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APPLIED SCIENCES RESEARCH AND UTILIZATION OF LUNAR RESOURCES

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Edited by

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Proceedings of the
Fourth Lunar International
Laboratory (LIL) Symposium

APPLIED SCIENCES RESEARCH AND UTILIZATION OF LUNAR RESOURCES

PREFACE

THE Fourth Lunar International Laboratory (LIL) Symposium was organized for the International Academy of Astronautics by its Lunar International Laboratory (LIL) Committee. The Committee was established, upon the initiative of the Editor, to study the technical problems related to the construction of a manned research center on the Moon and to consider the fields in which research should initially be undertaken.

The LIL Committee at the time of the organization of the Fourth LIL Symposium consisted of the following members of the Academy: Dr. C. A. Berry (U.S.A.); Prof. N. Boneff (Bulgaria); A. C. Clarke, Esq. (U.K.); Prof. A. Dollfus (France); Prof. M. Florkin (Belgium); Prof. K. Ya. Kondratyev (U.S.S.R.); Prof. Z. Kopal (U.K.); Prof. Sir Bernard Lovell (U.K.) (*Vice-Chairman*); Prof. L. Malavard (France); Dr. F. J. Malina (U.S.A.) (*Chairman*); Prof. H. Oberth (Ger. Fed. Rep.); Dr. W. H. Pickering (U.S.A.); Prof. L. I. Sedov (U.S.S.R.); Dr. S. F. Singer (U.S.A.); Dr. H. Strughold (U.S.A.); Prof. H. C. Urey (U.S.A.); and Prof. F. Zwicky (Switzerland).

The First LIL Symposium, held at Athens in 1965, was devoted to research in the fields of the geosciences and astronomy. The proceedings were published in 1966 by Springer-Verlag, Vienna.

The Second LIL Symposium, held at Madrid in 1966, dealt with life sciences research and lunar medicine. The proceedings were published by Pergamon Press, Ltd., Oxford, in 1967.

The Third LIL Symposium, held at Belgrade in 1967, was concerned with research in physics and chemistry. The proceedings were published by Pergamon Press, Ltd., Oxford, in 1969.

The papers dealing with applied sciences research and utilization of lunar resources that were presented at the Fourth LIL Symposium are contained in this volume. The Symposium was held on 17 October 1968 during the XIXth International Astronautical Congress at New York.

The two half-day sessions of the Symposium were chaired respectively by Mr. P. A. E. Stewart of Rolls-Royce, Ltd., Bristol, and Prof. E. M. Knoernschild of D.V.L., Stuttgart. The discussions that took place during the Symposium have not been included in the Proceedings in order to speed up publication. The LIL Committee wishes me to express its appreciation especially to the authors who prepared papers for the meeting.

At the session of the Board of Trustees of the Academy in New York, it was decided to broaden the scope of the LIL Committee by transforming it into the Manned Research on Celestial Bodies (MARECEBO) Committee. The new Committee, under my chairmanship, while continuing efforts to promote the creation of a Lunar International Laboratory, will also begin to give consideration to the possibilities and advantages of carrying out research in manned centers on planets, such as Mars. During the XXth International Astronautical Congress at Mar del Plata in October 1969 the MARECEBO Committee plans to hold a Second LIL Discussion Panel to review work on the project since 1960 and to consider further steps that might be taken to advance the creation of an international manned research center on the Moon.

On behalf of the LIL Committee and the contributors to the Fourth LIL Symposium, I thank Dr. C. S. Draper, President of the Academy, and the Secretariat of the Academy for their aid in organizing the Symposium; the International Astronautical Federation and the American Institute of Aeronautics and Astronautics for making it possible for the Symposium to be held at New York; and the publisher, Pergamon Press, Ltd., Oxford, for friendly cooperation in publishing the Proceedings.

Boulogne sur Seine, France FRANK J. MALINA

CONTENTS

REVIEW OF RECENT RESULTS FOR THE LUNAR SURFACE

A. A. Loomis*

Abstract—Résumé—Резюме

The lunar surface can be divided into at least nine different terrain types. These have different combinations of albedo, small-scale roughness, local and regional relief, young-crater densities and therefore apparent relative ages.

