Using LRO Diviner to Construct Crater Ages and Ejecta Distributions on the Moon

by

Isabella Mary Wise

Bachelor of Arts – Department of Astrophysical & Planetary Sciences

Undergraduate Honors Thesis

Defense Copy

Thesis Defense Committee:

Prof. Paul Hayne	Advisor	Department of APS
Prof. David Malaspina	Honors Council Representative	Department of APS
Prof. Betsy McIntosh	Outsider Reader	School of Education

To defend on:

April 11, 2023

This thesis entitled:
Using LRO Diviner to Construct Crater Ages and Ejecta Distributions on the Moon
written by Isabella Mary Wise
has been approved for the Department of Astrophysical & Planetary Science

Prof. Paul Hayne

Prof. David Malaspina

Prof. Betsy McIntosh

Date

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Wise, Isabella Mary (B.A., Astrophysics)

Using LRO Diviner to Construct Crater Ages and Ejecta Distributions on the Moon

Thesis directed by Prof. Paul Hayne

Collecting samples from the Moon provides direct information about the ages of the Moon's surface from radiometric dating techniques. However, some sample ages could be biased by material contributed from individual craters nearby, which is presently unknown. Using H-parameter data (Hayne et al., 2017), coming from the Diviner Lunar Radiometer Experiment aboard NASA's Lunar Reconnaissance Orbiter, as a proxy for the abundance of rock fragments in regolith around craters, the age of the craters can be derived. From the preliminary dataset for the craters, location, diameters, and ages from the Mazrouei et al. (2019) database, we will attempt to improve the fit between model crater ages and the time-variation of the H-parameter. After creating a database of the average H-parameter values for each crater and their corresponding ages, the layering at sample sites given the ejecta thickness and distance of all the craters from the database will be able to be derived. From these results collectively, it will be able to be determined if individual craters dominate the material at a given location. This investigation will reveal the influence individual craters have on samples from lunar sites. Using the methods of this research, it may be possible to apply this on a larger scale and give a better understanding of layering at a given location.

Acknowledgements

I would like to express my sincere gratitude for the guidance and support that my advisor and mentor, Prof. Paul Hayne have provided me throughout this project. His expertise and encouragement have been invaluable to me and have helped me to achieve my goals. His commitment to my success and his willingness to share his knowledge and experience have made a significant impact on my development. I am grateful for the time and effort that Prof. Hayne have invested in me, and I truly appreciate his patience and understanding as I navigated through the challenges and obstacles that I faced.

I am grateful to Prof. Betsy McIntosh for her support as my outside reader. What I have learned in working with her in the LA program since the spring of 2021 is something that I will take with me for the rest of my life. Being a learning assistant (LA) and a LA mentor has provided me with valuable experience and skills that will help me in my future endeavors. It has helped me develop communication, time management, pedagogical, adaptability and leadership skills, and provide me with a deeper understanding of the learning process.

Thank you to Prof. David Malaspina for guidance with the honor thesis process.

I would also like to acknowledge my friends and family for their support and encouragement. Their belief in me has motivated me to work hard and pursue my dreams, and I am grateful for the sacrifices that they have made to help me reach my goals. Their encouragement, kindness, and understanding have been instrumental in helping me to overcome challenges and achieve my goals.

Contents

Tables

Table

Figures

Figure

Chapter 1

Introduction

Radiometric dating techniques are a reliable way to find the ages of the lunar surface. The early chronology of the lunar surface can be developed by looking at different compounds in lunar samples. The current estimate for the age based on Apollo samples of the Moon is 4.51 billion years ago (Barboni et al., 2017). There is a current understanding that lunar samples and meteorites give more information than just the age of the Moon. The samples give insight into global events that have happened, especially the period of Late Heavy Bombardment. Evidence shows that the Moon and other airless bodies went through a period of large impact events about 3.7 to 3.9 million years ago (Bottke & Norman, 2017). However, contributions from individual craters near the sample site can contaminate the lunar samples. These contributions at present are unknown.

There must be a greater understanding of the breakdown of lunar ejecta to understand the contributions of craters at a given location on the Moon. During a meteorite impact on an airless body like the Moon, the material is ejected from that site at high velocities and falls back onto the lunar surface. The ejecta thickness of a given crater decreases rapidly further, radially away from the rim of that crater. The ejecta thickness decreases at a rate of $(distance)^{-3}$. However, for large craters, where there is more material that is thrown during impact, there is a greater influence than smaller craters. As the ejecta contributes to the background regolith, the rock begins to breakdown. Originally the ejecta was dense and blocky. Over time the ejecta begins to breakdown into loose material. The rock breakdown and rock abundance give more insight into the history of the lunar surface. Ghent et al. (2014) developed a new method of dating craters based on ejecta rock abundance. The initial correlation was based on ages calculated from counting craters.

Counting craters has been a technique to discover crater ages without getting direct lunar samples. The crater count method was developed in the 1960s and was calibrated with the ages of lunar samples found using radiometric techniques. The method operates on the assumption that the age of the surface is the same as the lunar samples and that there were no impact craters at that time (Bland, 2003). Therefore, the impact rates over time can be found by counting the number of craters on the given surface. By retrieving impact rates and crater counts, this method can calculate the age of a given crater on the lunar surface. However, crater counting is time-consuming as it requires manually identifying craters on the lunar surface. Therefore, in this paper, the primary method to calculate the ages of craters will be based on understanding how ejecta breakdown over time.

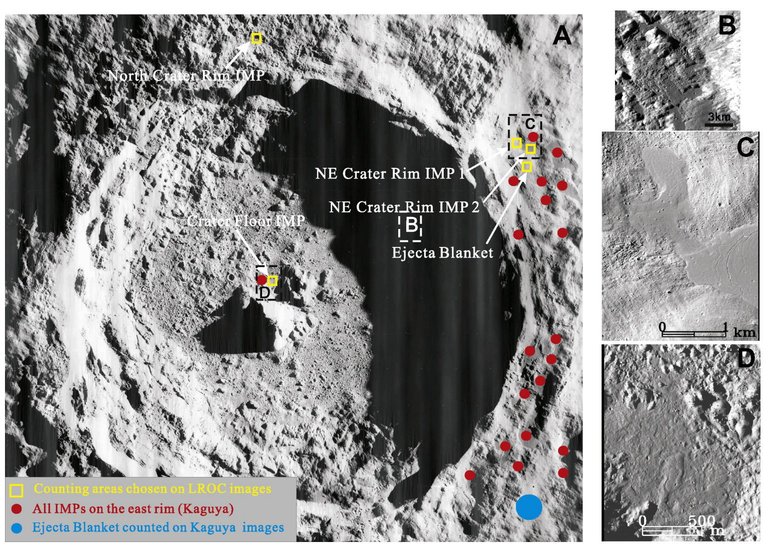

Figure 1.1: From Xiao et al. (2012), these lunar craters count on Tycho craters. The crater counting areas are not to scale. The yellow boxes represent crater counting done using the Lunar Reconnaissance Orbiter Camera (LROC). The dots represent crater counting that was done using Japan's Kaguya lunar orbiter. The red dots were completed using impact melt pools, and the blue dots used the ejecta blanket.

