mare are on average ~30–60 m thick with a range of 20 to 220 m, (4) our thickness estimates are in excellent agreement with previous estimates of various authors [e.g., *Schaber*, 1973; *Schaber et al.*, 1976; *Gifford and El-Baz*, 1981; *Howard et al.*, 1972; *Neukum and Horn*, 1975], (5) flow unit volumes range from 30 to 7700 km^3, averaging 590–940 km^3, (6) our volume estimates are consistent with estimates for lava ponds that were filled during a single eruptive phase [e.g., *Yingst and Head*, 1997, 1998], (7) Mare Serenitatis is unusual in that no resurfacing flows could be identified in our crater counts, perhaps due to the lack of relatively young flows there, (8) separation of CSFD curves suggests that mineralogically similar source regions can be long-lived or repetitively active.

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References

Baldwin, R. B., *The face of the Moon*, Chicago Univ. Press, 239 pp., 1949.
Brett, R., Thicknesses of some lunar mare basalt flows and ejecta blankets based on chemical kinetic data, *Geochim. Cosmochim. Acta*, *39*, 1135–1141, 1975.
DeHon, R. A., Thickness of mare material in the Tranquillitatis and Nectaris basins, *Proc. Lunar Planet. Sci. Conf.*, *5th*, 53–59, 1974.
DeHon, R. A., Thickness of the western mare basalts, *Proc. Lunar Planet. Sci. Conf.*, *10th*, 2935–2955, 1979.
DeHon, R. A., and J. D. Waskom, Geologic structure of the eastern mare basins, *Proc. Lunar Planet. Sci. Conf.*, *7th*, 2729–2746, 1976.
Gifford, A. W., and F. El-Baz, Thickness of mare flow fronts, *Lunar and Planet. Sci. IX*, 382–384, 1978.
Gifford, A. W., and F. El-Baz, Thicknesses of lunar mare flow fronts, *Moon and Planets*, *24*, 391–398, 1981.
Head, J. W., Lunar volcanism in space and time, *Rev. Geophys. Space Phys.*, *14*, 265–300, 1976.
Head, J. W., Lava flooding of ancient planetary crusts: Geometry, thickness, and volumes of flooded lunar impact basins, *Moon and Planets*, *26*, 61–88, 1982.
Head, J. W., and L. Wilson, Lunar mare volcanism: Stratigraphy, eruption conditions, and the evolution of secondary crusts, *Geochim. Cosmochim. Acta*, *56*, 2155–2175, 1992.
Hiesinger, H., R. Jaumann, G. Neukum, and J. W. Head, Ages of mare basalts on the lunar nearside, *J. Geophys. Res.*, *105*, 29,239–29,275, 2000.
Hiesinger, H., J. W. Head, U. Wolf, and G. Neukum, New age determinations of lunar mare basalts in Mare Cognitum, Mare Nubium, Oceanus Procellarum, and other nearside mare, *Lunar and Planet. Sci. XXXII*, #1815, 2001.
Hörz, F., How thick are lunar mare basalts?, *Proc. Lunar Planet. Sci. Conf.*, *9th*, 3311–3331, 1978.
Howard, K. A., J. W. Head, and G. A. Swann, Geology of Hadley Rille, *Proc. Lunar Planet. Sci. Conf.*, *3rd*, 1–14, 1972.
Lloyd, D. D., and J. W. Head, Lunar surface properties as determined from earthshine and near-terminator photography, *Proc. Lunar Planet. Sci. Conf.*, *3rd*, 3127–3142, 1972.
Neukum, G., and P. Horn, Effects of lava flows on lunar crater populations, *The Moon*, *15*, 205–222, 1975.
Pike, R. J., Size dependence in the shape of fresh impact craters on the Moon, in *Impact and Explosion Cratering*, edited by D. J. Roddy, R. O. Pepin, and R. B. Merrill, 489–509, Pergamon, N.Y., 1977.
Pike, R. J., Geometric interpretation of lunar craters, *U.S. Geol. Survey Prof. Paper, 1046-C*, 1980.
Schaber, G. G., Lava flows in Mare Imbrium: Geologic evaluation from Apollo orbital photography, *Proc. Lunar Planet. Sci. Conf.*, *4th*, 73–92, 1973.
Schaber, G. G., J. M. Boyce, and H. J. Moore, The scarcity of mappable flow lobes on the lunar maria: Unique morphology of the Imbrium flows, *Proc. Lunar Planet. Sci. Conf.*, *7th*, 2783–2800, 1976.
Schultz, P. H., R. Greeley, and D. E. Gault, Degradation of small mare surface features, *Proc. Lunar Planet. Sci. Conf.*, *7th*, 985–1003, 1976.
Yingst, R. A., and J. W. Head, Volumes of lunar lava ponds in South Pole-Aitken and Orientale basins: Implications for eruption conditions, transport mechanisms, and magma source regions, *J. Geophys. Res.*, *102*, 10,909–10,931, 1997.
Yingst, R. A., and J. W. Head, Characteristics of lunar mare deposits in Smythii and Marginis basins: Implications for magma transport mechanisms, *J. Geophys. Res.*, *103*, 11,135–11,158, 1998.

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