Surveyor pictures show that the surfaces of the maria are extensive rubble sheets. The particulate materials are of variable and uncertain thickness but over large areas may be of the order of 10 meters. Underlying the surface rubble, apparently, is rock of basaltic composition. This rock is chemically similar to common Earth basalts but also may correspond to at least one class of the high-calcium achondritic meteorites. *Surveyor* alpha-scattering data for the highlands show a close similarity to the maria for most elements except the iron group. The reason for the higher albedo of the highlands than the maria may be due to either finer mean particle size or compositional differences. The existence of solid rock closely underlying the highland surface is unproven.

The particle-size distribution of the surficial debris in the maria is uncertain because most particles are below the limit of resolution of the *Surveyor* cameras—about ½ mm for areas directly under the spacecraft. The uppermost surface has a higher albedo than the underlying material; the reason for this is not clear. The bearing strength of the upper few centimeters was found to be about 3×10^5 dynes/cm^2 at all *Surveyor* landing sites, allowing for small sinkage. Cohesion is slight.

Very few slopes on the Moon are as steep as the angle of repose of particulate materials of over 30 degrees. Many large slopes are about 13–16 degrees and have a crenulated appearance. Some long slopes have partially buried craters at their feet. They steepen slightly at the base and appear to be or to have been actively moving downward.

Résumé des Resultats Récents Concernant la Surface de la Lune. La surface de la Lune peut être divisée en neuf types de terrain différents au moins. Ceux-ci présentent différentes combinaisons d'albedo, de rugosité à petite échelle, de relief local et régional, de densités en cratères jeunes et donc d'âges relatifs apparents.

Les images fournies par *Surveyor* montrent que les surfaces des mers sont des couches étendues de moellons. Les matériaux particulaires ont une épaisseur variable et incertaine, mais qui sur de larges surfaces peut être de l'ordre de 10 mètres. Sous les moellons des surfaces il y aurait une roche de composition basaltique. Cette roche est chimiquement semblable aux basaltes communs de la Terre, mais peut aussi correspondre à au moins une classe des météorites achondritiques à haute teneur en calcium. Les donneés de diffraction alpha fournies par *Surveyor* pour les montagnes présentent une ressemblance étroite avec les mers pour la plupart des éléments sauf le groupe du fer. La raison pour laquelle l'albedo des montagnes est plus élevé que celui des mers peut être, soit une taille moyenne des particules plus faible, soit des différences de composition. L'existence de roche solide juste au-dessous de la surface des montagnes n'est pas prouvée.

La distribution de taille des particules des débris superficiels dans les mers est incertaine parce que la plus grande partie des particules sont inférieures à la limite de résolution des caméras de *Surveyor*—soit environ ½ mm pour des surfaces situées directement sous le véhicule. La surface supérieure a un albedo plus élevé que le matériau qui se trouve au-dessous; la raison n'en est pas claire. On a trouvé que la force portante des quelques centimètres supérieurs était d'environ 3×10^5 dynes/cm^2 à tous les points d'atterrissage de *Surveyor*, compte tenu d'un petit enfoncement. La cohésion est faible.

Très peu de pentes sur la Lune sont aussi escarpées que l'angle d'éboulement des matériaux

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particulaires de plus de 30 degrés. Beaucoup de grandes pentes ont de 13 à 16 degrés et ont un aspect crénelé. Certaines des longues pentes ont à leurs pieds des cratères partiellement enterrés. Elles deviennent légèrement plus escarpées à la base et semblent se déplacer ou s'être déplacées activement vers le bas.

Обзор последних результатов изучения лунной поверхности. Лунная поверхность может быть подразделена по крайней мере на девять различных типов. Они характеризуются различными сочетаниями альбедо, мелких неровностей и шероховатостей, местного и регионального рельефа, плотности молодых кратеров и по-видимому имеют различный возраст.