The main question being answered in this paper is the geographic origins of the samples collected from the lunar surface. Currently, the origins of the material are unknown. To find out about the geographic origins of the sample, the ages of the craters and the ejecta thickness of the local craters must be found. I hypothesize that the material at any given sample site tends to be dominated by ejecta from individual craters. Although ejecta from larger craters will dominate the lunar surface because the ejecta can reach further, the individual, local craters will dominate the sample site. A result of this paper is building a model layering of the lunar surface based on craters with diameters greater than or equal to ten kilometers.

Chapter 2

Data Sets

The Diviner Lunar Radiometer Experiment aboard NASA's Lunar Reconnaissance Orbiter is a radiometer with two solar and seven infrared channels to measure the brightness temperatures of the lunar surface to produce thermal maps in the different spectral channels. From brightness temperatures, the density of the regolith at depth z was modeled and found to depend on the sole variable of the H-parameter (Hayne et al., 2017). The H-parameter quantifies the density of the upper $\sim$ 10 centimeters of regolith, which is sensitive to the concentration of small rocks relative to loose granular material. The smaller H-parameter values correlate to a denser material, and larger H-parameter values correlate to loose material. Therefore, craters with smaller H-parameter values are younger because the ejecta around the crater, or ejecta blanket, has not yet broken down into a finer material. In this paper, the use of the H-parameter data acts as a proxy for the abundance of rock fragments in regolith around craters to derive the age of the craters.

Previous work has established the relationship between rock abundance and crater ages (Ghent et al., 2014; Hayne et al., 2017). Ghent et al. (2014) established the relationship between the 95th percentile value of the rock abundance and the age of craters with nine index craters with established ages by crater counting. The nine craters were Aristarchus, Byrgius A, Copernicus, Giordano Bruno, Jackson, King, Moore F, Necho, and Tycho. Hayne et al. (2017) established the relationship between the H-parameter and the ages of the same nine craters. A larger sample of craters was used to expand and improve the fit between H-parameter and crater ages. The Mazrouei et al. (2019) database provides a preliminary data set for the craters, locations, diameters, and ages. The Mazrouei database defined 111 craters younger than a billion years old and have diameters of 10 kilometers or greater. The data set provides these necessary parameters to improve the fit between crater ages and the H-parameter. The crater ages from the Mazrouei database were derived from 95th-percentile rock abundance based on a previously established regression in Ghent et al. (2014). The data set determined the ages of many craters that have not been previously determined. Therefore, many craters in the data set are without names and labeled as “No name.”

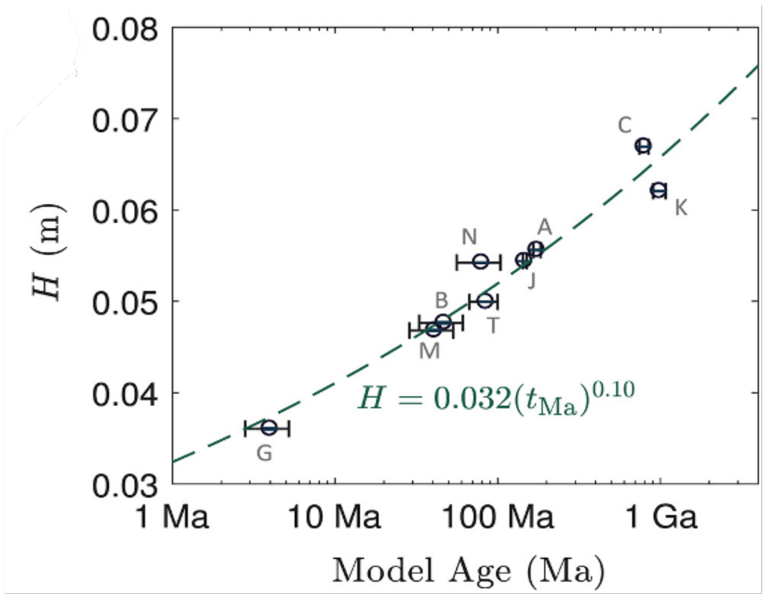

Figure 2.1: From Hayne et al. (2017), the average H-parameter measured from the rim of the crater to 2 crater radii away for the nine craters explored by Ghent et al. (2014). The curve was modeled using a nonlinear least squared fit of $H = H_0(t_{Ma})^b$ with $H_0 = 0.032$ and $b = 0.10$.

Chapter 3

Approach and Methods

In this study, there were multiple steps to create a result of the ejecta stratigraphy of any given sample site. First, the criteria for choosing a database to work with the H-parameter data to compare with crater ages had to be determined. Once determining a database of the preliminary craters with their location, diameter, and age, the fit between the average H-parameter and crater ages from Hayne et al. (2017) could be improved. Another understanding was discovered about the difference in the average H-parameter from the rim to one crater radii from the rim as well as from the rim to one crater radii from the rim. The model ejecta thickness from a given crater is related to $(distance)^{-3}$. The ejecta stratigraphy will be determined given the ejecta thickness and the distance from the crater. The layering will also be developed with the model crater ages determined by the average H-parameter.

3.1 Criteria

Some criteria had to be met to choose a preliminary data set to improve the model fit between crater ages and the H-parameter. Since H-parameter provides information about the density of the material in the ejecta blanket, after a billion years, the ejecta has broken down and mixed with the regolith. Therefore, the craters in the database would also need to be younger than a billion years old to derive the approximate ages of the craters. In Figure 3.1, the average H-parameter increases with age, and the comparison is shown. Copernicus has a known age of 797 million years, and Giordano Bruno has a known age of 4 million years. On the contour plot of Copernicus, the average H-parameter from the rim to two crater radii from the rim is ~ 0.068 m, marginally smaller than the background H-parameter of ~ 0.08 m. On the contour plot of Giordano Bruno, the average H-parameter from the rim to two crater radii from the rim is ~ 0.031 m, significantly smaller than the background H-parameter. Therefore, the average H-parameter of the ejecta blanket of a given crater must be smaller than the background H-parameter to derive the crater ages. The Mazrouei database has ages that are all younger than a billion years old and meets the first criterion.

