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LUNAR STRATIGRAPHY AS REVEALED BY CRATER MORPHOLOGY
A CRITICAL REVIEW

Prepared under Contract No. NSR-05-003-189 by
F. E. Heuzé

UNIVERSITY OF CALIFORNIA, BERKELEY

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INDEX

PREFACE

This paper presents the results of one phase of studies conducted during the period March 3, 1967 - February 1, 1968, under NASA research contract NSR-05-003-189, "Materials Studies Related to Lunar Surface Exploration," with the University of California, Berkeley, California.

This research effort is sponsored by the Lunar Exploration Office, NASA Headquarters, and is monitored by the Space Sciences Laboratory, George C. Marshall Space Flight Center.

LUNAR STRATIGRAPHY AS REVEALED BY CRATER MORPHOLOGY

I. INTRODUCTION

1. The stratigraphy of the moon's surface has been under investigation for a number of years and the consensus is that, over the maria, a fragmental layer of fine grained material overlays a hard base composed of one or several layers of possible volcanic origin. However, it is not until very recently (1966) that the first conclusive attempts were made to determine the extent and the thickness of this surficial layer.

Many scientific and engineering justifications can be proposed to such an effort. The selenological history will be uncovered in part through a detailed analysis of lunar formations[11*] and of the erosional processes active on the moon. The bearing of stratigraphy studies on the engineering aspects of lunar exploration has many aspects:

(a) The trafficability of planned traverses depends upon terrain roughness and profile and soil properties but, also, upon the depth of a "soft" surficial layer.

(b) The efficiency and depth of planned borings for sampling or testing purposes can then be optimized in terms of power requirements and adequate drilling tools.

(c) Analysis of foundations settlements for major structures (nuclear plants, observatories, etc.) requires a knowledge of vertical soil/rock profile.

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* Numbers refer to the list of publications appended to this report and summarized in Table I.

(d) Excavations and cut-and-cover operations for foundations and thermal or radiation shielding will also be best achieved through a prior answer to the questions: what kind of material is available? and how much of it can actually be used?

2. Earlier studies[1,2,3] concerned themselves with the morphology of lunar craters in order to determine their origin. A scaling law[1] was proposed relating crater depth (d) and diameter (D):

$$D = 0.025\, d^2 + d + 0.630$$

This relationship was applicable to man made impact craters and to the small lunar craters (D less than a few kilometers). Thus a first evidence of the impact origin of some lunar craters was presented. Large craters on the moon were recognized[2] as not being of impact origin but rather of volcanic origin.

3. Salisbury and Smalley[22] (1963) then reviewed direct and indirect evidence for the nature, origin, and geometry (depth and extent) of the lunar surface materials.

They presented their conclusions as to the nature as follows:

Measurement	Conclusion
Infrared Emission	Low thermal conductivity
Radio Emission	Low thermal conductivity
Radar Reflection	Low density. Surface gradient 1 in 11 on a meter and 10 cm scale
Polarization	Agglomerated powder composed of opaque grains
Photometry	Highly porous, complex and irregular surface. Relief many times the wavelength of light
Albedo and Color	Non-terrestrial reflectivity

The mechanisms cited for producing a fragmental layer were: meteorid impact, micrometeorid infall, radiation, internal seismic shock, volcanism, and thermal fracture. The pulverizing effect of meteorid impacts was retained as being by far the most important of these mechanisms.

Besides considerations of entrapment of meteoridal debris and electrostatic transport, their major conclusions were concerned with roughness and depth of the blanket. The size of blocks ejected from craters, a trafficability constraint, was established from terrestrial analogs to be related to the volume of craters they originated from. Typical block sizes would be 4.5 m around craters 100 m in diameter and 16 m around craters with D = 1 km if no secondary fragmentation occurs. Average depth estimates were obtained for maria and highlands based upon frequency and volume of primary craters. These and other conclusions are presented in Table I.

4. However good these estimates proved to be in the light of later investigations, they could not be used as such for detailed planning of missions at specific sites. With the advent of the first spacecrafts and the availability of higher resolution photographs of the moon (Rangers), further studies[4,5,6,7] were made to estimate the depth of unconsolidated materials resting on a harder base on the lunar surface. They were followed as resolution still improved (Orbiters and Surveyors) by the development of new techniques based upon direct observations[8-10,12-15] or modeling[16,18-21].