Снимки, полученные с *Сервейера*, показывают, что поверхности «морей» представляют собой обширные пласты обломочных россыпей. Толщина слоя этих россыпей различна и неопределенна, но на обширных площадях может достигать 10 *м*. Под поверхностным обломочным слоем по-видимому лежит базальтовая порода. По своему химическому составу эта порода сходна с обычным земным базальтом, однако она также может соответствовать по крайней мере одному классу ахондритических метеоритов с высоким содержанием кальция. Обследование с *Сервейера* возвышенностей с помощью альфа-лучей показало близкое сходство с «морями» в отношении всех элементов, кроме группы железа. Причина более высокого альбедо возвышенностей по сравнению с «морями» может заключаться либо в более мелком среднем размере обломков, либо различиями в составе. Наличие твердой породы непосредственно под поверхностью возвышенностей не доказано.

Распределение частиц поверхностных обломков в «морях» по размеру неясно, поскольку большинство частиц выходит за пределы разрешающей способности камер *Сервейера* — около $\frac{1}{2}$ *мм* для участков, расположенных непосредственно под космическим кораблем. Самый верхний слой имеет более высокое альбедо, чем материал основания: причина этого неясна. Было обнаружено, что выдерживающая способность нескольких верхних сантиметров составляет примерно 3×10^5 *ди/см*^{2} на всех посадочных площадках *Сервейера* с учетом небольшого оседания. Сила сцепления невелика.

Очень немногие склоны на Луне имеют крутизну, равную углу естественного откоса обломочных материалов, превышающему 30 градусов. Многие обширные склоны имеют наклон 13—16 градусов и имеют неровную поверхность. У подножья некоторых длинных склонов расположены частично засыпанные кратеры. Они слегка круче у основания, и кажется, что они перемещались в прошлом или перемещаются сейчас вниз.

I. TERRAIN CHARACTER

Prior to the *Ranger* project, there was considerable speculation regarding the surface of the Moon with respect to both engineering properties and scientific hypotheses of origin of various terrain features. Now, after the *Ranger*, *Surveyor* and *Lunar Orbiter* projects, a considerable number of these uncertainties have been resolved and several new questions have been raised. This review presents scientific and engineering data acquired during the last few years and discusses the implications these data have on both engineering and scientific aspects of future missions.

Figure 1 is a map of the front side of the Moon showing the landing sites of the several *Surveyors*, which will be discussed separately. *Surveyors* 1, 3, 5, and 6 landed in broad, flat, mare areas. *Surveyors* 1 and 3 were both in Oceanus Procellarum. Both were near the equator of the Moon and both were in areas selected to be as little disturbed by secondary impacts from Copernicus as possible. *Surveyor* 5 landed in an old rayed area of Mare Tranquillitatis. *Surveyor* 6 landed in Sinus Medii and *Surveyor* 7 landed somewhat north of the crater Tycho in the highlands.

Figure 2 shows characteristic dark mare terrain from the *Surveyor* 1 spacecraft. The horizon should be horizontal; it is inclined because of the geometry of the camera and mirror system on the spacecraft. On a scale of meters, the surface is

