ANALYSIS OF CRATER DISTRIBUTIONS IN MARE UNITS ON THE LUNAR FAR SIDE

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Abstract. Mare material is asymmetrically distributed on the Moon. The Earth-facing hemisphere, where the crust is believed to be 26 km thinner than on the farside, contains substantially more basaltic mare material. Using Lunar Topographic Orthophoto Maps, we calculated the thickness of the mare material in three farside craters, Aitken (0.59 km), Isaev (1.0 km), and Tsiolkovskiy (1.75 km). We also studied crater frequency distribution in five farside mare units (Aitken, Isaev, Lacus Solitudinis, Langemak, and Tsiolkovskiy) and one light plains unit (in Mendeleev). Nearly 10 000 farside craters were counted. Analysis of the crater frequency on the light plains unit gives an age of 4.3 billion yr. Crater frequency distributions on the mare units indicate ages of 3.7 and 3.8 billion yr, suggesting that the units are distributed over a narrow time period of approximately 100 million yr. Returned lunar samples from nearside maria give dates as young as 3.1 billion yr. The results of this study suggest that mare basalt emplacement on the far side ceased before it did on the near side.

1. Introduction

It has long been known that the lunar far side has considerably less mare material than does the near side, where its abundance suggested to Galileo that the mare-filled basins were seas. Many modern investigators at first attributed the lack of mare material on the far side to the lack of basins. However, it was soon realized (Hartmann, 1966) that the basins are randomly distributed on both sides of the Moon, but that greater flooding occurred on the near side. As a result the mare units are not randomly distributed. The reason for this is not known.

Basins on both sides of the Moon are approximately equal in number, have similar diameters, and presumably had similar depths of penetration. The lithosphere that they penetrate, therefore, must be different. Kaula *et al.* (1972) calculated a 2–3 km offset towards the Earth of the center of mass of the Moon from its center of figure. They attribute this to a 26 km difference in crustal thickness, and calculate that the farside crust is 74 km thick while the nearside crust is only 48 km thick (Kaula *et al.*, 1974). A thicker crust would account for the lack of mare material in small farside craters and basins, but it would not account for its absence in the large basins which presumably penetrated the lithosphere, or should have at least tapped the asthenosphere through faulting. The asymmetry in crustal thickness, the difference in mare-basalt distribution, and the hiatus between basin formation and mare filling have not yet been fully explained.

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Turcotte (1975) suggests that mare basalt was generated by tidal interactions either initiating convective flow or leading directly to melting during an early Earth–Moon close approach. Schultz *et al.* (1976) suggest that mare flooding may have been initiated by large tidal variations that occurred while the Moon was orbiting in a region between 30 and 45 times the radius of Earth.

Variations in crustal thickness and mare abundance may be either primary or secondary. Primary asymmetries, those resulting from accretion, would suggest that the Moon accreated under the gravitational and geochemical influence of a large, nearby second mass – i.e. the Earth. A primary origin for the asymmetries, therefore, would support either some type of a fission model or else a heterogenous accretion model for the origin of the Earth–Moon system. It is unlikely, however, that the axes of such a system would be centered on the present sub-Earth point, and it is therefore difficult to consider the asymmetries as primary. On the other hand, if it can be determined that the asymmetries are secondary, or created following an early differentiation phase, the capture hypothesis could be supported (Firsoff, 1969). However, the process of capture itself would be catastrophic. It may be that the earliest episodes of mare flooding on both sides of the Moon were initiated as a response to an intense and sudden tidal interaction between the Earth and Moon. Such an interaction would be experienced more intensely on the near side than on the far side and may account for the greater volume of basalt on the near side. Whether a Moon consolidated enough to support basins could then develop a discrepancy in crustal thickness in response to the gravitational pull of a newly nearby planet, needs to be investigated.

If it can be determined that the asymmetry of the basaltic volume is of secondary origin, and if the timing of the emplacement of mare material on the far side reflects that on the near side, constraints may be placed on theories of lunar evolution and on the origin of lunar asymmetries.