II. DETERMINATION OF SURFICIAL LAYER THICKNESS

Four techniques can be recognized among the latest attempts to analyze surficial lunar stratigraphy.

1. Comparative Study of Rangers Photographs - Laboratory Simulation of Overlay Deposition

Observing Ranger VII photographs, Jaffe[4] noted the "soft" appearance of some lunar craters and inferred that this was attributable to an overlay of dust or other granular material deposited after crater formation.

The erosional and depositional processes which affect the relatively small lunar craters are lunar "dusting" and downslope movement. Lunar dusting refers to the process by which fragments produced by primary and secondary impacts rain down onto the lunar surface. If the assumption is made that meteorite impact on the lunar surface takes place in a random manner, then it follows that a lunar dust blanket of uniform thickness would result if the fragments were deposited on an even surface. The term downslope movement can be used to include three different types of erosional processes. One type consists of the slumping of the walls of the crater. Another type of downslope movement occurs when the fragments produced by meteorite impacts elsewhere rain down onto the crater wall and bounce down the slope. A downslope movement associated with this latter type occurs when fragments which hit the crater wall induce the particles composing the wall to also move down the slope[4,21]. If the assumption is made that the slumping process is not important in changing the morphology of small craters, then the lunar dusting process is seen to be the most influential.

To obtain an experimental relation from which to determine the depths of overlay on lunar craters, a number of dusting experiments were performed. They consisted of reproducing in the laboratory three types of craters. Two of them were made by impressing the surfaces of flattened spheres into dry silica sand, and the third was made to be somewhat flat-bottomed with conical sides produced by slumping. The criterion for choosing these particular shapes was that they showed similarity to those appearing on some Ranger VII photographs. Once a crater had been impressed into the sand, it was sprinkled with sand. Measurements of the depth of overlay at a number of places on its surface were made.

Pictures of the experiments were then matched with those taken of lunar craters by Ranger VII, and measurements in the laboratory were scaled up to what hopefully was the depth of the overlaying materials on the lunar surface. Jaffe concluded that at the sites of Ranger VII photographs, the depth of overlay was at least five meters, and possibly much more. The technique was refined and applied to Ranger VII[5] and Ranger VIII and IX[6] photographs giving results consistent with those of the first study.

Objections have been raised[7] against such a procedure; namely the insufficient considerations of crater age, of all possible erosional processes (including impacts), and the apparent dependency of the results on crater diameter for small craters ($D < 30$ m). However, the main shortcoming of the technique remains the fact that only a lower bound of layer thickness is provided. It cannot be assumed that the layer existing prior to impact has significantly different properties than the one depositied after impact. "Upper bound" techniques had then to be developed.

2. Direct Study of Orbiters and Surveyors Photographs - Block Fields, Terraces, and Outcrops

Further improvement of photographic resolution was achieved by the Orbiter spacecrafts missions[8,9,10]. Two direct techniques were then used by the Lunar Orbiter Photo Data Screening Group to analyze the lunar surface stratigraphy.

Wherever well developed annular terraces or prominent layers can be recognized on crater walls, direct measurements of the thickness of each layer can be achieved knowing the slope angle of the walls. This can usually be done for medium size craters (100 to several hundred meters), where the upper part of the walls is not covered by debris. In the presence of smaller craters one might thus look for the presence or absence of boulder fields inside and outside the crater. These boulders are assumed to originate from the hard substratum by fragmentation upon meteoritic impact. Accordingly, for a particular area of the lunar surface, the depth of the smallest crater or craters with blocky rim or floor is assumed to be the thickness of the surficial unconsolidated layer. Indeed, a scarcity of block fields, a subdued crater appearance, and/or the absence of outcrops are indicative of fairly deep fragmental layer. These techniques applied to a variety of sites (see Table I) gave very consistent results.

Successful Surveyors and Lunas missions[12-16] provided the highest resolution photographs. Their interpretation for stratigraphy determination also relied upon observations of block fields, and their results agree with those of Orbiter photograph studies (see Table I).

Besides thickness estimates, these studies resulted in some major conclusions which can be summarized as follows.

