Basalt Thickness of Mare Tranquillitatis using Two Methods

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PROBLEM

The purpose of this experiment is to evaluate two methods of calculating basalt thickness in Mare Tranquillitatis.

INTRODUCTION

Lunar maria are large impact craters or basins that have been filled with basalt. While the Moon was still cooling, lava seeped into these basins through cracks, cooling to form the maria. This study compares two methods of determining the thickness of basalt in Mare Tranquillitatis: the Pre-Mare Crater Method and the Post-Mare Crater Method. The first method uses craters from before the mare was formed and the latter uses craters from after the mare was formed, as the names imply. Previous work (De HONs map reference) has been conducted using these methods to calculate mare thickness; however the tools used to collect that data are outdated. The current study, conducted using data from the Lunar Reconnaissance Orbiter and Clementine camera, compares the two methods for determining mare thickness.

The Pre-Mare Crater Method used craters that were formed inside the large impact basins before they filled with lava. By measuring the diameter of these craters, the original rim height can be estimated using a relationship defined by Pike (1974, 1977). As the lava filled the giant impact basins, lava also seeped into smaller craters within the basin, creating a flat bottom inside these partially-filled craters. The difference between the original and current rim height of the partially filled craters gives the thickness of the basalt around each crater.

The Post-Mare Crater Method used craters that formed after the mare basins filled. Craters that penetrate the mare to the low iron material (anorthosite) below have low iron in the ejecta closest to the crater rim. Comparing the radius of the low-iron ejecta to the total ejecta gives an estimate of basalt thickness at that location.

The data collected from the craters was used to create an isopach map of the thickness of the mare. The thickness of the mare can be used to construct pre-flooding topography maps of the Moon's surface and to estimate the volume of the basalt filling the basins. This information provides information about the lunar thermal history and the origin of basalt surface structures, and can be used to form a timeline of the formation of the moon and the dynamics of the mantle and core (De Hon, 1979).

METHODS

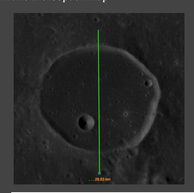
Method One: Pre-Mare Craters

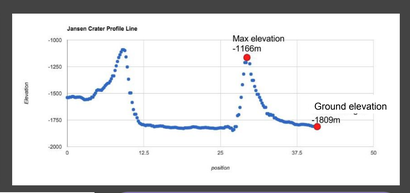
To calculate the thickness of basalt using craters that were formed prior to mare formation, the current rim height of the crater was subtracted from its calculated original rim height. This difference is the thickness of the basalt at this location.

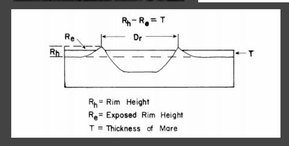
Quickmap, a web-based mapping tool that utilizes images from a Lunar Reconnaissance Orbiter Camera (LROC), was used to perform crater measurements. In order to provide a clearer and more practical map for data collection, the mapping software's visual settings were modified. An equidistant cylindrical projection was used to identify craters on the moon. To increase visual perception of partially buried craters across the entire map, the sunlit region overlay was turned off to deactivate shadows. To quickly identify and reference craters, nomenclature of the surface map was enabled.

The names, locations, and diameters of 20 partially buried craters in Mare Tranquillitatis were collected. The coordinates of the center point of the crater and name, if available, were recorded into a spreadsheet. The crater's diameter was measured using the line tool within Quickmap. Using the profiling tool, profile lines of the craters were created from north to south and exported to excel for examination

To calculate basalt thickness, the northern and southern rim elevations were established using the topographic data. The current exterior wall height was then calculated by subtracting the ground elevation, which is the elevation of the surface outside of the crater, from the rim elevation. The original rim height was calculated using Pike's equation: $h = 0.036\ D^{1.014}$ for craters less than 15 kilometers in diameter or $h = 0.399\ D^{0.236}$ for craters more than 15 kilometers in diameter, with D representing the crater's diameter in kilometers and h representing the original rim height. Then, the thickness of the mare was calculated by subtracting the highest current exterior wall height from the original rim height. Finally, the mare thickness at the edge of each crater was calculated to make the isopach map.