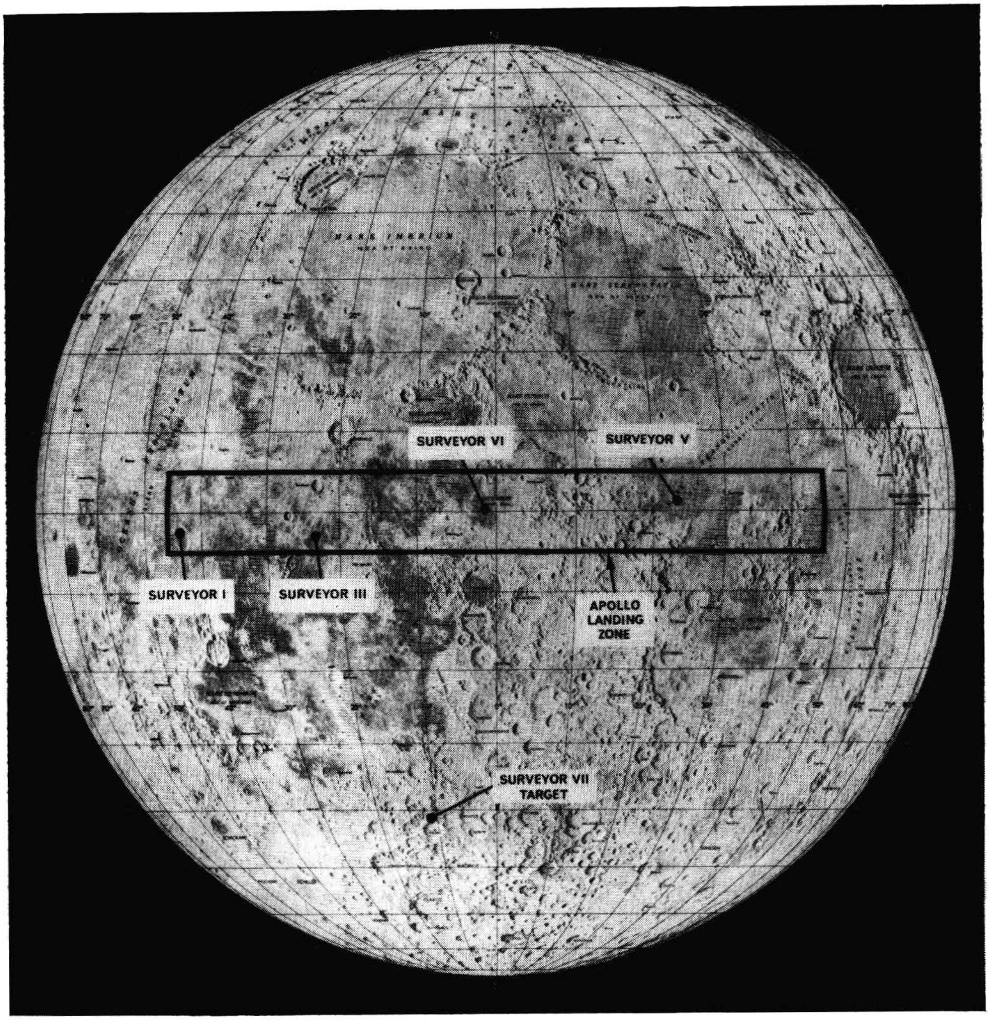

FIG. 1. *Surveyor* landing locations.

gently rolling with sharper, newer craters distributed about here and there in a seemingly very random manner. A good example is the small crater in the left central part of the photograph which is about 10 meters in diameter and 3 meters deep. Apparently this small crater has not penetrated to solid bedrock that might underlie the fragmental rubble we see at the surface because no concentration of larger rock fragments exists immediately surrounding the crater rim. The rock in the near foreground is characteristic of many of the rocks seen near the *Surveyor* 1 site, in that it does not appear to be freshly broken and angular. Rather, it appears rounded and weathered or eroded by some mechanism. The mare surface here, then, is a laterally extensive rubble sheet at least several meters thick, containing within it fragments from a size smaller than the resolution of the television camera (that is, much less than a millimeter) to fragments larger than a meter.