> Young or fresh craters[9] will provide most of the needed information.
>
> The impact origin of small and medium size craters is hypothesized from the following observations: lunar crater size-frequency distribution[13] is similar to the one of experimental impact craters, and block size distribution[9] around lunar craters is similar to the one around explosion craters (i.e. Danny Boy).
>
> The fragmental lunar surface layer is very weakly cohesive since the impact craters observed have raised rims which would not exist in a cohesive materials[16]. This obviously corroborates the Surveyors soil experiments and extends their results to greater depths. However, the cohesion is thought to increase somewhat with depth[9].

It is to be mentioned that a drainage origin into subsurface fissures has also been proposed for a few small craters[14,15].

The technique presented here appears the most reliable for it does not involve any correlation or scaling. However, impact cratering experiments (Gault, Quaide, and Oberbeck 1966,1967) have suggested still another method of analysis whose application was attempted on a large scale.

3. Comparative Study of Orbiter Photographs - Impact Crater Morphology

a. The Technique

Quaide and Oberbeck[18] presented the basis for their studies as follows. "In laboratory cratering studies inspired by the Ranger photographs, Gault, et al., 1966, observed that impacts against targets of fragmental materials overlying a rock substrate could produce craters with a peculiar concentric or terraced structure. They found that craters with normal spherical segment or conical geometry developed when the fragmental materials were of such thickness that the rock substrate did not interfere with crater growth. Examination of Orbiter I photographs revealed that numerous craters with concentric geometry are present on the lunar surface, and that they might be used to estimate the thickness of the fragmental surface layer. Careful study of selected photographs revealed further that all fresh craters with diameters less than a few hundred meters can be structurally classified and that the crater structure is size dependent. This prompted an investigation of the conditions of formation of all crater structures arising through impact against a target consisting of fragmental materials resting on a cohesive substrate. These studies show that all the morphologic classes recognized can be produced by impact if the thickness of a fragmental surface layer resting on a cohesive substrate is varied."

The application of this procedure was restricted to craters with a diameter $D < 500$ m giving the stratigraphy to a depth of about 50 m. In view of the possible engineering applications mentioned above, this is a satisfactory depth limit. The study was also restricted to "fresh" craters defined as those with sharp appearance if $D < 70$ m or those surrounded by light rays or halos if $D > 70$ m for Orbiter I medium resolution photographs. This boundary will change if the photographic resolution changes.

Three[18], then four[20], morphologic classes were thus recognized to which an R value bracket was assigned for impact tests with R being defined as

$$R = D_A/t \quad \text{or} \quad D/t$$

where

D or D_A = apparent crater diameter (rim to rim)

t = surficial layer thickness

The four classes can be approximately presented here as*

normal craters : $R < 4$

flat bottom craters : $4 < R < 7.5$

central mound craters : $4 < R < 7.5$ (maximum mound height fro $R \simeq 6$)

concentric craters : $R > 7.5$

Identifying the crater type and measuring D, one can thus compute t. Latest refinements in the correlation[20] include the effect of such variables as impact velocity, angle of impact, projectile properties, angle of repose of surficial debris, strength of substrate, and gravity. The substrate strength has a non neglible effect on R. A new parameter D_F/D_A (where D_F = diameter of the floor of the surficial crater in flat bottom and concentric craters) is also introduced and found to be subject to boundaries for each crater class. Application of this technique to selected Orbiter photographed sites givesresults very similar to those obtained by the Orbiter Screening Group (see Table 1).

Other major conclusions of these studies can be summarized as follows.

> A new weight of evidence has been produced in favor of the impact origin of small lunar craters.
>
> The surficial layer is a slightly cohesive fine grained aggregate with in situ angle of repose from 33 to 35°.

---

*See Ref. 18 and 20 for detailed presentation of R boundaries.

Some past volcanic activity is exhibited under the form of terrace levels of flow layers.

Rock, not permafrost, is exposed on terraces in crater walls.

b . Objections to the Validity of the Technique

Whatever good agreement with other determinations was obtained by this method, it has been found inapplicable by some investigators. Moore[10] (Orbiter V-8 site) states, "Attempts to calculate the thickness of the soil-like layer using the method and data of Oberbeck and Quaide(18) (1967) indicate that the computed thickness is unfortunately a function of crater diameter and not any given thickness of a soil-like layer". Harbour[19] (Orbiter III P-12 site) also comments, "Using moderate resolution photographs Quaide and Oberbeck (1967) estimated the thickness of the regolith in this area as 5 to 15 meters by noting the morphology of fresh craters less than 40 m in diameter. However craters much smaller than those they observed possess the same morphologic features.... . The variety of morphology of fresh craters in this area and the variety in size of craters of similar morphology indicates the size and morphology relationships cannot be applied in any simple way to determine depth of the lunar regolith."