Sample Calculation- Jansen

Diameter = 20.4km

Original height of rim using Pike's equation

$h = 0.399D^{0.236} = 0.399\ (20.4)^{0.236} = 0.813$ km = 813m

Current height of rim = -1166m - (-1809m) = 643m

Thickness of basalt = 813m - 643m = 170m

Method Two: Post-Mare Craters

To calculate the thickness of basalt using craters that formed after the mare formed, the ejecta of each crater was examined. If the crater was deep enough to penetrate through the basalt to the low-iron ground below the basalt, then low-iron material would be found in the ejecta. The extent of this low iron ejecta is used to find the thickness of basalt.

The names, locations, and diameters of craters that were at least 10 kilometers in radius and not partially filled were recorded into a spreadsheet.

Due to erosion from lunar winds, the diameter of a crater becomes greater over time. The transient diameter, or the original diameter, was required for accurate measurements. The transient diameter can be approximated using the following equation (Melosh, 1989, p. 143).

For D<15km $D_t = .84\ D$

For D>15km $D_t = [\ (13.5D^3H) / (1 + 6\ (1 + (D_f/D) + (D_f/D)^2)^{-1}\ ]^{0.25}$,

where D is the current diameter of the crater, D_f is the diameter of the crater's floor, H is the crater's depth, and D_t is the transient diameter

The depth of each crater was measured using data from Quickmap profile lines. For complex craters, the diameter of the inner floor was measured using the line tool.

The maximum depth of excavation, H_{exc}, was found using the relationship $H_{exc} = 0.1D_t$ (Croft, 1980, Melosh, 1989).

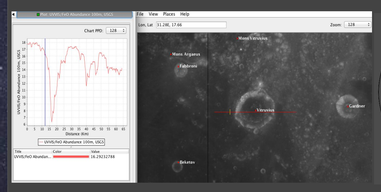
The ejecta, material excavated from the crater during formation, of the 17 craters were visually identified and then measured using the line tool. The radius of the ejecta, R_{ce}, was then determined by measuring the distance from the north end of the ejecta, to the center of the crater.

The program JMARS for Earth's Moon was used to collect data on low-iron ejecta surrounding the crater. To show the percentage abundance of low-iron surrounding the crater, the UVVIS/FeO (Ultraviolet Visible/Iron (II) Oxide) Abundance Layer was added.

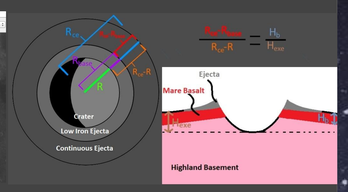
The craters previously identified in quickmap were located in JMARS and two perpendicular FeO profile lines were drawn through their center. These profile lines were used to find the location of the low-iron boundary. The distance from the boundary of the low iron to the center of the crater was recorded in all four cardinal directions. If the crater overlapped with another crater or the low-iron boundary was unclear, then some profile lines were omitted. The average distance from the crater center to the low-iron boundary in each direction was calculated.

The distance from the boundary of the low iron to the center of the crater was recorded in all four cardinal directions. If the crater overlapped with another crater or the low-iron boundary was difficult to determine, then some directions were omitted or the intercardinal directions were used. The average distance from the center to the low-iron boundary, R_{base} , in each direction was calculated.

Once the low-iron radius is determined, the thickness of the basalt, H_b, is found by finding the fraction of the maximum excavation depth, H_{exc}, that is contained within the basalt.



Screenshot of JMARS Low Iron Profile Line



The proportion of the radius of the ejecta of a crater without iron content and the radius of the ejecta with iron content is equal to the proportion of the height of the basalt layer and the height of the crater.

Sample Calculation- Vitruvius

Diameter = 30.94km

Depth = 1.889km

Floor Diameter = 20.406km

R_{ce} =Distance from center to edge of ejecta = 23.3km

R_{base} = Distance from center to edge of low iron ejecta = 15.13km

Transient Diameter (because diameter has increased over time due to crumbling)

$D_t = [\ (13.5D^3H) / (1 + 6\ (1 + (Df/D) + (Df/D)^2)^{-1}\ ]^{0.25}$

$D_t = [\ (13.5(30.94km)^3(1.889km) / (1 + 6\ (1 + (20.406km / 30.94km) + (20.406km/30.94km)^2)^{-1}\ ]^{0.25}$

$D_t = [\ 755,312.4694 / 3.8646\ ]^{0.25}$

D_t = 21.026km

R = 10.513km

H_{exc} (Height excavated from crater) = $0.1D_t$ = 2.1026km

H_b = Basalt thickness = $[1 - (R_{base}-R)/(R_{ce}-R)] * H_{exc}$

$H_b = [1 - .361]\ 2.1026 = 1.343$km = 1343m

ISOPACH MAPS

Figure 1 is the original isopach map used for reference.
Figures 2 and 3 are isopach maps made using 3DField software.