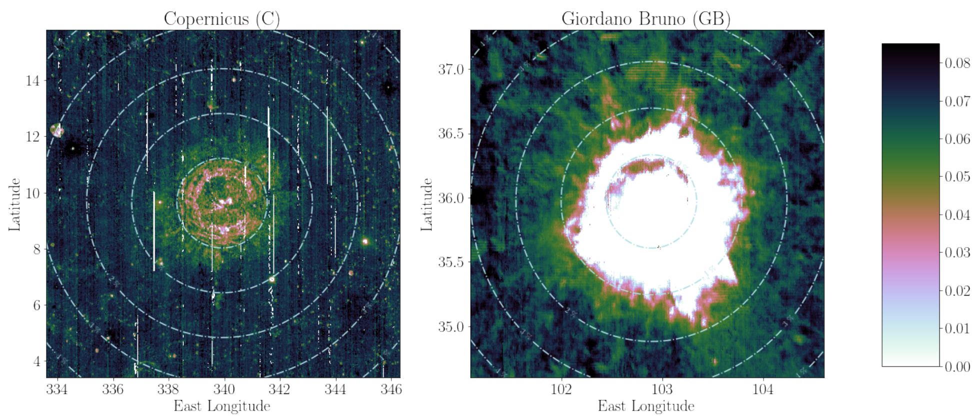

Figure 3.1: A comparison of Copernicus and Giordano Bruno shows that the average H-parameter of the ejecta blanket increases with age. The ages of Copernicus and Giordano Bruno are provided in Ghent et al. (2014), and the methods to establish the ages are referenced therein. The light blue dashed lines represent the distance from the crater centers regarding crater radii.

Another criterion was that the craters had to have a latitude between +70° and -70°. When creating global maps of the H-parameter, artifacts that were produced by topography became evident (Hayne et al., 2017). Therefore, the maps were created only from +70° to -70° latitude. To get an accurate representation of the rock abundance surrounding craters, the data set to use must identify enough craters between +70° and -70° latitude. The Mazrouei database has 105 of the 111 craters investigated that fit within this criterion.

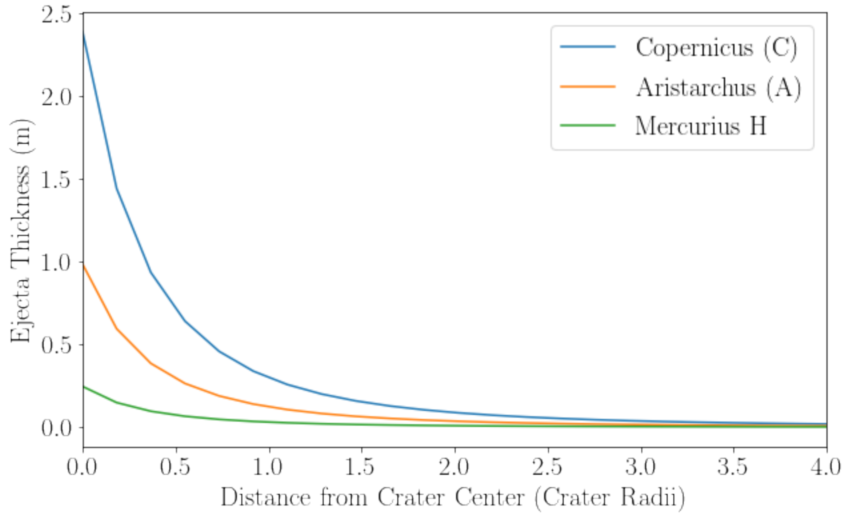

Figure 3.2: The relationship between ejecta thickness and the distance from the crater center is characterized by this equation: $h(r) = h_0(D/2) * (2r/D)^{-B}$. The parameter for ejecta thickness is crater diameter in meters (D), crater depth/diameter ratio (beta), distance from the center of the crater in meters (r), and power-law exponent (B). For this study, we used a beta=0.1 and B=3. Copernicus has a 97 km diameter, Aristarchus has a 40 km diameter, and Mercurius H has a 10 km diameter. After 1 crater radii, the ejecta thickness of all the craters falls below 50 cm. After 2 crater radii, the ejecta thickness of all the craters falls below 10 cm. After 3 crater radii, the ejecta thickness of all the craters falls below 5 cm.

The data set also must hold constraints to build a stratigraphy model. The craters must be large enough to contribute significantly at a given location. The ejecta blanket for a typical crater is mainly between the rim of the crater and two crater radii from the rim. In Figure 3.2, the maximum ejecta thickness of the three craters at three crater radii from the center of the crater is 5 centimeters. Therefore, much of the ejecta accumulates from the crater center to 3 crater radii away. Craters smaller than one kilometer in diameter would only significantly contribute to one kilometer away. Therefore, it is important to focus on craters with a large ejecta range to understand the layering of the lunar surface. In the Mazrouei database, the craters are all greater than or equal to 10 kilometers; therefore, it meets this criterion.

3.2 Fit between H-parameter and Crater Age

One variable explored was the effect of the crater radius on the relationship between the H-parameter and crater age. As shown in Figure 3.2, much of the ejecta extend from the crater center to about 3 crater radii from the center. Therefore, the H-parameter would detect there be denser material in this region. The relationship between the average H-parameter and crater radii must be explored to understand the ejecta in the ejecta blanket of a crater. The H-parameter data is mapped using longitude and latitude. The way to determine how far the distance between a given point and the center of the crater is in crater radii is to calculate the great circle distance of a sphere.

Haversine Formula:

$$d = 2 * R * \arcsin \sqrt{\sin^2(\frac{lat2 - lat1}{2}) + \cos(lat1) * \cos(lat2) * \sin^2(\frac{lon2 - lon1}{2})}$$

The haversine formula depends on R, the radius of the Moon (1737.4 kilometers), the crater center (lon1, lat1), and the given location (lon2, lat2). It takes two given locations in longitudinal and latitudinal coordinates on a given planetary body and finds the distance in kilometers. Then, dividing by the crater radius, the distance in crater radii can be derived. Since the H-parameter average is of the ejecta blanket and does not include the crater itself, using the distance from the crater center in terms of crater radii, the distance from the crater rim can be achieved. Therefore, with these distances, we can explore the average H-parameter changes from the rim to one crater radii from the rim and from the rim to two crater radii from the rim. From that relationship, we can see how the H-parameter and crater age change at different crater radii. Going forward, when referring to crater radii, it will always be measured from the rim of the crater.