Five conclusions concerning the relationship between crater morphology and size are then possible according to Harbour.

1. Multiple layers may occur in the area and may affect the morphology of craters bottoming near their upper boundary.
2. Crater morphology may be governed more by velocity and density of the projectile than by layering of the target material.
3. The thickness of the regolith may vary within short distances.
4. Cohesion of mare material may vary within short lateral distances.
5. The regolith varies both in thickness and properties.

c. Discussion

Latest studies by Quaide and Oberbeck[20] (1968) seem to exclude alternative 2, the effects of projectile properties having been analyzed and found to be minimal. Alternative 1 would apply to the layers of consolidated igneous rocks deposited upon successive volcanic floodings. The minimum depth of rubble/soil cover above them is an average 10 meters. Alternatives 3, 4, and 5 can apply to this layer. At a given site, the erosion-deposition processes due to impact will give it a complex structure[22] owing to the wide variation in the size of craters formed through the ages and the intricate overlapping of their ejecta. Each crater, however small, might then reflect this non homogeneity and increase in bearing capacity which is known to start at the very surface of the blanket (Surveyor experiments[12, 13, 14]).

4. Use of a Mathematical Model (Time-Dependent Lunar Crater Rim-Erosion and Floor-Deposition)

Meteoritic bombardment being taken as the primary source of erosion on the lunar surface, a simplified mathematical model for time dependent erosion of lunar craters was presented by Ross[21]. The model takes into consideration the angular distribution of impacting meteorites and ejecta and the topography and mechanical properties of the lunar surface. Calculations indicate that craters 1, 10 ($D/d = 3$) and 100 ($D/d = 5$) meters in diameter disappear almost completely after 10^7, 10^8, and 10^9 years, respectively. Mass movement of eroded material is thought to accompany the meteoritic erosion process and probably result in an erosion rate 50 to 100 times greater than erosion due to ejection without downslope movement. This is believed to be a continuous process and no mention is made of large slope failures or slumps having been identified by the author.

Assuming the maria are at least 2×10^9 years old, it is inferred that several generations of impact craters of the order of 10 m in diameter have been effectively removed as topographic features since formation of the maria. This process would have produced a depositional overlay at least 2 or 3 meters thick. The total depth of rubble and unconsolidated material is thought by Ross to be somewhat greater and to vary considerably.

Discussion

Here, as in Jaffe's work, the question arises, from an engineering standpoint, of the usefulness of determining the thickness of an "overlay" when the total depth of unconsolidated material remains unknown. It is not clearly stated either what the significant differences might be in the engineering properties of these two constituents of the lunar surface or how sharply one could or should draw a boundary between them.

III. CONCLUSION - FURTHER RESEARCH

Altogether, studies based upon visual observation of lunar craters, comparison with experimental results, or analytical models have appreciably narrowed the range of conclusions regarding the lunar surface stratigraphy. Most of the maria's surface is believed to be overlain by a layer of fine grained, cohesionless to weakly cohesive fragmented rock whose thickness varies from a few meters to a few tens of meters, the average being 10 meters. Compressibility decreases and average grain size increases from the surface down. Rubble is probably present. Still, this fragmental blanket can be excavated and handled without the use of explosives except in the vicinity of large craters where large size blocks, several cubic meters, would be buried. Further research is needed to determine if excavation and backfilling of this material of limited thickness would provide adequate meteorite and radiation shielding of structures. Drilling and construction planning based upon the above conclusions must consider the

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*For the reader's convenience, salient conclusions of each reviewed work are summarized in Table I.

stability problem; uncased boreholes are unlikely to be stable and medium-height slopes might have to be rather flat to stand up (embankments, excavation walls, etc.). Additional research is therefore also suggested in the field of slope stability of the lunar surface blanket. Beneath it, non-fragmented rock layers are thought to exist as a result of successive lava floodings. As mentioned by Watkins and Whitcomb[23], "Near surface lunar rocks may be shattered and broken as a result of stresses created during formation of large craters". This will have bearing upon underground storage projects or sealing off of underground cavities for dwelling purposes in the event the blanket is too thin to provide adequate shielding.