Figure 1. Reference Map (DeHon 1974)

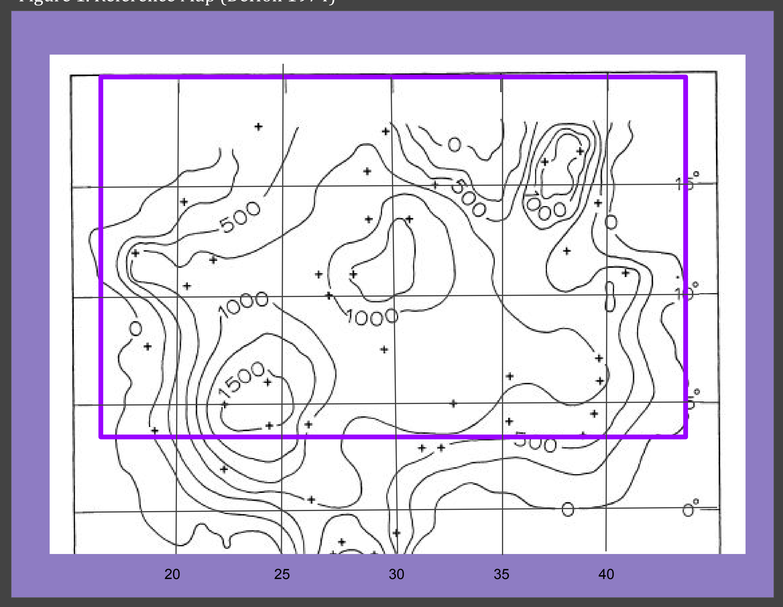


Figure 2. Pre-Mare Crater Isopach

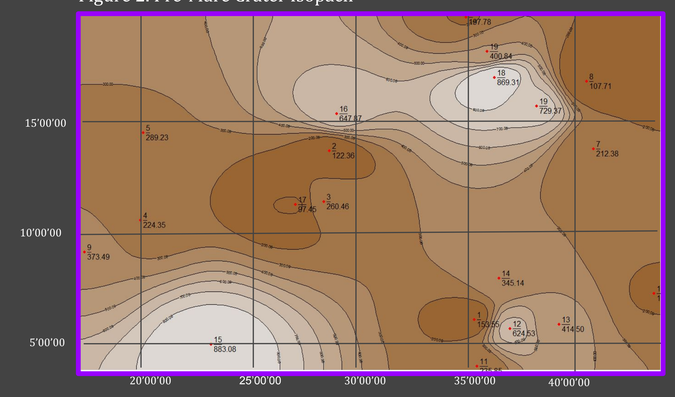
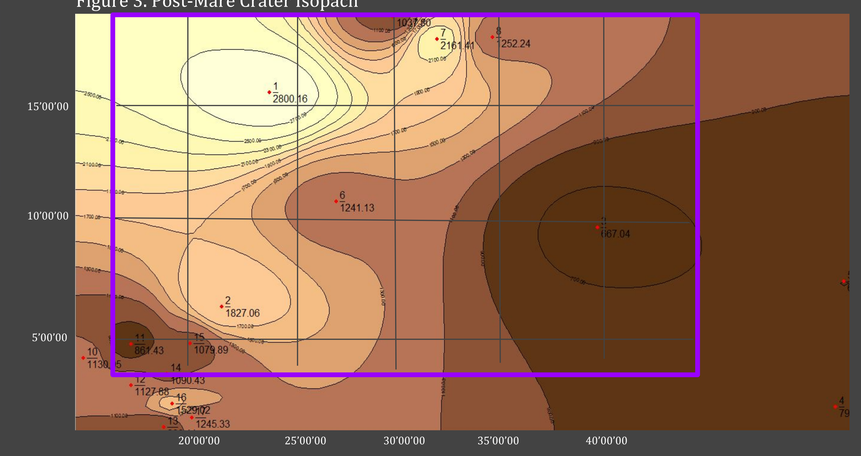


Figure 3. Post-Mare Crater Isopach



RESULTS

Pre-Mare Craters
Partially Filled

Figure 4.