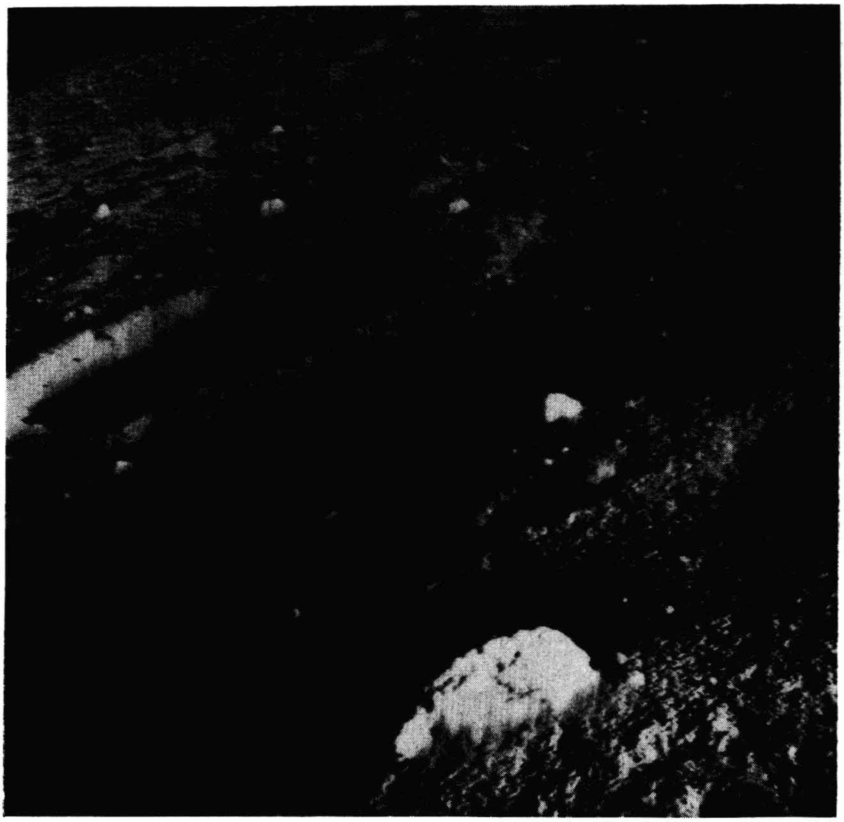

FIG. 2. Mare rubble terrain near *Surveyor* 1.

Figure 3 is another view from *Surveyor* 1. The concentration of rocks lies along the near rim of a 170-meter crater, which is probably about 30 meters deep. This crater evidently did penetrate solid bedrock and much of this rock lies distributed about the rim in the blocks we can see. The larger blocks are 1 to 2 meters across. Note that these blocks also are rounded and somewhat soft in appearance, relative to what one would expect of freshly broken, hard, crystalline rock.

Figure 4 is a mosaic of the skyline a few hundred meters from *Surveyor* 1, in which a fresh, relatively young crater has been excavated on the rim of a yet older, larger crater. The young crater has as its rim deposit a very blocky rubble. Of all the areas near the *Surveyor* 1 landing site, this rubble would be that most likely to impede the progress of a manned or unmanned vehicle attempting to traverse the area. This crater is about 70 meters across and probably about 15 or 20 meters deep.

Figure 5 is a histogram of slope distributions calculated for flat mare areas such as that in which *Surveyor* 1 landed from data compiled by photoclinometry of *Ranger* 7 photographs. These slopes are on a 4-meter base line; that is, they are the slopes which would be encountered statistically by random placing of two points in any direction, when the two points are 4 meters apart. Only the very latest *Ranger* photographs had resolutions capable of yielding 4-meter base line statistics. It is as yet unclear whether this histogram adequately portrays the majority of the large, flat mare areas. Some of the later *Surveyors* appear to have landed inside larger craters or on slopes somewhat steeper than a few degrees and this may or may not be mere statistical chance. The median slope derived from this analysis of the *Ranger* 7 photography is about $4\frac{1}{2}°$. Note that very few slopes are calculated