3.3 Ejecta Stratigraphy

The lunar regolith can be broken down into three regions: a surficial regolith layer (5-20 meters), an upper regolith layer (1-3 kilometers), and a lower regolith layer (20-25 kilometers) (Richardson & Abramov, 2020). Regarding this paper and crater ejecta, the surficial regolith layer is created from smaller impacts. In comparison, the upper regolith layer is created from larger impacts producing more significant ejecta. Therefore, the ejecta from the craters in this study is predominantly at depths anywhere from 5 meters to 3 kilometers.

An ejecta stratigraphy can be developed at any given location on the lunar surface using the relationship between the H-parameter and crater ages. By using the ejecta thickness equation of

$$h(r) = h_0(D/2) * (2r/D)^{-B}$$

and crater ages, a stratigraphy can be built by stacking the ejecta thickness of each crater in chronological order. The parameter for ejecta thickness is crater diameter in meters (D), crater depth/diameter ratio (beta), distance from the center of the crater in meters (r), and power-law exponent (B). For this study, we used a beta=0.1 and B=3. The model stratigraphy can be used to compare to lunar samples by estimating the amount of ejecta from craters greater than 10 kilometers from the Mazrouei database as well as manually identifying.

Chapter 4

Results

There were three main results of this study:

(1) A database of average H-parameter values versus crater ages was created. The relationship was also explored at a different distance within the ejecta blanket, the rim to one crater radii and the rim to two crater radii.

(2) A model for producing stratigraphy at any given latitude and longitude location, using the crater ejecta model with crater database. The stratigraphy gives more insight into the material's origin within lunar samples.

(3) A comparison to Apollo 17 samples can be made with the model stratigraphy using the Mazrouei database of craters.

4.1 H-parameter and Crater Age

To understand the fit between the average H-parameter of the ejecta blanket with the ages of the craters, we explored how the average H-parameter changes at different crater radii away from the rim of the crater. Using this overall understanding of H-parameter averages and the ages of the craters from the Mazrouei database, the fit between them was adjusted from the nonlinear least squares fit from Hayne et al. (2017). The fit from Hayne et al. (2017) was $H = 0.032*(t_{Ma})^{0.10}$. The new fit for the average H-parameter from rim to one crater radii away is $H = 0.027*(t_{Ma})^{0.14}$ and the new fit for the average H-parameter from rim to two crater radii away is $H = 0.040*(t_{Ma})^{0.09}$.

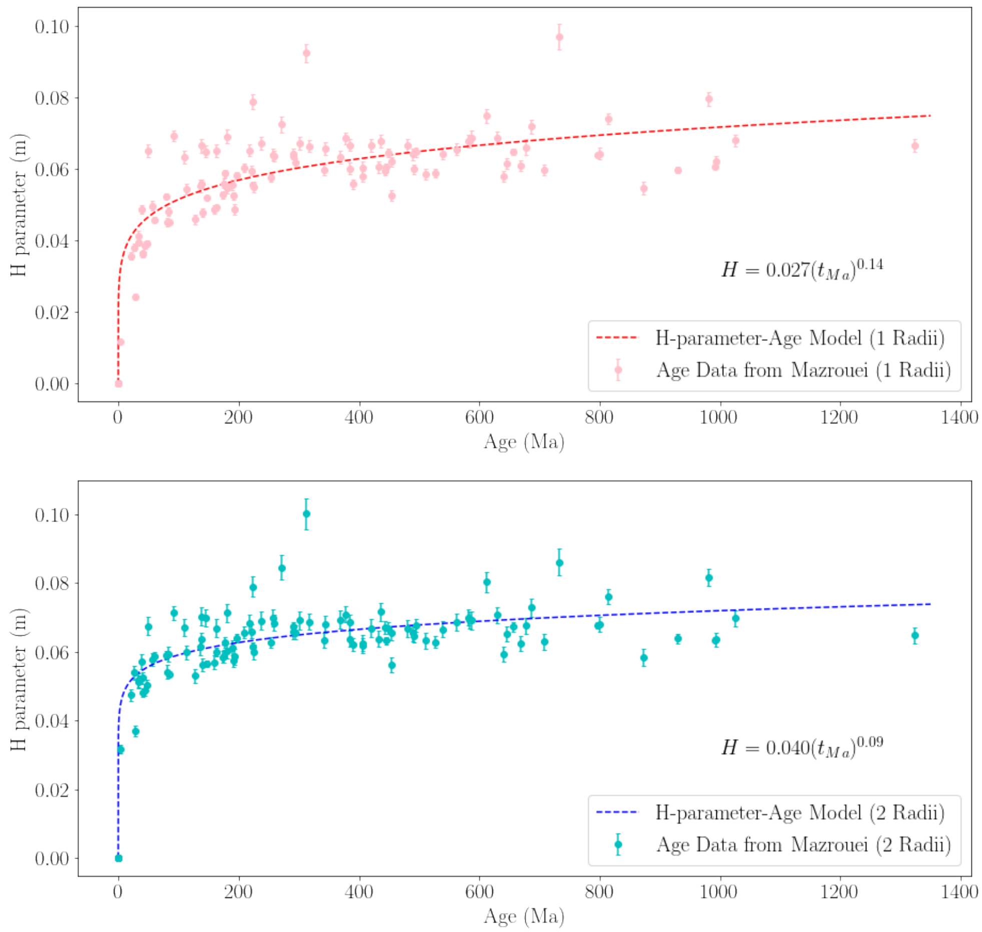

Figure 4.1: The nonlinear relationship between the average H-parameter and the crater age. The fit of both curves is in the form: $H = a(t_{Ma})^b$, where t_{Ma} is the age in terms of millions of years. The upper plot examines the ejecta blanket from the crater rim to one crater radii. The best-fit parameters for one crater radii away are $a_1 = 0.027$ and $b_1 = 0.14$. The lower plot examines the ejecta blanket from the rim to two crater radii. The best-fit parameters for one crater radii away are $a_1 = 0.040$ and $b_1 = 0.09$.