In this study we examine lunar farside mare units and one plains unit. Following a discussion of mare distribution and its association with other lunar features, the thicknesses and volumes of some of the mare units are calculated. Standard crater counting techniques are applied to units located along the groundtracks of the Apollo 15, 16, and 17 spacecraft.

2. Farside Mare Units

2.1. Distribution and Associations

Farside mare units, considered to be basaltic in composition because similar units on the near side have been identified as basalts, are located in topographically low areas associated with basins, especially in the large basins; Australe, Smythii, Marginis and Lomonosov/Fleming (Figure 1). Al-Khwarizmi/King and Mendeleev conspicuously lack any mare material. The lack of basalt in the area where al-Khwarizmi/King and Lomonosov/Fleming basins intersect, which must be heavily fractured and faulted, suggests that the source area for the basalt is highly localized and was not present in this area.

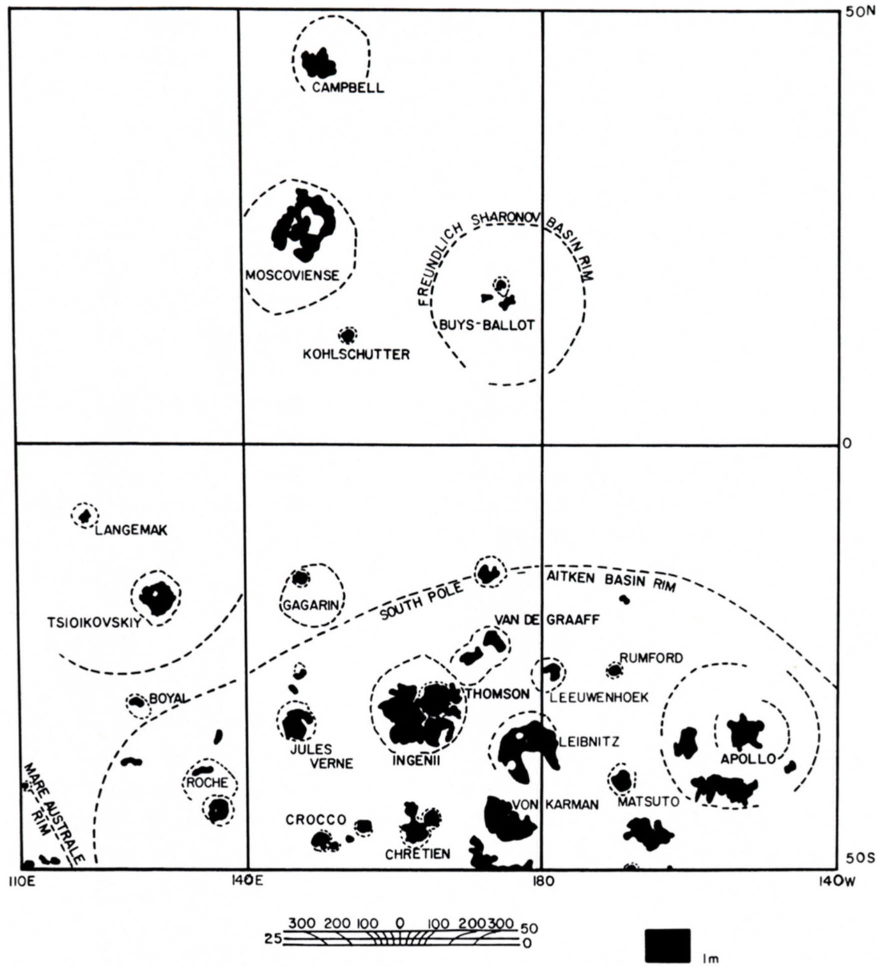

Fig. 1. Distribution of mare units on part of the far side of the Moon.