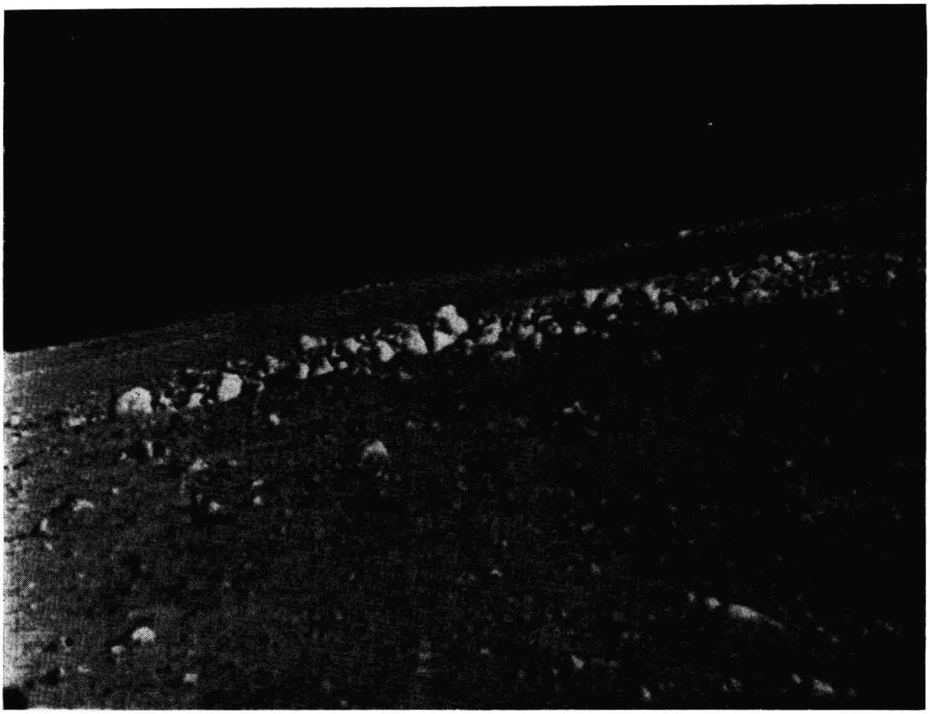

FIG. 3. Rock-rimmed mare crater.

to be steeper than 15°. It may be some time before similar slope distribution information is acquired again. The distance-ranging capability of *Surveyor* was inadequate for good statistics and clinometry with Lunar Orbiter photographs has not been completely successful to date.

In contrast to the rubble lying near the *Surveyor* 1 site, Fig. 6 shows steep slopes and more freshly broken rubble on the interior of the crater in which *Surveyor* 3 landed. There are more rocks lying near the spacecraft and the rocks themselves have a sharper, more angular, harder, more freshly broken appearance. The large, curved fracture surfaces on some of the rocks are highly suggestive of the appearance of freshly broken basalts or other hard, fine-grained, crystalline rocks on Earth.

Figure 7 contrasts with the mare areas in that the overall topography is generally smooth but rather hilly. This is a mosaic from the *Surveyor* 7 landing site, north