When creating an initial fit between the average H-parameter and the Mazrouei crater ages, it became evident that one fit for all the craters would not represent the relationship properly. Initially, the processes of ejecta breakdown are more rapid. Therefore, the average H-parameter is lower than the fit would suggest. Also, craters older than 500 million years can have new impacts on the crater floor. Given that all the craters in the Mazrouei database are greater than 10 kilometers, the potential new impacts could be large enough to affect the average H-parameter values in the ejecta blanket of the preliminary craters. Therefore, the derived H-parameter ages would be younger than the actual crater.

The King crater is an example of an older, known crater with estimates significantly younger. King is a very larger crater with a diameter of 76 kilometers. The known age of King is 992 +87/-89 Ma using a combination of techniques such as crater counting and measurements of the proximal ejecta blanket (Ashley et al., 2012). The average H-parameter from the rim to one crater radii is 0.0606 with a derived age of 309 $\pm$ 21 Ma. The average H-parameter from the rim to two crater radii is 0.0635 with a derived age of 232 $\pm$ 37 Ma. These estimates are significantly lower than the known age of King. Within one crater radii of King's rim, the Al-Tusi melt pond formed as a result of the impact. However, in Ashley et al. (2012), they found that using crater counting of 9,198 craters in a 23 km^2 area, the Al-Tusi melt pond age is 385 +51/-53 Ma. Therefore, the average H-parameter of the ejecta blanket of King includes this melt pond and is more accurately calculating the age of the melt pond instead of the crater.

The nonlinear least squares fit shown in Figure 4.1 does a good job of the general trend of the relationship between the H-parameter and crater ages. Many factors can skew this relationship, as previously mentioned. There are 13 craters with modeled ages, calculated from one crater radii, that agree within one standard deviation with the ages in the Mazrouei database. Also, 26 craters with modeled ages, calculated from two crater radii, agree within one standard deviation with the ages in the Mazrouei database. This breakdown of the model crater ages compared to the Mazrouei ages shows that the fit between the average H-parameter and crater ages is best from the rim to two crater radii. Expanding to two crater radii allows more of the ejecta blanket to be considered. The ejecta blanket can be misleading to the model ages for some craters due to additional craters or uneven ejecta. Therefore, including more of the ejecta blanket has proven to give better age estimates of the craters. Table 4.1 explores the characteristics of these craters that agree within one standard deviation.

Name	Diameter (km)	Mazrouei Age (Ma)	Model Age 1 (Ma)	Model Age 2 (Ma)	Agreement
Lalande	24	495	492.28 ± 68.85	496.50 ± 155.68	Both
Larmor Q	23	178	249.50 ± 32.02	199.82 ± 58.98	Only 2 CR
Cleostratus J	21	443	274.86 ± 37.71	434.28 ± 138.56	Only 2 CR
No name	19	449	476.67 ± 63.67	427.08 ± 133.33	Both
Carrel	17	295	352.77 ± 55.67	340.48 ± 121.62	Only 2 CR
No name	14	290	468.49 ± 78.24	355.85 ± 135.53	Only 2 CR
Darney C	13	582	679.46 ± 117.69	722.01 ± 287.23	Only 2 CR
Egede A	13	84	62.93 ± 11.14	104.11 ± 42.04	Only 2 CR
No name	13	113	146.03 ± 26.41	116.36 ± 47.25	Only 2 CR
No name	11	563	532.85 ± 93.39	567.08 ± 232.71	Both
Lagrange H	11	583	676.21 ± 128.78	640.80 ± 278.87	Only 2 CR
Cameron	11	480	604.50 ± 114.33	419.63 ± 181.22	Only 2 CR
Aratus	11	421	592.29 ± 113.05	427.00 ± 189.59	Only 2 CR
No name	11	137	164.33 ± 35.77	161.61 ± 75.19	Only 2 CR
No name	10	587	746.54 ± 143.41	629.73 ± 279.92	Only 2 CR

Table 4.1: These craters all agree within half a standard deviation with the Mazrouei database either at two crater radii away (Only 2 CR) or at both two crater radii and one crater radii away (Both) shown in the "Agreement" column. These 15 craters out of the 26 agree within one standard deviation and half a standard deviation. The "Model Age 1" is the age derived from the average H-parameter from the rim to one crater radii. The "Model Age 2" is the age derived from the average H-parameter from the rim to two crater radii. All the ages are in terms of millions of years.

From Table 4.1, there are several characteristics that these craters have in common that made this method of deriving the age successfully. All the craters that agree with the Mazrouei ages have diameters less than 25 kilometers. This means there is less likely that a new impact would strike the face of the craters and cause the derived ages to appear younger than they are compared to larger craters. These craters are also all younger than 600 million years old and older than 75 million years. Similar to the smaller diameter, younger craters are less likely to have new impacts on their face than older craters. These craters within half and one standard deviation away from the Mazrouei ages give the best-fit parameters for the correlation of the average H-parameter and the crater ages. This precise fit for this sampling of craters shows that this method of crater aging works best for young craters aged 80 to 600 million years and with diameters less than 30 kilometers.

4.2 Model Ejecta Stratigraphy

Since the regions of the lunar regolith are well-defined (Richardson & Abramov, 2020), the ejecta from the craters in this study are predominantly at depths anywhere from 5 meters to 3 kilometers. Therefore, by comparing the ejecta distribution of the craters from the Mazrouei database with the ages of craters from this study and the Mazrouei database, a model of the ejecta stratigraphy can be developed. This current model can be used as a basis for the general layering of larger craters with a diameter greater than 10 kilometers. The current version of this model would not account for the mixing and smaller meteorites. However, it would give a good understanding of the origins of the bulk of the regolith at a given site.

Comparing the model ejecta stratigraphy with sample lunar core samples from Apollo 17 will determine the validity of this model. Since the preliminary data set for this paper only accounts for 10-kilometer craters, determine a more accurate and extensive stratigraphy of the ejecta material manual identification must be done for craters within about a 50-100 kilometer radius, depending on crater diameter, from the sample site. The upper limit of 100 kilometers away is decided since a large enough ejecta thickness must be evident in the lunar core. Compared to Apollo 17, ten craters were young enough to read an average H-parameter above the background and well-defined. These craters have diameters between 17 kilometers and 1 kilometer. To see evidence of the ejecta thickness, we assessed that the thickness would need to be 0.5 centimeters or greater. Therefore, given these parameters, Table 4.2 shows the 12 craters that have been shown to contribute to the stratigraphy at this sample site over the last billion years. The table also explores the slightly different stratigraphy models that can be created with ages determined by Mazroeui et al. (2018), the average H-parameter from the crater rim to one crater radii away, and the average H-parameter from the crater rim to two crater radii away.