Previous discussion of techniques applied to lunar stratigraphy determination leads to the conclusion that for final mission planning, at a given site, extensive high resolution photographic coverage is mandatory, and the interpretation should rely upon visual observation[8,9,10] with the other procedures still being too open to discussion. However, if the required resoltuion for using this technique is not achieved and if only the gross morphology of craters can be recognized, the method developed by Quaide and Oberbeck[18,20] can then be used for a first estimate.

ACKNOWLEDGEMENT

The assistance of J. J. Roggeveen is acknowledged for preliminary investigations on this report.

TABLE I

STUDIES OF LUNAR CRATERS MORPHOLOGY AND LUNAR SURFACE STRATIGRAPHY.

REF.	TECHNIQUE	LOCATION ON MOON	CRATER D RANGE (m)	ORIGIN OF CRATER	DEPTH OF SURFICIAL LAYER (m)	REMARKS
1	COMPARE D/d FOR LUNAR AND MAN MADE CRATERS	--- (TELESCOPIC OBSERVATIONS)	UP TO 30 KM	METEORITIC IMPACT	---	SCALING LAW OBTAINED: $D = 0.025\, d^2 + d + 0.630$
2 AND COMMENT	STUDY OF D/d FOR LUNAR CRATERS	--- (TELESCOPIC OBSERVATIONS)	> 1 MILE (1.6 KM)	---	---	WHEN D $\nearrow$, d/D $\searrow$ SHARPLY FOR EXPLOSION-IMPACT CRATERS. NOT TRUE FOR LARGE D'S. THUS THEY ARE NOT OF EXPLOSIVE IMPACT ORIGIN.
3	COMPARE D/d FOR MOON AND EARTH METEORITIC CRATERS	--- (RANGER VII PHOTOGRAPHS)	26 FEET (8 M) TO 26 MILES (40KM)	METEORITIC IMPACT	---	SCALING LAW OF REF. (1) CHECKED. APPLIED TO EARTH-METEORITIC AND MOON CRATERS. THUS THOSE MOON CRATERS STUDIED ARE OF IMPACT ORIGIN.
4	COMPARE MOON CRATERS WITH LABORATORY ONES WITH SAND OVERLAY	MARE COGNITUM (RANGER VII PHOTOGRAPHS)	3 M TO 13 KM	METEORITIC IMPACT	> 5 M (OVERLAY)	R = D/d VARIES FROM 20 TO 80 FOR D = 5 TO 600 M IN LUNAR CRATERS. THICKNESS OF COHESIONLESS OVERLAY IS ONLY A SMALL PART OF t OF SURFICIAL LAYER.
5	IBID	IBID	IBID	IBID	IBID	REFINED TECHNIQUE OF LABORATORY SIMULATION. AGAIN, t ESTIMATED FOR OVERLAY SPRINKLED OVER TERRAIN AFTER CRATER FORMATION.
6	IBID	MARE TRANQUIL. ALPHONSUS HIGHLANDS (RANGER VIII/IX PHOTOGRAPHS)	< 30 M > 75 M	METEORITIC IMPACT	4 M TO 40 M (AVERAGE 16 M) 20 TO SEVERAL TENS OF METERS	DEPTH OF OVERLAY FOR LOW COHESION SOILS 3 TO 10 TIMES GREATER THAN FOR COHESIONLESS OVERLAY. THREE GROUPS OF LABORATORY OVERLAY USED. GROUPS 2 AND 3 CORRESPOND TO COHESION OF SURVEYOR I LANDING SITE. ($\sim 10^4$ DYNES/CM^2 OR 0.15 PSI)
7 COMMENT AND REPLY	COMPARE ACTIVE EROSION PROCESSES (IMPACT) WITH PASSIVE ONES (JAFFE'S EXPERIMENT)	---	---	IMPACT ?	---	NO AGES MENTIONED IN JAFFE'S STUDIES. EROSION PROCESSES MUST BE FURTHER STUDIED. OVERLAY THICKNESS SEEMS TO BE DIAMETER DEPENDENT FOR D < 30 TO 50 M.