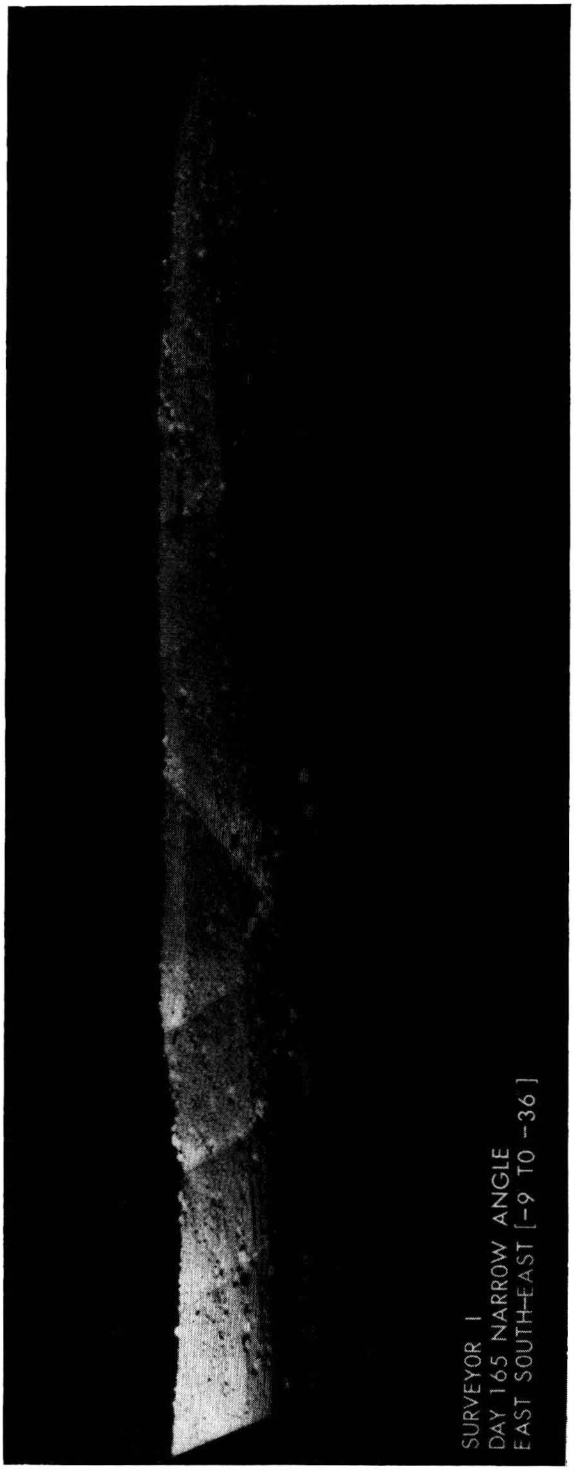

FIG. 4. Crater with blocky raised rim.

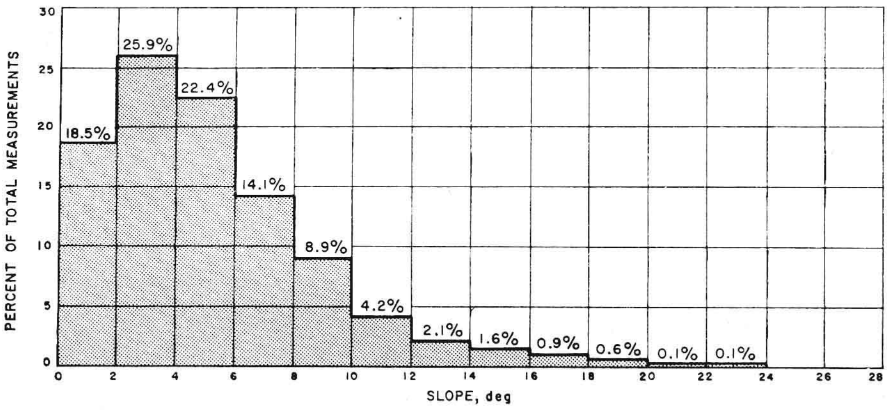

FIG. 5. Histogram of mare slope distribution on 4-meter base line.

FIG. 6. Inside of crater, *Surveyor* 3.

of Tycho in the southern lunar highlands. Whereas the overall relief in the mare areas, except for the large craters, was only a few meters, the overall relief here between ridge tops and valley bottoms is about 160 meters. The ridges on the skyline are a little over 2 kilometers away. The large concentration of rocks in the near foreground may be due to fragmentation of a large secondary block which produced the nearby hole in landing or may represent rocks dug from the hole by impact of some other body. The details of the surface on the scale of millimeters and centimeters is much the same here as it was in the mare areas. It is quite rough,

FIG. 7. Hilly terrain near *Surveyor* 7.

which is no surprise considering the well-known back-scattering properties of the surface at optical wavelengths.

II. CHEMICAL COMPOSITION

Table 1 presents a comparison of alpha-scattering chemical analyses of the lunar surface from *Surveyors* 5, 6 and 7. The analyses are presented in atomic percent; that is, numbers of atoms rather than weight percent as oxides, as rock analyses are normally presented. Below the *Surveyor* analyses are several common terrestrial rock groups, plus analyses from various meteorite groups. The best match to the *Surveyors* 5 and 6 analyses, those from the flat, mare areas, are the basalt group and the eucrite/howardite basaltic achondrite group. On the basis of Table 1 alone, it is difficult to select among these alternatives except on the basis

TABLE 1. COMPARISON OF *Surveyor* CHEMICAL ANALYSES WITH SOME ROCK AND METEORITE TYPES (From Franzgrote *et al.*, 1968)