Names	Diameter (km)	Mazrouei Age (Ma)	Model Age 1 (Ma)	Model Age 2 (Ma)	Ejecta Thickness (cm)	Distance (km)
Ching-te	3.7	–	366.6	422.7	4.7	23.1
Gardener	17.6	–	358.3	332.9	20	114.1
No Name	4	–	314.1	258.5	3.2	29.4
Clerke	6.7	–	313.2	333.4	4	53.5
MOCR	1.2	–	176.3	181.3	2.5	6.5
King	76	992	308.9	231.9	0.5	2669.5
No name	11	873	151.8	87.9	1.5	145.4
Copernicus	97	797	455.4	491.9	7.8	1518
Dawes	18	454	365.2	331.2	8.6	155.5
Carrel	17	295	352.8	340.5	0.8	311.9
Proclus	28	253	216.7	200.5	1.7	480.6
Tycho	86	85	40.5	31.1	1.5	2251.6

Table 4.2: The first five craters are identified manually in the area surrounding the sample site. The last seven craters are craters from the Mazrouei database with a large enough ejecta thickness to be significant to the lunar sample. The ejecta thickness was determined using $h(r) = h_0(D/2) * (2r/D)^{-B}$ and converted into centimeters. The distance was calculated using the haversine formula for the great circle distance on the Moon. As the first five craters were not defined in the Mazrouei database, these craters do not have ages derived from the 95th percentile of rock abundance. The "Model Age 1" is the age derived from the average H-parameter from the rim to one crater radii. The "Model Age 2" is the age derived from the average H-parameter from the rim to two crater radii. All the ages are terms of millions of years.

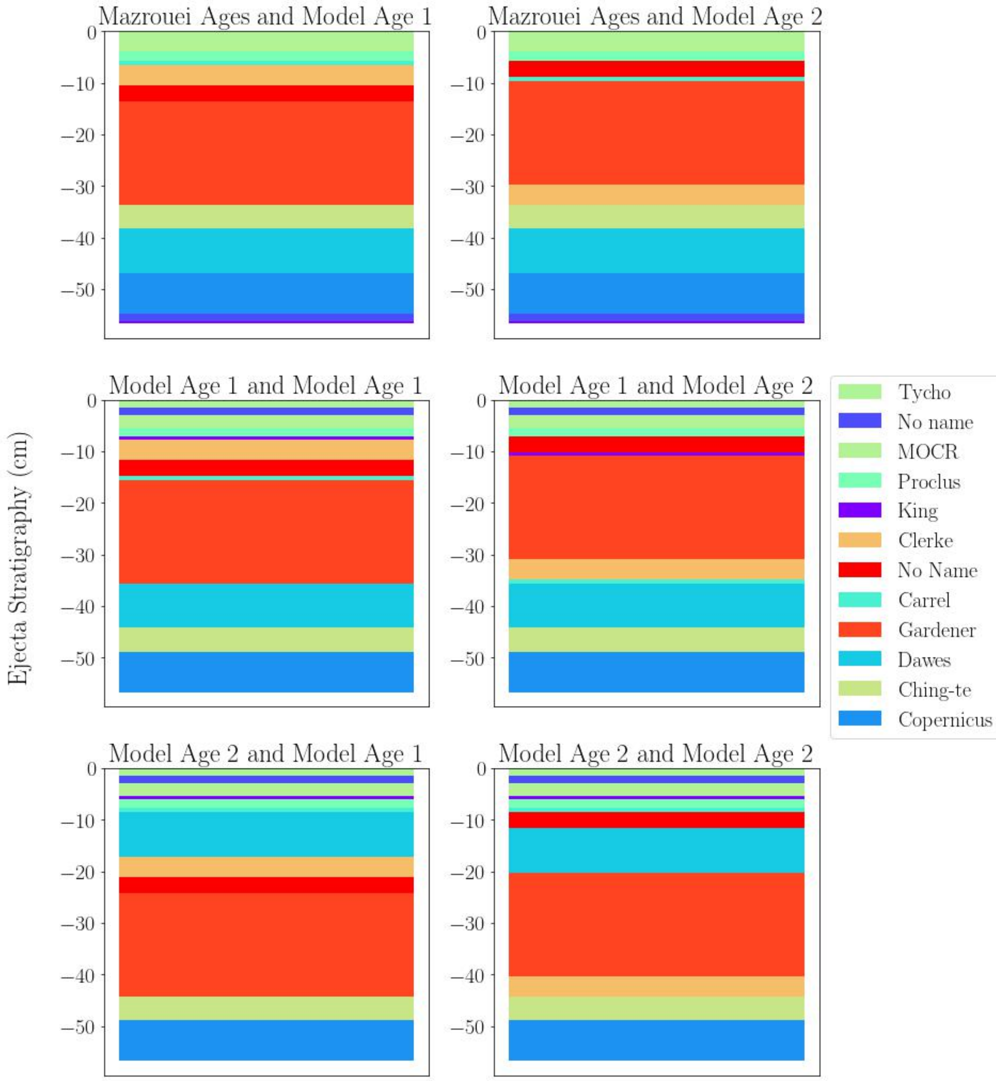

Figure 4.2: The figures are the visual representation of the stratigraphy from Table 4.2. The legend identifies the craters with the same color through all the model ejecta stratigraphy. The titles of the individual stratigraphy are to reference which combination of age modeling was used to create the stratigraphy. For example, the "Model Age 1 and Model Age 2" refers to the craters from the Mazrouei database having ages determined by the average H-parameter from rim to one crater radii and the craters identified manually having ages determined by the average H-parameter from rim to two crater radii.

These models of ejecta stratigraphy, visualized in Figure 4.2, give multiple options for the potential layering of the lunar surface. Based on previous analysis of the different models' validity to determine the craters' ages, the stratigraphy "Mazrouei database and Model Age 2". The Mazrouei ages for these craters are the most accurate, as some of the ages come from extensive research identified by Ghent et al. (2014). The Model Age 2 is best for the manually identified craters since, in section 4.1, the modeled ages with average H-parameter from rim to two crater radii have the best estimates.