Crater #	Crater Name	Latitude	Longitude	Diameter (km)	Hb, Mare Thickness (m)
1	Aryabhata	6.20	35.17	21.89	153.55
2	Jansen	13.55	28.64	24.20	122.36
3	Jansen H	11.34	28.39	7.20	260.46
4	Maclear	10.52	20.11	20.34	224.35
5	Al Bakri	14.34	20.25	12.21	289.23
6	Maraldi	19.36	34.80	39.62	197.78
7	Lyell	13.63	40.56	31.16	212.38
8	Franz	16.57	40.24	25.48	107.71
9	Sosigenes	9.13	17.59	17.17	373.49
10	Lawrence	7.35	43.29	25.25	194.88
11	Maskelyne F	4.18	35.30	20.93	235.85
12	Unnamed	5.80	36.80	22.00	624.53
13	Unnamed	6.00	39.00	21.00	414.50
14	Unnamed	8.00	36.30	9.85	345.14
15	Lamont	5.13	23.31	83.00	883.08
16	Jansen R	15.16	28.97	16.20	647.87
17	Unnamed	11.20	27.10	10.15	97.45
18	Maraldi D	16.74	36.08	66.48	869.31
19	Maraldi E	17.87	35.75	31.82	400.84
20	Unnamed	15.50	38.00	15.89	729.37

Post-Mare Craters
With Low-Iron Ejecta

Figure 5.

Crater #	Crater Name	Latitude	Longitude	Diameter (km)	Hb, Mare Thickness (m)
1	Plinius	15.36	23.61	41.31	2800.16
2	Arago	6.15	21.43	25.50	1827.06
3	Cauchy	9.55	38.62	11.50	667.04
4	Anville	1.84	49.51	10.25	791.19
5	Asada	7.24	49.90	12.37	691.00
6	Carrel	10.67	26.68	15.59	1241.13
7	Vitruvius	17.66	31.28	30.94	2161.41
8	Gardner	17.75	33.81	17.62	1252.24
9	Fabbroni	18.66	29.27	10.55	1037.60
10	Cayley	3.94	15.09	14.20	1130.95
11	Ariadaeus	4.55	17.28	10.40	861.43
12	Dionysius	2.77	17.29	17.25	1127.88
13	Schmidt	0.96	18.78	11.13	900.11
14	Ritter B	3.25	18.93	14.20	1090.43
15	Manners	4.57	19.99	15.05	1079.89
16	Ritter	1.96	19.17	29.52	1529.02
17	Sabine	1.38	20.07	29.75	1245.33

Post-Mare Craters
No Low-Iron Ejecta

Figure 6.

Crater Name	Latitude	Longitude	Diameter (km)	Crater Depth (m)	Comment
Zahringer	5.51	40.21	11.19	1912.00	Low FeO Interior
Taruntius F	3.92	40.51	10.16	825.00	Low FeO Interior
Dawes	17.21	26.34	17.60	607.50	Low FeO Interior
Ritter C	2.75	18.86	12.68	1879.00	No Low FeO

20 partially filled craters were studied in order to calculate depths using the Pre-Mare Method (Figure 4.). The craters used for the first method fell between 17°E and 44°E longitude and 4°N and 20°N latitude of Mare Tranquillitatis. The calculated thicknesses ranged from 97-883 meters, with an average thickness of 388 meters. Areas of deeper mare, averaging 600 meters appeared in both the northern central area studied, from 17°N, 36°E to 15°N, 28°E, reaching from Maraldi D to Jansen R. Another high peak was found in the area of the crater Lamont in the south western region, peeking at about 880 meters. Between the deepest regions, a valley exists with an average depth of 200 meters.

For the Post-Mare Method, 17 craters were used, all falling between the slightly larger area between 1°N and 19°N, and 15°E and 50°E. Using this method, calculated thicknesses ranged from 667-2800 meters, with an average of 1260 meters. The deepest points of the Mare occupied the majority of the northwestern region, spanning between 5°N and 19°N, and 15°E and 31°E. This region, however, only had three craters that served as data points.

Using the second method, several craters were found to not have low iron readings. This would function as a lower bound of the mare depth, as these craters have not fully penetrated the Mare.

DISCUSSION

The contour map created with the Pre-Mare Method thickness data displayed similar contour patterns to the De Hon 1974 isopach map, but with lower thickness values. On average, the thicknesses were approximately 40% less than those calculated by De Hon. Upon closer examination of De Hon's data, it was found that some of the craters that he had included were complex craters, not partially filled craters, therefore they potentially would have created artificially inflated results.