Wilhelms and El-Baz (1977) mapped three mare units in a geologic map of the east side of the Moon (50° E to 140° E) by comparing the crater distributions of large diameter (> 10 km) craters on the units. They suggest that the oldest, Imbrian basalt (Im_1), which occupies the Australe basin and a few craters in the northwestern part of the map, is older than most nearside mare material. The middle unit (Im_2), in Tsiolkovskiy, Langemak, Bolyai and Lacus Solitudinis, may be of late Imbrian age as it appears to have fewer craters. The youngest unit (EId), which is found only in Waterman crater, Lacus Solitudinis and Smythii basin may be thin beds of lava or a pyroclastic facies of mare material.

The mare material on the south side of the Moon is divided by Wilhelms *et al.* (1979) into three units. Im_1 is a unit older than many upper Imbrian craters and older than all the known mare materials on the central far side. It is lighter in color than unit Im_2, the intermediate unit, and EIm, the youngest material. The mare units are all associated with the Australe and South Pole/Aitken basins.

In the geologic map of the central far side, Stuart-Alexander (1978) mapped only one unit (Im) of Imbrian mare material, which she suggested may be younger than the Orientale basin. Much of the mare material is within or associated with the South Pole/ Aitken basin which is one of the topographically low areas on the Moon. Moscoviense, Campbell and the Freundlich/Sharonov basins each have isolated patches (Figure 1). The only mare occurrence that is not associated with a basin is in the Nectarian age crater Kohlschütter, southeast of Moscoviense, Kohlschütter, however, may be on an unmapped ring of Moscoviense.

On the north side of the Moon, only Compton and Campbell craters have any mare material (Lucchitta, 1978). On the west side, all of the mare materials is associated with the Orientale basin, which is excluded from this study.

2.2. THICKNESS AAND VOLUME OF FARSIDE MARE BASALT

The prevalence of 'ghost craters' of varying depth and preservation state on lunar mare units suggests that basins and craters were filled over a long period of time by multiple flow units, probably from several source vents.

Few fresh flow scarps from which thicknesses of individual flow fronts may be measured are present in areas covered by high resolution photographs. Gifford and El-Baz (1978) measured 85 scarps, and found them to vary between 4 and 45 m in height, with 57% of the scarps under 15 m high. Based on study of returned lunar samples, Brett (1975) concluded that mare basalts were derived from cooling units less than 10 m thick. Thus, photogeologic and geochemical evidence both suggest that lunar basalt flows are rather thin (less than 100 m in thickness) in addition to being intermittent in frequency.

The total volume or the cumulative thickness of the basalt cannot be directly measured and is thus a more controversial issue. Hartmann and Wood (1971) found a flooding depth of approximately 3 km in several basins they examined. DeHon (1974; 1979), DeHon and Waskom (1976), and Mohan (1979) argue for very thick (400–2000 m) basalt coverage. Whitford-Stark (1979) estimates an average thickness of 750 m for Mare Australe fill. Hörz (1978) however, suggests that the basaltic basin fill is extremely shallow (less than 300 m for most mare basins).

Although lunar farside craters may not be directly compared with nearside basins, knowledge of the thickness of farside lunar basalts, even if grossly estimated, may contribute to our understanding of lunar igneous processes. A crater may, in its simplest form, be considered as a frustum, or a right conical segment. If the diameter, depth-to-mare fill and slope can be measured, the thickness and volume of basalt may be calculated to a first approximation.

Lunar Topographic Orthophoto Maps of three craters with mare material totally covering the bottom (Isaev, Aitken, and Tsiolkovskiy) were examined to determine the

TABLE I
Volume of mare material

	θ	d_1	d_2	d_3	t_1	t_2	t_3	V
Aitken	11.55°	127.3 km	89.13 km	83.35 km	4.49 km	3.9 km	0.59 km	3.4×10^3 km³
Isaev	12.17°	86.9 km	59 km	49.72 km	4 km	3 km	1 km	2.33×10^3 km³
Tsiolkoskiy	24.34°	180 km	165.85 km	157.98 km	4.98 km	3.2 km	1.78 km	3.6×10^4 km³

See Figure 2 for description of terms.