This model ejecta stratigraphy can be compared to the lunar samples of Apollo 17. The Apollo 17 mission took a deep drill core sample. The core was broken down and returned in three segments. The first segment contained core sections 70009, 70008, and 70007. The second segment contained core sections 70006 and 70005. The third segment contained core sections 70004, 70003, 70002, and 70001. The samples that can be compared to the model ejecta stratigraphy are from core section 70009 with sample numbers 433 and 434 and core section 70008 with sample numbers 455, 456, and 457. Sample 433 is at a depth of 9.1-9.6 centimeters, sample 434 is at a depth of 20.1-20.6 centimeters, sample 455 is at a depth of 27.8-28.3 centimeters, sample 456 is at a depth of 37.7-38.2 centimeters, and sample 457 is at a depth of 46.8-47.3 centimeters (Laul et al., 1978).

Figure 4.3 shows the percent fraction of the different soil sizes in each sample size within the core sample. In sample 455 in 70008, 60% of this sample is made up of soil size from 90 to 1000 microns. Therefore, there is more dense material at a depth of about 28 centimeters. From the model ejecta stratigraphy, sample 455 in 70008 is primarily like from the Gardener crater. Gardener is a 17-kilometer crater located about 114 kilometers from the sample site and contributes about 20 centimeters to the site. Given the average H-parameter from rim to two crater radii, the age of Gardener is 333 Ma.

Core Section Location	Sample Number (Depth)
70009	432 (0.6-1.1 cm)
70009	433 (9.1-9.6 cm)
70009	434 (20.1-20.6 cm)
70008	455 (27.8-28.3 cm)
70008	456 (37.7-38.2 cm)
70008	457 (46.8-47.3 cm)
70008	458 (57.3-57.8 cm)
70007	167 (70.4-70.9 cm)
70007	168 (80.9-81.4 cm)
70007	169 (89.4-89.9 cm)
70006	16 (97.7-98.2 cm)
70006	17 (108.2-108.7 cm)
70006	18 (117.2-117.7 cm)
70006	19 (130.2-130.7 cm)

Table 4.3: The sample numbers at specific depths of the larger core samples returned from Apollo 17.

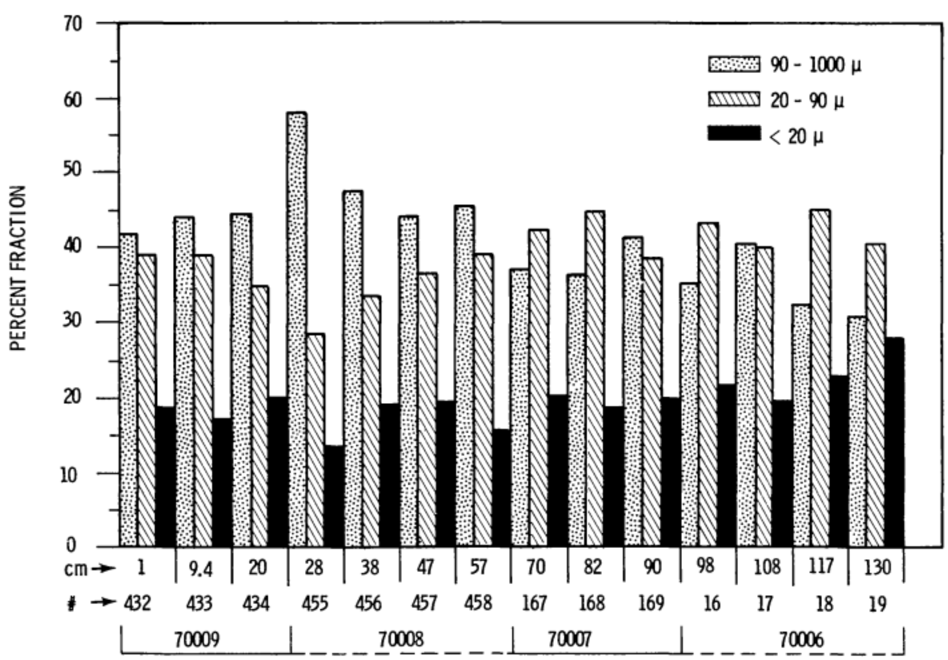

Figure 4.3: From Laul et al. (1978), these are the percent weight recoveries of different fragment sizes. The size fractions of soils come from the core samples of 70009-70006. The figure examines the percent fraction of the soil size for each sample number and depth.

Chapter 5

Discussion

Given the information mentioned in the previous chapters, we can determine the validity of using the H-parameter to calculate the ages of lunar craters. Using the results from Chapter 4 and the methods from Chapter 3, we can begin to answer the question of the geographic origins of the samples collected from the lunar sample. We can determine if individual craters or global events dominate the material at any given sample site.

5.1 Interpretations

The average H-parameter of the ejecta blanket indicates the age of the craters. The formula determines this age dating method: $H = H_0 * (t_{Ma})^b$. The parameters of H_0 and b are determined by the index craters chosen. This study used a larger sample of index craters than Hayne et al. (2017), so the parameters differed. In Chapter 4, we determined the best fit for the average H-parameter from the crater rim to 1 crater radii was $H = 0.027 * (t_{Ma})^{0.14}$ and the best fit for the average H-parameter from rim to two crater radii was $H = 0.040 * (t_{Ma})^{0.09}$. The craters with ages that agreed best with the ages from the Mazroeui database had ages between 75 and 600 million years old with diameters less than 25 kilometers. The index craters impact the parameters significantly. Therefore, by introducing more craters, there are improvements in the model fit. More modeling would need to be done to improve the fit for craters younger than 75 million years and older than 600 million years. The current issue with creating younger fits is that there are not many craters younger than 75 million years that have known ages to use as index craters. The issue with craters older than 600 million years has higher H-parameter values, and more processes happen over time to change the H-parameter. The higher H-parameter values will ultimately blend into the background and will no longer be able to be used to derive craters. Over time more impacts and other geological processes will cause the H-parameter value to be influenced and no longer represent the accurate crater age.

The model ejecta stratigraphy described in Chapter 4 will be used to answer the question of the geographic origins of lunar samples. When using the method of using the average H-parameter of the ejecta thickness to calculate crater ages, the model ejecta stratigraphy gives a good idea of the layering of the lunar surface. Since the model stratigraphy is derived from the H-parameter, there is a good idea of the layering built over the last billion years. The model has shown that individual craters dominate the location. The craters that dominate the most have larger diameters. For example, the model ejecta stratigraphy of the Apollo 17 sample site has 3 craters that contribute more than 5 centimeters of ejecta to the site. However, 12 craters contribute 0.5 centimeters of ejecta or more to the sample site. Therefore, the individual craters contribute significantly to the sample site. However, the three craters that contribute more than 5 centimeters are over 100 kilometers away, with diameters over 15 kilometers.