In analyzing the Pre-Mare and Post-Mare Methods, comparable lenses were found to exist in the areas of 5°N 23°E and 17°N 37°E on both of the isopachs maps made for this study. However, the basalt thickness determined using the Post-Mare Method was approximately 350% of the thickness determined using the Pre-Mare Method. The most notable of these instances occurs in the region of the adjacent craters Lamont and Arago, where the basalt thickness calculated using partially filled crater Lamont was 883.08m and the basalt thickness calculated using complex crater Arago was 1827.06m. Similar results were observed by Thompson (2009), in a study done on Mare Imbrium, where basalt thickness averaged more than double those found using partially filled craters.

A lens of thick basalt is found in the Pre-Mare map at 6°N 37°E that does not appear in the Post-Mare map; however, there are not post-mare craters in this region so this basalt thickness values in this area are determined by interpolation in the Post-Mare map. This is a major source of difference between the maps, as the thicknesses in areas without the appropriate crater type were interpolated and do not have some of the smaller lenses that exist around a specific crater.

Another possible source of the difference between the two maps is due to the manner in which mare formed with a succession of layers of basalt hardening. Some partially filled craters may have formed inside a lower layer of basalt as opposed to directly into the anorthosite, and then were filled in with only a top layer of the basalt. Consequently, there could be basalt that lies beneath these craters, possibly explaining why the thicknesses calculated using the Pre-Mare data are significantly lower than those calculated using the Post-Mare data.

This division between results may also stem from overestimations in the Post-Mare Method. The equations assume that the ratio of high iron ejecta to low iron ejecta surrounding a crater falls in the same proportion as the thickness of basalt to the thickness of anorthosite excavated from the crater. Ejecta does not fall in the exact ratio from where it was inside of the crater to the outside because there are a multitude of variables. Factors may need to be considered such as the anorthosite having a farther distance to travel upward out of the crater against gravity or the relative densities of basalt and anorthosite.

In addition to the estimations made in the methods that were used, there were also estimations in the acquiring of the data. Within the Pre-Mare Method the collection of data for larger craters was problematic due to the crumbling of the crater rim. In cases like the craters Lamont or Aryabhata, only a faint outline of the partial rim remained. With limited rim exposed, or with only a very discreet ridge for a rim, taking measurements of the height can vary by over 400 meters based on the point observed. For the Post-Mare Method, inaccuracies may have also occurred in measurement. The extent of the ejecta was difficult to determine, as it does not form a perfect circle and is difficult to identify visually.

As a result of the discrepancy in thickness between the two methods, depths of post-mare craters that did not penetrate through to the anorthosite below the basalt can provide a lower bound on the thickness of the basalt. These craters were identified due to their lack of low-iron ejecta. Craters with low iron found in the interior of the crater and not in the ejecta have an excavation height close to the boundary of the basalt and anorthosite. Craters Zahringer (5.51N, 40.21E) with a depth of 1912m and Taruntius F (3.92N, 40.51E) with a depth of 825m are both located in areas with estimated thickness in the 400m-500m range from the Pre-Mare Method and 500m-600m range from the Post-Mare Method. The depths of these craters are greater than the depths estimated by the methods of this study, indicating that both methods may give underestimates of the thickness of basalt. Crater Dawes (17.21N, 26.34E) has a depth of 607.5m, giving a lower bound of basalt thickness close to the range found in the Pre-Mare Method, 500m-600m, and lower than the range in the Post-Mare Method, 2300m-2500m. Crater Ritter C (2.75N, 18.86E) has a depth of 1879m. This crater is in an area south of the Pre-Mare Method map, but is located in an area with basalt thickness in the range of 1100m-1300m in the Post-Mare Method. This also indicates that the values calculated using both methods underestimate the thickness of basalt.

CONCLUSIONS

The purpose of this study was to evaluate two methods of calculating basalt thickness in Mare Tranquillitatis. Both methods determine similar areas with thick lenses, although these lenses vary greatly in magnitude. This indicates that the methods are good for finding relative high and low points, but not for their values. It was shown by measuring the depth of craters which did not fully penetrate the basalt that both methods have inaccuracies in basalt thickness magnitudes. Reviewing the research conducted, it is evident that more work needs to be done in refining methods to determine basalt thickness.

If both methods could be combined to create one isopach map, greater detail could be found. Because of the large difference in basalt thickness between the two isopach maps, the thickness values would need to be scaled to have common values in common areas. This could be done by finding depths of craters whose floor is at the boundary of the basalt and anorthosite and using them as standards to adjust the equations. Studies on other mare may provide more of these craters with low-iron in their center but not in their ejecta.

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