TABLE I CONT.

REF.	TECHNIQUE	LOCATION ON MOON	CRATER D RANGE (m)	ORIGIN OF CRATER	DEPTH OF SURFICIAL LAYER (m)	REMARKS
8	PRESENCE OR ABSENCE OF BLOCKY FIELDS AROUND CRATERS OR ON CRATER FLOOR. ALSO OBSERVATION OF EXPOSED LAYER BASE ON CRATER WALLS.	ORBITER II SITES P-2 * P-3,5 P-6 * P-7 P-9,11 MARIA	100 M > 1000 M > 175 M > 100 M > 400 M 10 TO 500 M	---	--- --- 10 M 15 TO 20 M 10 M ---	RATING OF SITES IN TERMS OF RELATIVE ROUGHNESS. LOOSELY COHESIVE SURFICIAL LAYER. CRATER SIZE-FREQUENCY IS NOT SOPHISTICATED ENOUGH A MEASURE OF TERRAIN ROUGHNESS.
9	STILL LOOK FOR: BLOCK FIELDS IN AND OUTSIDE CRATERS. WELL DEVELOPED ANNULAR TERRACES OR PROMINENT NARROW TERRACES ON CRATER WALLS.	ORIBITER III SITES P-1 P-2 P-5 P-7 P-9 P-11 * P-12	< 70 M > 200 M < 400 M > 800 M --- > 100 M --- --- ---	METEORITIC IMPACT •	> 10 M --- --- --- > 10 M 20 M 7 TO 10 M 8 TO 10 M 5 M	ALWAYS LOOK AT FRESHEST CRATERS. COHESION OF SURFICIAL LAYER INCREASES WITH DEPTH. BLOCK SIZE DISTRIBUTION AROUND CRATERS SIMILAR TO THE ONE OF DANNY BOY CRATER. THUS IMPACT ORIGIN HYPOTHESIZED.
10	PRESENCE OR ABSENCE OF BLOCK FIELDS. DEPTH OF ROCK OUTCROP ON CRATER WALLS. PRESENCE OF <u>BOULDER</u> TRACKS.	ORIBITER V SITES V-8 * V-10 V-13 V-16 V-24 V-28	30 TO 300 M --- --- --- --- ---	METEORITIC IMPACT AND POST-IMPACT VOLCANISM	> 1/2, 1 M VERY THICK > 10 M > 10 M FAIRLY DEEP 100 M	"COMPUTED THICKNESS BY QUAIDE AND OBERBECK METHOD (1967) IS UNFORTUNATELY A FUNCTION OF CRATER DIAMETER AND NOT ANY GIVEN THICKNESS OF A SOIL-LIKE LAYER" (QUOTE) <u>MINIMUM</u> DEPTH CAN BE DERIVED FROM BOULDER TRACKS. SCARCITY OF BLOCK FIELDS, SUBDUED CRATER APPEARANCE, AND ABSENCE OF OUTCROPS ARE INDICATIVE OF FAIRLY DEEP FRAGMENTAL LAYER.

TABLE I CONT.