	Element, atomic percent[a]							
	C	O	Na	Mg	Al	Si	"Ca"[b]	"Fe"[b]
Surveyor 5	<3	58±5	<2	3±3	6.5±2	18.5±3	13±3	
Surveyor 6	<2	57±5	<2	3±3	6.5±2	22 ±4	6±2	5±2
Surveyor 7	<2	58±5	<3	4±3	8 ±3	18 ±4	6±2	2±1
Chondrites								
LL group	—	58.0	0.7	15.2	1.0	16.0	1.0	8.1
Carbonaceous (type 1)	6.6	55.4	0.6	8.4	0.7	8.4	12.3	7.8
Eucrites	—	60.7	0.5	3.6	5.7	18.8	4.2	6.9
Howardites	—	60.3	0.4	7.1	4.6	18.5	3.1	5.8
Dunite	—	59.0	0.1	23.9	0.3	14.1	0.2	2.3
Peridotite	—	58.9	0.4	19.3	1.9	15.5	1.4	2.5
Anorthositic gabbro	—	61.4	2.6	1.2	9.4	19.0	4.4	1.7
Basalt tholeütic)								
Average oceanic	—	61.3	1.5	4.1	6.3	18.1	4.5	4.3
Average continental	—	61.5	1.7	3.2	7.0	18.8	4.3	3.7
Basalt (alkalic)								
Average oceanic	—	60.8	2.1	3.8	6.7	17.2	4.8	4.3
Average continental	—	60.8	2.4	3.9	6.8	17.2	4.8	3.9
Andesite	—	61.2	2.9	0.1	6.9	21.1	3.1	3.0
Granite	—	63.4	2.3	0.4	5.9	24.4	2.7	1.0
Tektite	—	64.0	1.0	1.1	5.4	25.2	3.4	1.5

[a]Excluding elements lighter than beryllium.
[b]"Ca" and "Fe" denote elements with mass numbers between approximately 30 to 47 and 48 to 65, respectively.

of the calcium and iron values. The *Surveyors* 5 and 6 calcium-plus-iron totals are 11% to 13%. The eucrite/howardite totals are similar. Basalt totals tend to be somewhat less. There is no direct evidence of carbon from the analyses on the surface, although the data only show at this point that there is less than 2% or 3% carbon. This small amount contrasts with the carbon in type 1 carbonaceous chondrites, which is over 6%.[(1)]

The *Surveyor* 7 analysis differed from the previous mare analyses only slightly, in that it is somewhat more sodic and aluminous and contains considerably less iron. There is no good match among any of the comparison rocks listed above for the *Surveyor* 7 analysis. None of the three *Surveyor* analyses matches the andesite, rhyolite or tektite analyses given at the bottom of the table. It should be noted at this point that one of the experiments, carried on all of the later *Surveyor* flights, was designed to test the magnetic susceptibility of soil particles. Magnets were carried on the footpads of *Surveyors* 5 and 6 and on the base plate of the soil sampler of *Surveyor* 7. The amount of particulate materials adhering to the magnet in all cases was quite small. Laboratory calibration experiments show that crushed basalts with a few percent magnetite at most best duplicated the results from the magnets on the lunar surface. Particulates in the laboratory which contain an appreciable amount of free iron made gross clumping about the poles of the

FIG. 8. Gravity map from Muller and Sjogren (1968).

magnets and this effect definitely was not present on the Surveyor magnets. The iron present in the alpha-scattering analysis, then, must be largely as iron oxides or as oxidized iron in silicates. In summary, therefore, the chemical analyses indicate that at least the maria are composed of rocks of basaltic chemical nature and the highlands may or may not be grossly similar. Some features of the highland *Surveyor* 7 analysis suggest that there is perhaps a rock mixture within the soil particles. The tentative identification of basaltic rocks in the broad maria corresponds well with the subjective feeling of most geologists that many of the freshly broken, angular rock blocks, for example those seen from *Surveyor* 3 and shown in Fig. 6, are fine-grained, crystalline rocks such as basalts. One further indication of the kinds of rocks which might exist in the mare areas has come rather recently from tracking analysis of *Lunar Orbiter* spacecrafts, carried out at the Jet Propulsion Laboratory.