TABLE II

Lunar features used for size-frequency distribution curves

Feature	Location	Geologic Unit	Diameter (km)	Images Used	Area (km^2)	No. of Craters	C_S	C_S meters	Age[d] (billion yr)
Isaev	17.8S 147.3E	IM[b]	86.9	A15, 8924, 8926, 8928	590	1030	−0.69	200	3.7
Langemak	9.8S 119E	IM_2[c]	102	A15, 9015, 9017	228	193	−0.67	214	3.7
Lacus Solitudinis	27S 104E	IM_2[c]	–	A15, 9961 9963, 9965	712	983	−0.59	257	3.8
Tsiolkovskiy	20.4S 128.9E	IM_2[c]	180	A15, 9592, 9598, 9600, 9602	7384	4717	−0.57	269	3.8
Aitken[a]	17S 173E	IM[b]	145	A17, 1920, 1922, 1924	1937	1604	−0.53	295	3.8
Mendeleev	6.3N 142.6E	INp[b]	130	A16, 4199, 4201	1805	1314	+ 0.15	1412	4.3

[a] Aitken data from Walker and El-Baz (1979).
[b] Stuart-Alexander (1978).
[c] Wilhelms and El-Baz (1977).
[d] Based on calibration curve (Boyce and Johnson; 1977).

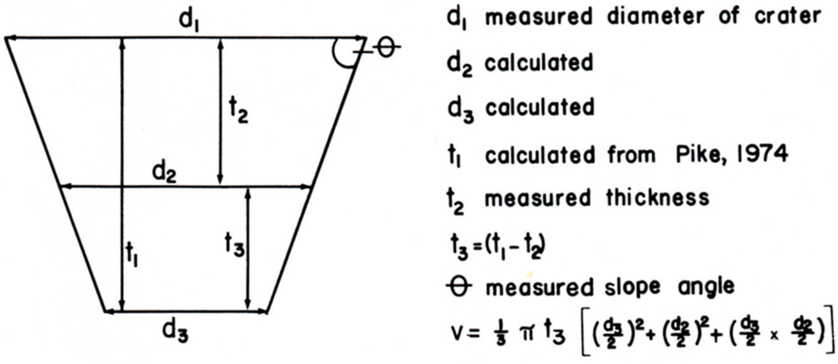

Fig. 2. Geometric solution for the volume of crater fill of mare material.

crater diameter and the average vertical distance from the rim to the mare fill. The slope of the crater wall is determined by averaging slope measurements at several areas of the wall, avoiding disturbed areas. The total depth of the crater may be calculated using Pike's (1974) equation for crater depth vs. crater diameter, and the thickness of the mare material may be determined by subtracting the rim-to-mare surface depth from the total calculated crater depth. The mare diameter and volume may then be determined from the equation for a frustum (Figure 2).

The results for Isaev, Aitken, and Tsiolkovskiy are given in Table I, and indicate that the calculated thickness of the mare fill ranges between 500 and 2000 m.

3. Crater Frequency Measurements

3.1. Method

Trask (1966) determined that a log–log plot of the cumulative number of craters with diameters greater than D per km^2, vs. D, the crater diameter, resulted in a frequency distribution which could be described by $F \propto D^{-2}$ for a steady state distribution in which craters are destroyed as rapidly as they are produced. Above a certain diameter, the plot is represented by $F \propto D^{-\lambda}$ where λ is approximately 3. Moore *et al.* (1980) refine the non-steady state distribution to $N = KD^{\alpha}$ where N is the cumulative number of craters with diameters equal to or greater than D, K is the net accumulated flux, and α is the population index, which varies for different diameter crater populations.

Morris and Shoemaker (1968) define C_S as the intersection of the steady-state curve with the second curve. C_S is proportional to the relative age of the unit, with a higher C_S value indicating an older unit. Boyce and Johnson (1977) calibrated C_S values from absolute ages of returned lunar samples.

In this study, crater size frequency data were collected using a Zeiss TGZ Particle Size Analyzer. C_S values were determined by graphical methods, and the calibration