REF.	TECHNIQUE	LOCATION ON MOON	CRATER D RANGE (m)	ORIGIN OF CRATER	DEPTH OF SURFICIAL LAYER (m)	REMARKS
11	ALBEDO OF MOON'S SURFACE. GROSS FEATURE ANALYSIS.	EARTH SIDE (TELESCOPIC OBSERVATIONS)	LARGE	IMPACT AND VOLCANISM	---	GROSS STRATIGRAPHY OF MOON'S EARTH SIDE INFERRED FROM TELESCOPIC OBSERVATIONS. CLASSIFICATION OF MATERIALS AND RELATIVE AGE DETERMINATION.
12	PRESENCE OR ABSENCE OF BLOCKS ON CRATER RIM.	SURVEYOR I LANDING SITE	0.7 TO 80 M	METEORITIC IMPACT	1 M	THE DEPTH OF THE SMALLEST CRATERS WITH BLOCKY RIMS IS ASSUMED TO BE THE THICKNESS OF THE SURFICIAL LAYER. NEED HIGH RESOLUTION PHOTOGRAPHS. HAVE TO ASSUME D/d RATIO (D ONLY MEASURED); I.E. D/d = 1/3 TO 1/4 FOR FRESH CRATERS.
13	IBID (BLOCKY RIMS)	SURVEYOR III LANDING SITE	SEVERAL METERS	METEORITIC IMPACT	> 1 M SEVERAL TENS OF METERS AT CENTER	IMPACT ORIGIN HYPOTHESIZED FROM CRATER SIZE-FREQUENCY DISTRIBUTION RESULTS. THE FLOOR SURFACE IN BROAD CRATERS LOOKS SIMILAR TO THE ONE IN BETWEEN CRATERS. (OVERLAY DEPOSITED AFTER CRATER FORMATION, EJECTA, AND FALL-BACK.)
14	IBID (BLOCKY RIMS)	SURVEYOR V LANDING SITE	---	IMPACT AND DRAINAGE	< 5 M	DRAINAGE ORIGIN OF SOME CRATERS INFERRED FROM THEIR ALIGNMENT AND ASSOCIATION.
15	IBID (BLOCKY RIMS)	IBID	---	IBID	A FEW METERS (TYPICALLY 3M)	RATIO D/d ASSUMED TO BE IN BETWEEN 1/3 AND 1/4.
16	COMPARE LABORATORY IMPACT CRATERS AND MOON CRATERS.	LUNA 9 LANDING SITE	10 TO 100 CM (LABORATORY - UP TO 50 CM)	METEORITIC IMPACT	> 20 CM (CRATER DEPTH) MUCH DEEPER IN FACT	IMPACT CRATERS HAVE DISTINCT, WELL DEFINED RAISED RIMS WHEN IN NON COHESIVE OR WEAKLY COHESIVE SOIL. COHESIVENESS PREVENTS RAISED RIMS IN SMALL CRATERS. AGE ALSO MATTERS: YOUNG CRATERS ONLY SHOULD BE STUDIED (HAVE WELL DEFINED RIMS).
17		LUNA 13 LANDING SITE	---	METEORITIC IMPACT		NO "DUST LAYER ON THE MOON(?). UPPERMOST 20 TO 30 CM HAVE EARTH-SOIL LIKE PROPERTIES.

TABLE I CONT.

REF.	TECHNIQUE	LOCATION ON MOON	CRATER D RANGE (m)	ORIGIN OF CRATER	DEPTH OF SURFICIAL	REMARKS
18	CRATER MORPHOLOGY EXPERIMENTALLY RELATED TO THICKNESS t OF LAYER OVER HARD BASE (IMPACT TESTS). RESULTS APPLIED TO LUNAR CRATERS IN TERMS OF R = D/t.	(ORBITER I PHOTOGRAPHS) OCEANUS PROCELLARUM SURVEYOR I LANDING SITE	40 TO 250 M (EMPHASIS ON 70 TO 250 M)	METEORITIC IMPACT OR VOLCANISM	5 TO 15 M (85% OF SITE) AVERAGE IS 8 TO 9 M	EMPHASIS AS MUCH ON ORIGIN AS ON MORPHOLOGY OF LUNAR CRATERS. CRATERS STUDIED ARE SMALL ONES AND FRESH ONES ONLY. FOUR MORPHOLOGIC TYPES RECOGNIZED: NORMAL, FLAT-BOTTOM WITH OR WITHOUT CENTRAL MOUND, AND CONCENTRIC. EACH TYPE HAS ITS RANGE OF R = D/t. CONCENTRIC ONES GIVE BEST ESTIMATE OF THICKNESS t OF SURFICIAL LAYER. ROCK NOT PERMAFROST IS EXPOSED ON TERRACES IN CRATER WALLS. HIGHLAND STUDIES ARE INCONCLUSIVE.
19	STUDY OF CRATER MORPHOLOGY BY QUAIDE AND OBERBECK TECHNIQUE.	ORBITER III AND IV PHOTOGRAPHS III 12*-1	FEW METERS TO SEVERAL 100'S M	IMPACT	2 TO 8 M	EVEN VERY SMALL CRATERS POSSESS MORPHOLOGIC FEATURES IDENTIFIED BY QUAIDE AND OBERBECK. THUS UNCERTAINTY ON VALIDITY OF THE TECHNIQUE. POSSIBILITY OF EXISTENCE OF MULTIPLE LAYERS OR THICKNESS AND PROPERTIES OF LAYER MAY VARY WITHIN SHORT DISTANCES (?).
20	IBID A NEW PARAMETER IS INTRODUCED D_F/D_A	ORBITER II AND III SITES II P-13 II P-7 III P-12	< FEW 100'S M < FEW 10'S M (NORMAL) 10'S TO 100'S M (CONCENTRIC)	METEORITIC IMPACT AND VOLCANIC CONTRIBUTION (INTERBEDS)	2.5 TO 5.5 M 6.0 TO 9.0 M 3.5 TO 5.5 M	D_F/D_A AS WELL AS D_A/t USED FOR THICKNESS DETERMINATION. SURFICIAL LAYER IS A SLIGHTLY COHESIVE, FINE-GRAINED AGGREGATE. IN-SITU ANGLE OF REPOSE ≃33 - 35°. (SIMILITUDE WITH 31° FINE QUARTZ SAND). REFINED TECHNIQUE INVESTIGATE EFFECTS OF VELOCITY, ANGLE OF IMPACT, PROJECTILE PROPERTIES, ANGLE OF REPOSE, STRENGTH OF SUBSTRATE AND GRAVITY. EVIDENCE OF VOLCANIC CONTRIBUTION UNDER THE FORM OF TERRACE LEVELS OF FLOW LAYERS.