5.2 Future Work

This age dating technique of using the H-parameter could be used for more craters on the lunar surface. However, the current databases of lunar craters are limited in determining the freshness of the crater with a raised rim or bright ejecta. Therefore, to determine the ages of more craters, we need to manually identify craters with high enough H-parameters to determine the crater ages. The current model for ejecta thickness only considers the ejecta thickness and the crater ages. More work will need to be done to include mixing into the stratigraphy to make this model more in-depth and accurate to a sample on the lunar surface. Over time, the ejecta in the regolith will begin to mix, and the layers of the ejecta will not be as defined as in this model. Also, there will need the influence of micrometeorites in the stratigraphy.

Chapter 6

Conclusion

In this paper, we explored the process to improve the fit between the average H-parameter of the ejecta blanket and crater age and a model of the ejecta stratigraphy of the lunar surface. The work in this paper gave more insight into the geographic origins of lunar samples and determined that individual craters have dominated the lunar surface over the last billion years. The findings of this study can help determine new sample sites to collect samples when looking for the ages of certain craters on the surface. It can also be used to compare to other lunar samples and compare the ages determined by the H-parameter to the radiometric age dating technique on the sample.

It may be possible to apply this on a larger scale and give a better understanding of layering at a given location using the methods of this research. Given that the Robbins (2019) database is a good source of thousands of craters, this would be a complete picture of what contributes to the layering than the Mazrouei database. By calculating the ages of the craters in this database from the H-parameters, a new "age" column can be created in the Robbins' database. The more extensive set of craters may improve the model used to predict the stratigraphy expected before taking a lunar sample in the future.

Bibliography

[1] J. W. Ashley, M. S. Robinson, B. R. Hawke, C. H. van der Bogert, H. Hiesinger, H. Sato, E. J. Speyerer, A. C. Enns, R. V. Wagner, K. E. Young, and K. N. Burns. Geology of the king crater region: New insights into impact melt dynamics on the moon. Journal of Geophysical Research: Planets, 117(E12), 2012.

[2] J. L. Bandfield, J. T. Cahill, L. M. Carter, C. D. Neish, G. W. Patterson, J.-P. Williams, and D. A. Paige. Distal ejecta from lunar impacts: Extensive regions of rocky deposits. Icarus, 283:282–299, 2017. Lunar Reconnaissance Orbiter - Part II.

[3] M. Barboni, P. Boehnke, B. Keller, I. E. Kohl, B. Schoene, E. D. Young, and K. D. McKeegan. Early formation of the moon 4.51 billion years ago. Science Advances, 3(1):e1602365, 2017.

[4] P. Bland. Crater counting. Astronomy Geophysics, 44(4):4.21–4.21, 08 2003.

[5] W. F. Bottke and M. D. Norman. The late heavy bombardment. Annual Review of Earth and Planetary Sciences, 45(1):619–647, 2017.

[6] C. I. Fassett and B. J. Thomson. Crater degradation on the lunar maria: Topographic diffusion and the rate of erosion on the moon. Journal of Geophysical Research: Planets, 119(10):2255–2271, 2014.

[7] R. Ghent, L. Carter, J. Bandfield, C. Tai Udovicic, and B. Campbell. Lunar crater ejecta: Physical properties revealed by radar and thermal infrared observations. Icarus, 273:182–195, 2016.

[8] R. R. Ghent, P. O. Hayne, J. L. Bandfield, B. A. Campbell, C. C. Allen, L. M. Carter, and D. A. Paige. Constraints on the recent rate of lunar ejecta breakdown and implications for crater ages. Geology, 42(12):1059–1062, 12 2014.

[9] P. O. Hayne, J. L. Bandfield, M. A. Siegler, A. R. Vasavada, R. R. Ghent, J.-P. Williams, B. T. Greenhagen, O. Aharonson, C. M. Elder, P. G. Lucey, and D. A. Paige. Global regolith thermophysical properties of the moon from the diviner lunar radiometer experiment. Journal of Geophysical Research: Planets, 122(12):2371–2400, 2017.

[10] T. C. Labotka, D. T. Vaniman, and J. J. Papike. The apollo 17 drill core: Comparative modal petrology and phase chemistry of the ¿ 20μm and ¡20μm soil fractions. Geophysical Research Letters, 6(6):503–506, 1979.

[11] J. C. Laul, D. T. Vaniman, J. J. Papike, and S. Simon. Chemistry and petrology of size fractions of Apollo 17 deep drill core 70009-70006. Lunar and Planetary Science Conference Proceedings, 2:2065–2097, Jan. 1978.

[12] S. Mazrouei, R. R. Ghent, W. F. Bottke, A. H. Parker, and T. M. Gernon. Earth and moon impact flux increased at the end of the paleozoic. Science, 363(6424):253–257, 2019.

[13] T. McGetchin, M. Settle, and J. Head. Radial thickness variation in impact crater ejecta: implications for lunar basin deposits. Earth and Planetary Science Letters, 20(2):226–236, 1973.

[14] C. Meyer. Lunar sample compendium. NASA STI/Recon Technical Report N, 6:11039, 12 2004.

[15] J. E. Richardson and O. Abramov. Modeling the formation of the lunar upper megaregolith layer. The Planetary Science Journal, 1(1):2, mar 2020.

[16] S. J. Robbins. A new global database of lunar impact craters ¿1–2 km: 1. crater locations and sizes, comparisons with published databases, and global analysis. Journal of Geophysical Research: Planets, 124(4):871–892, 2019.

[17] G. J. Taylor, R. D. Warner, and K. Keil. Stratigraphy and depositional history of the Apollo 17 drill core. Lunar and Planetary Science Conference Proceedings, 2:1159–1184, Jan. 1979.

[18] Z. Xiao and R. G. Strom. Problems determining relative and absolute ages using the small crater population. Icarus, 220(1):254–267, 2012.

[19] M. Xie, T. Liu, and A. Xu. Ballistic sedimentation of impact crater ejecta: Implications for the provenance of lunar samples and the resurfacing effect of ejecta on the lunar surface. Journal of Geophysical Research: Planets, 125(5):e2019JE006113, 2020. e2019JE006113 2019JE006113.