TABLE I CONT.

REF.	TECHNIQUE	LOCATION ON MOON	CRATER D RANGE (m)	ORIGIN OF CRATER	DEPTH OF SURFICIAL LAYER (m)	REMARKS
21	MATHEMATICAL MODEL FOR LUNAR CRATERS TIME-DEPENDENT RIM-EROSION AND FLOOR-DEPOSITION.	MARIA (RANGERS, ORBITERS, SURVEYORS PHOTOGRAPHS)	1, 10, 50 M WITH D/d = 3	IMPACT	2 TO 3 M FOR OVERLAY	AGENTS OF EROSION SUGGESTED: FOR SMALL CRATERS - SMALL METEORITES; FOR LARGE CRATERS (D > 1 KM) - VOLCANISM, ISOSTRATIC COMPENSATION, LARGE METEORITES. MARIA FORMED AND ERODED FOR 10^9 YEARS. DENSITY OF SURFACE MATERIALS TAKEN AS 1 OR 1.5 G/CM^3.
			50, 100, 1000 M WITH D/d = 5	IMPACT OR VOLCANISM	> 10 M OVERLAY + RUBBLE	
			> 1 KM	IBID	> 10 M	
22	FREQUENCY AND VOLUME OF PRIMARY CRATERS	(TELESCOPIC OBSERVATIONS)		METEORID IMPACT	AVERAGES FOR RUBBLE	SURFACE LAYER COMPOSED PRIMARILY OF RUBBLE MANTLED WITH HIGHLY POROUS WEAKLY COHESIVE "DUST". DEPTH OF RUBBLE INCREASES ABRUPTLY AROUND CRATERS: IS MUCH SMALLER IN BETWEEN THEM. RUBBLE INCLUDES BLOCKS WHOSE HIGHLY VARIABLE SIZE IS RELATED TO THE VOLUME OF THE CRATERS THEY COME FROM. ABOVE RUBBLE, A STEADY-STATE THIN EQUILIBRIUM LAYER OF "DUST" IS ACHIEVED ON LEVEL GROUND. DEPTH OF RUBBLE MUCH GREATER IN HIGHLANDS "SHADOW AREAS" THAN IN MARIAS DUE TO HIGHER CRATER FREQUENCY.
		MARIA	100 M		15 M	
		MARIA (INTERCRATERS)	---		< 1 M	
		SOUTHERN HIGHLANDS	1.6 KM		83 M	
		SOUTHERN HIGHLANDS (INTERCRATERS)	---		14 M	
		APENNINE MOUNTAINS	---		1000 M	

SYMBOLS

d	DEPTH OF CRATER
D OR D_A	APPARENT DIAMETER OF CRATER (RIM TO RIM)
D_F	FLOOR DIAMETER OF FLAT-BOTTOM AND CONCENTRIC CRATERS
t	SURFICIAL LAYER THICKNESS
R	= D/d
*	INDICATES CANDIDATE APOLLO SITES

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